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Application of Metaheuristic Optimization Methods for Reliability Enhancement of Meshed Distribution System based on AHP

K. B.Kela[1] ,Bhavik N.Suthar[2] , L. D. Arya[3]

[1] *Electrical Engineering Department , L D College of Engineering, Ahmedabad , Gujarat-380015, India*
[2] *Electrical Engineering Department , Government Engineering College, Bhuj, Gujarat- India*
[3]*Electrical Engineering Department, Medi-Caps University, Indore (MP)-453331, India*

Abstract: *This paper describes a methodology for enhancing the reliability performance of meshed distribution system. In this paper, the reliability indices for sample meshed distribution network is optimized. An objective function in terms of customer and energy based reliability indices and their respective target values is selected. The weightage coefficients for these indices are determined by a multi criteria decision making method named Analytic Hierarchycal Process (AHP). These indices are dependent on the failure rates and repair times of the sections present in the distribution systems. By modifying failure rates and repair times, the cost associated to them modifies. Hence, the optimization of objective function is achieved by modifying failure rate and repair time of each section of the sample distribution system considering the budget allocated to achieve the same. The problem has been solved by applying Jaya and Flower Pollination (FP) optimization algorithms. The algorithms have been implemented on the sample meshed distribution system.*

Keywords*- Meshed distribution systems , Reliability indices ,Repair time ,Failure rate ,Jaya optimization algorithm, Flower Pollination Algorithm (FP);AHP*

I. INTRODUCTION

As the distribution systems proves to be final link between transmission network and end customers, they are expected to render continuous and quality electric service to their customers at a reasonable rate with economical use of available facilities and options. It is required to intensify fault prevention and corrective maintenance measures for maintaining reliable services to the customers. Additional budget is required for the same. In fact by doing so, failure rate and repair time of the sections are modified. Generally during planning stage, fault tolerant measures should be included. Later on such additional measures may not be always justified as they require extra budget to fulfill them. In this paper, the objective has been to achieve desired reliability goals having modified the failure rates and repair times of the distributor sections. Here, this modification has been done by providing rational weightage to the customer and energy oriented reliability indices. Regarding the evaluation and enhancement of distribution reliability, various aspects have been presented so far by researchers [1]. Chowdhury *et al.* [2] has done a casual analysis of distribution system reliability performance. The methodology used to assess the historical reliability performance of utility electric distribution systems is outlined here. Louit*et al.* [3] developed a technique for determination of optimal interval for major maintenance activities in distribution systems. Arya *et al.* [4] proposed a methodology for reliability optimization of radial distribution systems by applying differential evolution. The optimal values of repair times and failure rates of each section are determined here. Arya *et al.*[5] has described a methodology for reliability assessment of electrical distribution system accounting random repair time omission for each section. R. Arya *et al.*[6] has described an algorithm for optimum modifications for failure rate and repair time for a radial electrical distribution system. Coordinated aggregation based particle swarm optimization (CAPSO) has been used for optimization. The same author [7] has described an analytical methodology for reliability evaluation and enhancement of distribution system having distributed generation (DG). In this paper, standby mode of operation of DG has been considered for this purpose. Bakkiyaraj and Kumarappan [8] used Monte Carlo simulation (MCS) along with PSO for reliability planning of power network in terms of forced outage rate (FOR) allocation. Damghani*et al*.[9] used PSO for multi objective planning and redundancy allocation. R. Arya *et al*.[10] has found distribution reliability indices neglecting random interruption duration. The methodology is based on smooth boot strapping technique along with Monte Carlo simulation (MCS). Gupta et*al*. [11**]** presented an efficient Genetic Algorithms (GAs) based method to improve the reliability and power quality of distribution systems using network reconfiguration. Yssaad et*al*. [12] describedreliability centered maintenance optimization for power distribution systems**.** Bakkiyaraj*et al.* [13] has given optimal reliability enhancement model by applying population based natural computational optimization algorithms.Hashemi-Dezaki*et al.* [14] has proposed a novel approach of internal loops (ILs) to optimize electrical distribution system reliability. Li Duan*et al.* [15] has presented a method for the reconfiguration of distribution network for loss reduction and reliability improvement by enhanced genetic algorithm. Yssaad*et al.* [16] has presented a new rational reliability centered maintenance optimization method for power distribution system.

This paper deals with developing an algorithm to enhance the reliability indices of distribution system using an analytic hierarchical process (AHP) [17]. The AHP method has proven to be effective in solving multi-criteria problems, involving many kinds of aspects. In view of this a multi-objective function has been proposed to achieve the motives of the paper giving proper weightage to all the terms in the function.

II. CUSTOMER ORIENTED AND ENERGY BASED RELIABILITY INDICES

Various customer oriented reliability indices being used frequently by distribution utilities are SAIFI, SAIDI and CAIDI. They are defined as follows [1]:
System average interruption frequency index (SAIFI)

$$\mathrm{SAIFI} = \frac{\sum \lambda_{sys,i} N_i}{\sum N_i} \quad (1)$$

System average interruption duration index (SAIDI)

$$\mathrm{SAIDI} = \frac{\sum U_{sys,i} N_i}{\sum N_i} \quad (2)$$

One of the most important energy based reliability indices is average energy not supplied (AENS), which is defined as follows.

$$\mathrm{AENS} = \frac{\sum L_i U_{sys,i}}{\sum N_i} \quad (3)$$

where 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. Expressions for evaluation of $\lambda_{sys,i}$ and $U_{sys,i}$ for each load point are given as follows.

$$\lambda_{sys,i} = \sum \lambda_k \quad (4)$$

$$U_{sys,i} = \sum \lambda_k r_k \quad (5)$$

λ_k, r_k denote failure rate and average repair time of k^{th} distributor segment respectively, where $k \epsilon s$, s being the set of distributor segments connected in series up to i^{th} load point.

III. PROBLEM FORMULATION

This sections describes a method for reliability enhancement of radial distribution system. Here, to achieve this , optimal values of failure rates and repair times of the distributor segments are found. These are the primary reliability indices and they measure the adequacy of the system undoubtedly. Though these indices are of fundamental importance, they may not always give the total performance of the system. As severity of the outages are given by customer and energy based indices mentioned in section 2. , they are frequently used to depict the characterization of distribution system.
These indices implicitly represent the various associated cost which may be mitigated by selecting proper desired values of these indices. SAIFI represents cost associated to system failure considering relative weightage of customers also connected to the load points. Similarly, SAIDI is related to the system interruption duration which is the product of system failure rate and average annual outage $(\lambda_{sys} r_{sys})$ of the system. CAIDI represents customer satisfaction of overall system. Average energy not supplied (AENS) implicitly represents cost of energy not supplied to consumer and hence is an indicator of not only customer satisfaction but also represents loss of revenue to the utility. Hence, these indices are so important that their desired target values are required to be selected. As these indices mainly depend on failure rates and repair times of the distributor sections, modification of them will require additional budget to achieve the desired targets. Hence lesser are the target values of these indices, higher will be the cost associated with preventive maintenance and corrective repair.
Though all these indices keep significance from the performance point of view of the system, AENS may be given little more significance sometimes as it is related to energy not supplied during the interruptions. Considering this, weightage to this indices has been decided. This has been done by Analytic Hierarchy Process (AHP) which is used to solve multi objective problems effectively.
In view of this, reliability optimization problem is formulated as follows. The objective function to be minimized is selected as,

$$J = \left(w_1 \frac{\mathrm{SAIFI}}{\mathrm{SAIFI_t}}\right) + \left(w_2 \frac{\mathrm{SAIDI}}{\mathrm{SAIDI_t}}\right) + \left(w_3 \frac{\mathrm{AENS}}{\mathrm{AENS_t}}\right) \quad (6)$$

Objective function (6) is minimized subject to following inequality constraints.
(i) Constraints on the decision variables

$$\lambda_{k,min} \leq \lambda_k \leq \lambda_{k,max} \quad (7)$$

$$r_{k,min} \leq r_k \leq r_{k,max} \quad (8)$$

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

(ii) Total modification cost of failure rates and repair times of all the sections should be less than the specified budget allocated.

$$\sum_{K=1}^{N_C} (\alpha_K / \lambda_K^2 + \beta_K / r_K) \leq CBUDGET \quad (9)$$

Where,

λ_k ,r_k are average failure rate and repair time of k^{th} section. $\lambda_{k,min}$ and $r_{k,min}$ are reachable minimum 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. $SAIFI_t$, $SAIDI_t$, and $AENS_t$ are target values of the respective indices. *CBUDGET* is the total budget available for preventive maintenance and corrective repair. α_K, β_K are cost coefficients. w_1,w_2 and w_3 are the relative weightage given to the normalized values of SAIFI, SAIDI and AENS in the objective function (6).The objective function of equation (6) is minimized subject to constraints (7), (8) and (9). Thus optimal values of failure rate and repair time for each section of the distribution systems are obtained. The overall failure rate is contributed by various failure modes. Some may have constant failure rates while some failure modes contribute to increasing failure rate. Such types require preventive maintenance and repairing or replacement of subcomponent in time so as to have overall failure rate practically constant. The optimization in this paper is proposed to carry out considering overall failure rate which is combination of failure rates due to various failure modes.

By failure rate optimization, targets can be assigned to the crew involved in maintenance activities: preventive maintenance and corrective repair and persons involved in managerial work. Thus, by doing so ultimately failure rates can be reduced reaching to their root causes. The modes responsible for higher failure rates should be given more weightage in regards to preventive maintenance efforts. In the same way, targets may be set to reduce corrective repair time. The objective function is the sum of the normalized weighted values of SAIFI, SAIDI and AENS. The weightage are decided by AHP which is explained in the later section. Constraints (7) and (8) give bounds on the decision variables. Lower bounds give minimum reachable value of the decision variables decided with respect to reliability growth testing model [18]. Similarly upper bounds on these decision variables are obtained using the reliability monitoring mode. As the values of decision variables change, cost varies. Cost required to achieve lesser values of decision variables will be higher and vice versa. Based on the past data, a cost curve can be plotted and a cost function can be decided. In this paper, based on Duane's growth model [18], the typical cost functions have been selected for each component. Inequality constraints on total cost of repair time and failure rate has been considered and given as relation (9).The formulated problem is proposed to be solved using Jaya [19] and Flower Pollination (FP) [20] optimization algorithms for the meshed sample networks and a comparison is made. Thus optimal values of repair time and failure rates are obtained for each section of the distribution system considering budget allocated for them.

IV. ANALYTIC HIERARCHICAL PROCESS (AHP)

The AHP method has proved to be effective in solving multi-objective problem [17]. It is used as the decision making technique because of its efficiency in handling quantitative and qualitative criteria for solution of a problem.

The AHP divides a complex decision problem in to a hierarchical structure. A pairwise comparison is made to decide relative weightage for different individual options/alternatives /objectives. Pairwise comparisons are usually quantified by the linear scale or the nine-point intensity scale proposed by Saaty [17]. By doing pairwise comparison, each linguistic term is transformed in to numerical intensity values like {9,8,7,6,5,4,3,2,1,1/2,1/3,1/4,1/5, 1/6,1/7,1/8,1/9}. A judgement matrix is formed based on this as follows.

$$M = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{10}$$

Where, $a_{ij} \in \{9,8,7,6,5,4,3,2,1, 1/2\ ,1/3\ ,1/4\ ,1/5\ ,1/6\ ,1/7\ ,1/8\ ,1/9\}$ and $a_{ii} = 1$

where $1 \leq i,j \leq n$. a_{ij} shows pairwise judgement representation. Here, $a_{ij} = \frac{1}{a_{ij}}$.

If M is perfectly consistent, then the principal eigenvalue D_{max} is equal to number of comparisons n.

That is $Mw = nw$.

Where, $w = (w_1, w_2, \ldots, w_n)^T$ is the principal eigenvector corresponding to D_{max} .

The effectiveness of the judgement matrix M and consistency of the results are checked by an index called consistency ratio (CR) as follows [21].

$$CR = \frac{\left(\frac{D_{max} - n}{n-1}\right)}{RI} \tag{11}$$

Where, D_{max} is the largest eigenvalue of matrix M and RI is the random index. Here RI=0.58 for n=3 [17].

The AHP algorithm :

The steps of the AHP algorithm are as follows.

1. Set up the hierarchical model by comparing the different objectives to be evaluated.
2. Construct a judgement matrix M. It reflects the user's knowledge about the relative importance of each objective. For the objective function used in this paper, the matrix formed is as shown in Table 2.
3. Calculate the maximum eigenvalue and corresponding eigenvector for the judgement matrix M. By normalizing the eigenvector the vector containing the weightage of different objectives is found as shown in Table3.
4. Find consistency ratio CR by (11)
5. A consistency ratio of 0.10 or less is considered acceptable.

V. JAYA ALGORITHM: AN OVERVIEW

Jaya algorithm is an optimization algorithm developed by R V Rao [19] in 2015 to solve constrained and unconstrained optimization problems. The algorithm is based on the concept that the solution obtained for a given problem should always try to get closer to success (i.e. reaching the best solution) and try to avoid failure (i.e. moving away from the worst solution). The algorithm strives to become victorious by reaching the best solution and hence it is named as Jaya (a Sanskrit word meaning victory).
Following are the notations used for describing the Jaya.
M : population size , D : number of variables ,k_{max} : maximum number of allowable generations

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

$$S^0 = [X_1^0, X_2^0, \ldots \ldots, X_M^0] \quad (12)$$

$$X_i^0 = [X_{i1}^0, X_{i2}^0, \ldots., X_{iD}^0]^T \quad (13)$$

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

$$X_{ij}^0 = X_{j,min} + (X_{j,max} - X_{j,min})rand_j \quad (14)$$

$X_{j,min}$ 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

$$X_{j,i}^{(k+1)} = X_{j,i}^{(k)} + rand1_j(X_{j,best}^{(k)} - |X_{j,i}^{(k)}|) - rand2_j(X_{j,worst}^{(k)} - |X_{j,i}^{(k)}|) \quad (15)$$

$X_{j,best}^{(k)}$ is the current best solution and $X_{j,worst}^{(k)}$ is the current worst solution found among all solutions at the current generation/iteration. $rand1_j$ and $rand2_j$ are two different random numbers in the range [0,1].

Step-(c)Comparing the fitness of the updated vectors with the initial vectors

$$X_i^{(k+1)} = \begin{cases} X_i^{k+1}, & if\ f(X_i^{k+1}) < f(X_i^{(k)}) \\ X_i^{(k)} & otherwise \end{cases} \quad (16)$$

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. The procedure is terminated if a maximum number of generations (k_{max}) have been executed or no improvement in objective function is noticed in a pre-specified generations.

V1. Solution Methodology using Jaya algorithm

Step 1. Data input $\lambda_{i,max}$, $r_{i,max}$ $\lambda_{i,min}$, $r_{i,min}$, $SAIFI_t$, $SAIDI_t$, $CAIDI_t$and $AENS_t$.

Step 2. Initialization: Generate a population of size 'M' for failure rate λ and repair time r each, 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 (7) and (8).

Step 3. Evaluate SAIFI, SAIDI, CAIDI and AENS as described in sec.2 for vectors of the population.

Step 4. Calculate value of objective function J for all vectors in the population i.e.$J(X_i^{(k)})$, $i = 1, \ldots \ldots \ldots \ldots \ldots, 'M'$ as given by relation (6).

Step 5. Based on the value of objective function, identify the best and worst solution vectors $X_{best}^{(k)}$ and $X_{worst}^{(k)}$ respectively

.**Step 6.** Set generation counter $k = 1$.

Step 7. Select target vector, $i = 1$

Step 8. Find the updated value of the vector by relation (15).

Step 9. Compare the fitness of the updated vectors with that of the initial vectors and retain the best ones using relation (16).

Step 10. Increase target vector$i = i + 1$. If $i \leq M$, repeat from Step 8 otherwise increase generation count $k = k + 1$

.**Step 11**. Repeat from step 7 if the desired optimum value is not found or $k \leq k_{max}$.

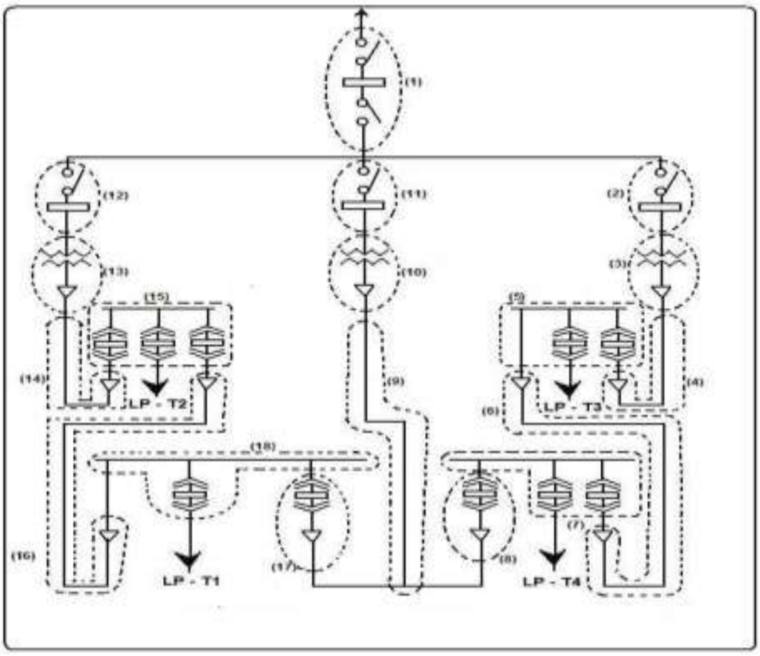

Fig 1. Sample Meshed Distribution System

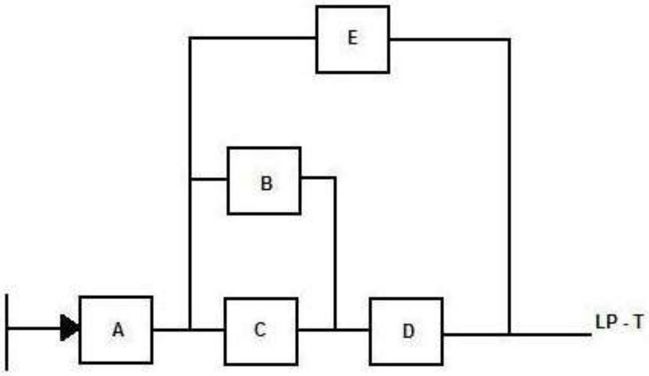

Fig 2. Reliability logic diagram of the sample meshed distribution system

VII. RESULTS AND DISCUSSIONS

The developed algorithm has been implemented on the sample test system and results are described as follows. The developed algorithm in this case has been implemented on a sample meshed distribution system [22]as shown in Fig 1. for reliability optimization. The system data related to current and minimum failure rates and repair times of different distributor sections, average load and number of customers at load points and cost coefficients for each segment of the distributor have been taken from [23]. The total budget *CBUDGET* has been given Rs. $4x10^6$ as required in relation (9). Table 1. shows selected control parameters for Jaya, and FP techniques. Fig 2. is a reliability logic diagram of the meshed distribution system of Fig.1 to evaluate reliability indices at load points LP-T1 to LP-T4. Table 2. gives the judgement AHP matrix. Table 3. gives the values of the three coefficients w_1, w_2 and w_3 found by AHP. Table 4. gives optimized values of failure rates and repair times as obtained by all the techniques. Table 5. shows the current and optimized values of all reliability indices and objective function obtained by all the methods.

Table 1. Control Parameters for Jaya and FP for meshed network

Sr No.	Parameters	Values of parameters
1	Population size(Jaya and FP)	20
2	Max generation specified(k_{max})(Jaya, FP)	150
3	Updated step size ($\propto$) (FP)	0.01
4	Distribution factor (β) (FP)	1.5
5	Switch probability (FP)	0.8

Table 2. AHP Matrix

	SAIFI	SAIDI	CAIDI	AENS
SAIFI	1	1/5	1/5	1/5
SAIDI	5	1	1	1
CAIDI	5	5	1	1
AENS	5	1	1	1

Table 3. Coefficients

w_1	w_2	w_3	w_4
0.0625	0.313	0.313	0.313

Table 4. Optimized values of failure rates and repair times as obtained by Jaya and FP, and corresponding cost incurred for meshed network

Variables	Magnitudes as obtained by Jaya	Magnitudes as obtained by FP
λ_1 /year	0.25420	0.25420
λ_2 /year	0.09000	0.09000
λ_3 /year	0.05600	0.05600
λ_4 /year	0.05676	0.05676
λ_5 /year	0.08330	0.08330
λ_6 /year	0.00883	0.00883
λ_7 /year	0.09230	0.09230
λ_8 /year	0.09000	0.17801
λ_9 /year	0.00846	0.00846
λ_{10} /year	0.02600	0.02600
λ_{11} /year	0.10303	0.10301
λ_{12} /year	0.10300	0.10300
λ_{13} /year	0.05600	0.11000
λ_{14} /year	0.05676	0.11353
λ_{15} /year	0.06833	0.06833
λ_{16} /year	0.00883	0.00883
λ_{17} /year	0.09000	0.17801
λ_{18} /year	0.08330	0.08330
$r_{1(h)}$	3.34873	3.34873
$r_{2(h)}$	3.06705	4.06154
$r_{3(h)}$	10.73228	10.73227
$r_{4(h)}$	2.12253	2.12253
$r_{5(h)}$	3.39403	3.39403
$r_{6(h)}$	9.25010	9.25010
$r_{7(h)}$	3.39403	3.39403
$r_{8(h)}$	3.75211	9.75211
$r_{9(h)}$	15.80000	15.80000
$r_{10(h)}$	27.56522	18.56000
$r_{11(h)}$	5.23492	5.23492
$r_{12(h)}$	2.01235	5.23492
$r_{13(h)}$	10.73225	21.73221
$r_{14(h)}$	5.56571	5.56571
$r_{15(h)}$	6.35252	6.35252
$r_{16(h)}$	9.25010	13.55510
$r_{17(h)}$	4.35432	9.75212
$r_{18(h)}$	3.39403	3.39403
Cost incurred(Rs.)	3844177.16421	3807227.21014

Table 5. Current and optimized reliability indices and corresponding value of objective function for meshed distribution system

Sr. No.	Index	Current Values	Optimized values		Threshold values
			Jaya	FP	
1	SAIFI(interruptions/customer)	0.689895	0.33777	0.33787	0.5000
2	SAIDI(h/customer)	4.854797	1.17374	1.17422	4.0000
3	CAIDI(h/customer interruption)	7.037003	3.47493	3.47536	5.0000
4	AENS(kW/customer)	20.53386	4.96135	4.96330	10.000
	Objective function (J)	1.381518	0.42401	0.42414	

VIII. Conclusions

The algorithm in this paper is used to find out optimum values of customer oriented and energy based reliability indices while specified budget is allocated to achieve the same. This algorithm is applied to sample meshed distribution network in this paper. The optimum values are found by a newly developed Jaya and Flower Pollination (FP) optimization algorithms. It has been authenticated by making comparison of the values found. It has been found that the values found by FP are quite near to those found by Jaya.

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