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Application of Sensitivity Analysis for Improving Reliability Indices of a Radial Distribution System

Rajesh Arya*, S.C. Choube**, L.D. Arya and R.K. Shrivastava*******

**Electrical Engineering Department, Medicaps, Indore, (MP)*
***Electrical Engineering Department, UIT-RGTU, Bhopal, (MP)*
****Electrical Engineering Department, SGSITS, Indore, (MP)*
*****Electrical Engineering Department, UIT-RGTU, Bhopal, (MP)*

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ABSTRACT : Fault avoidance and corrective maintenance are important measures for reliability improvement of a radial distribution system. The two measures decrease system down time and increases mean up time of the system. These happen due to the fact that failure rate and average repair time of the components are reduced. A methodology has been developed in this paper for failure rate and repair time allocation to each component of radial distribution system. A sensitivity based approach has been proposed. Penalty cost function has been introduced. The components having least sensitivity of penalty cost function with respect to system interruption time and failure rate have been selected for the improvement in failure rate and repair time. The algorithm has been implemented on a sample radial distribution system.

Keywords : Distribution system; Reliability; Unavailability; Failure rate

I. INTRODUCTION

A primary requirement of any distribution system is service continuity. Continuity of service is better judged by quantitative estimates of reliability indices. The important reliability indices are average interruption duration and average failure rate of the system. Many researchers have developed methodologies for reliability evaluation of distribution systems. For many years say until 1965, an acceptable level of reliability has been based on judgement and experience [1, 2, 3]. The indices commonly used to represent distribution system reliability are system failure rate and interruption durations at the load point.

Sallam et al [4] developed a methodology for evaluating optimal reliability indices for distribution system using gradient projection method. Once the optimal reliability indices are determined the modification of system by equipment replacement and future system planning may be performed so as to have minimum interruption cost. Chang and Wu [5] presented a methodology for obtaining optimal reliability design for an electrical distribution system using a primal dual interior point algorithm considering multiple load point. Chowdhury and Custer [6] presented a value based approach for designing urban distribution system. Bhowmik et al [7] described a distribution network planning strategy by considering a non-linear objective function with linear and non-linear constraints for radial distribution system. The algorithm includes substation as well as feeder optimization. Modified genetic algorithm has been used for reliability design of a distribution system by Su and Lii [8]. The total cost is minimized which implies apparatus cost investment and system interruption cost. Reliability constraint on load points has been considered.

It is noted from the above mentioned references that reliability of a system may be enhanced by adding redundancy or by reducing failure rate and repair time of each component. These are termed as fault tolerant and fault avoidance measures. During operational conditions usually fault avoidance measures e.g. preventive maintenance are less expensive than fault tolerance measures, further average repair time is reduced by additional incentives to repair crew or better repair facility. Thus availability of each component is increased thus system reliability indices are enhanced. Usually any optimization technique gives the optimal solution by affecting all the decision variables i.e. failure rate and repair time of all the components. This way corrective efforts/preventive maintenance efforts have to be intensified in all segments of the system which may require substantial managerial cost which may negate the advantages obtained by increased reliability indices. In view of this discussion in this paper an algorithm has been developed based on sensitivity coefficient which permits to reschedule the decision variables at selected components which are most effective in reliability enhancement. This way increased managerial efforts are required to be concentrated at these selected components.

II. APPROXIMATE RELATIONS FOR RELIABILITY INDICES FOR RADIAL DISTRIBUTION SYSTEM

A radial system is a series system. For each series path of a radial distribution system the failure rate for the system up to the end load point is given as follows [9].

$$\lambda_{sys} = \sum_i \lambda_i \qquad \text{... (1)}$$

The unavailability is expressed as

$$U_{sys} = \sum_i \lambda_i r_i \quad \text{... (2)}$$

In (2) above λ_i is expressed in per year and r_i, average repair time is usually expressed in hours. Hence U_{sys} system unavailability is given as hrs per year. In principle if λ_i and r_i are expressed in years than U_{sys} is a probability.

Average system interruption duration is given as

$$r_{sys} = \frac{\sum_i \lambda_i r_i}{\sum \lambda_i} \quad \text{... (3)}$$

In general for any equivalent component of a series system following relation follows

$$U_{sys} = \lambda_{sys} r_{sys} \quad \text{... (4)}$$

where

U_{sys} is unavailability in hrs/year

λ_{sys} is system failure rate/year

r_{sys} is average interruption duration

$\lambda_i r_i$ is failure rate and average repair time of ith component

It is obvious from (4) that one can select two indices independently and remaining one will be depending on two specified indices.

III. COST FUNCTION OR PENALTY FUNCTION IDENTIFICATION

There is always a cost associated with modifications in failure rate and repair time of a component owing to increased fault avoidance measures. The preferred approach is to formulate the cost function using previous data analysis and relationships may be obtained between cost of improvement and failure rate (repair time) modifications. In general such cost function is not available. Hence instead of actual cost for failure rate modification a penalty function of the following form has been used

$$C_i(\lambda_i) = \frac{\lambda_i^{\,0} - \lambda_i}{\lambda_i - \lambda_{i,\min}} \quad \text{... (5)}$$

In above $\lambda_i^0$and $\lambda_{i,\min}$ are current failure rate of the component and minimum reachable railure rate respectively.

Expression (5) indirectly reflects the penalty (cost) on failure rate modification. As one approaches towards li,min higher penalty is observed. In fact when li becomes equal to $\lambda_{i,\min}$ penalty cost approaches infinity. Further as λ_i is modified numerator also increased. Hence the $C_i(\lambda_i)$ is such that as failure rate reduces penalty increases. Further it is assumed that failure rates of the components will take values lower than current values. The penalty or cost is a function of range of improvement which is the difference between current failure rate (repair time) and minimum achievable failure rate (repair time). Total cost of failure rate modification for all components in a series path up to an end load point is given as

$$C_T(\lambda) = \sum_i C_i(\lambda_i) \quad \text{... (6)}$$

Similarly cost function for modification in average repair time is adopted as follows

$$C_r(r_i) = \frac{r_i^{\,0} - r_i}{r_i - r_{i,\min}} \quad \text{... (7)}$$

r_i^0 and $r_{i,\min}$ are current repair time and minimum reachable repair time of i^{th} component, r_i modified average repair time.

It is obvious that more is the decrement in repair time higher is the cost associated with it. As r_i equals to $r_{i,\min}$ the value of the penalty function becomes infinite. Total cost for repair time modification is given

$$C_T(r) = \sum_i C_i(r_i) \quad \text{... (8)}$$

IV. USING THE TEMPLATE

A Sensitivity of cost function (6) for modification in failure rate of k^{th} component is given as

$$\frac{\delta C_T}{\delta \lambda_k} = \frac{\lambda_{i,\min} - \lambda_k^{\,0}}{(\lambda_k - \lambda_{k,\min})^2} \quad \text{... (9)}$$

Now from relation (1) following sensitivity follows

$$\frac{\delta \lambda_{sys}}{\delta \lambda_k} = 1 \quad \text{... (10)}$$

Now the sensitivity for system cost changes with respect to system failure rate changes for failure rate modification for k^{th} component is written as

$$SC\lambda_k = \frac{\delta C_T}{\delta \lambda_k} \frac{\delta \lambda_k}{\delta \lambda_{sys}}$$

From (9) and (10) it follows

$$SC\lambda_k = \frac{\lambda_{k,\min} - \lambda_k^{\,0}}{(\lambda_k - \lambda_{k,\min})^2} \quad \text{... (11)}$$

The component which has got least magnitude of above sensitivity $SC\lambda_k$ must be selected for failure rate modification.

Similarly sensitivity of cost function (8) for modification in average repair time of k^{th} component is written as follows

$$\frac{\delta C_T(r)}{\delta r_k} = \frac{\delta C_k(r_k)}{\delta r_k} = \frac{r_{k,\min} - r_k^{\,0}}{(r_k - r_{k,\min})} \quad \text{... (12)}$$

Now the sensitivity of cost modification of repair time of the component with respect to change in average interruption time r_{sys} is written as follows

$$SCr_k = \frac{\delta C_T(r)}{\delta r_{sys}} = \frac{\delta C_T(r)}{\delta r_k} \cdot \frac{\delta r_k}{\delta r_{sys}} \quad \text{... (13)}$$

Now $\frac{\delta r_k}{\delta r_{sys}}$ is evaluated using relation (3) as follows

$$\frac{\delta r_k}{\delta r_{sys}} = \frac{\lambda_{sys}}{\lambda_k} \quad \text{... (14)}$$

Putting (12) and (14) in (13) following final relation for desired sensitivity is obtained

$$SCr_k = \frac{\delta C_T(r)}{\delta r_{sys}} = \frac{(r_{k,\min} - r_k^{\ 0})\lambda_{sys}}{\lambda_k (r_k - r_{k,\min})} \quad \text{... (15)}$$

Next section illustrates the application of these sensitivities in obtaining modification for failure and repair time of the selected components. A segment/component having least sensitivity $SC\lambda_k/SCr_k$ is selected for failure rate/repair time modification.

V. COMPUTATIONAL ALGORITHM

The objective is to allocate failure rate and repair time for various segments of distribution systems such that at each end load point (q = 1,..... ELP) following inequalities are satisfied

$$\lambda_{sys,q} \le \lambda_t \quad \text{... (16)}$$

$$r_{sys,q} \le r_t \quad \text{... (17)}$$

λ_t and r_t are target values of system failure rate and average interruption duration respectively.

$\lambda_{sys,q}$ is average system failure rate for q^{th} end load point.

$r_{sys,q}$ is average interruption duration for q^{th} end load point.

Now average interruption duration per year at q^{th} end load point is given as

$$U_{sys,q} = \lambda_{sys,q} . r_{sys,q}$$

The computational algorithm is explained in following steps

(*a*) Data input: Current failure rate (λ_i^0) and repair time (r_i^0). Specify $r_{i,\min}$ and $\lambda_{i,\min}$.

(*b*) Identify each end load point q = 1, ... ELP and segments in the serial path leading to q.

(*c*) Calculate $r^0_{sys,q}$, $\lambda^0_{sys,q}$ using relation (1) - (3).

(*d*) Set iteration count iter = 0.

(*e*) Select one of end load point q having greatest $\lambda_{sys,q}$.

(*f*) Evaluate sensitivity $SC\lambda_k$ and SCr_k for all components in the serial path leading q.

(*g*) Obtain modification in failure rate and repair time for the components having least value of the sensitivity $SC\lambda_p$ and SCr_1 respectively as follows

$$\Delta\lambda_p = -c.\lambda_p^{\ 0}$$
$$\Delta r_1 = -c.r_1^{\ 0}$$

c is a fraction of λ_p^0/r_q^0 say 0.2.

(*h*) Calculate $\lambda_{sys,q}$ and $r_{sys,q}$ with modified failure rate and repair time.

(*i*) If $r_{sys,q}$ and $\lambda_{sys,q}$ are within limits and satisfies (16) and (17), then take next end load points have been exhausted then stop.

(*j*) If in step (*i*) $\lambda_{sys,q}/r_{sys,q}$ do not satisfy the constraints (16) and (17) then, set iter = iter + 1 and repeat from step (*f*).

VI. RESULTS AND DISCUSSIONS

The developed algorithm presented in previous sections has been implemented on a sample radial distribution system[10]. The system has seven load points at 33 KV supplied from a substation as source (132/33 KV). The system has seven feeder / distributor segments. Each load point connected to lateral distributor via pole mounted transformers (33/0.4 KV) where a fuse gear is installed. In case a short circuit occurs on a lateral distributor causes fuse to blow. This will cause disconnection of the distributor from the main load points. It does not affect or cause the disconnection of any other load point. Hence reliability of the 33 KV load points is unaffected. Table-1 gives current values of failure rate and average repair time for each feeder section. These data include breaker, feeder section and bus bar failure rate and repair time but does not include failure data and repair data of lateral distributors. Same table also gives minimum reachable values of these rates and times. The system has three distant end load points *i.e.* 4, 6 and 8. Hence there are three radial paths for which system indices must be satisfied. These three end points involves components (1, 2, 3), (1, 4, 5) and (1, 2, 6, 7) in the series path respectively. At the end load point threshold values of failure rate ($\lambda_{sys,q}$) and average repair time ($r_{sys,q}$) have been taken as 0.5/year and 9 hrs respectively. The initial values of failure rates and repair times at each load point (LP) are given in Table-2. It is obvious from this table that failure rates and repair times of end point 4, 6 and 6 are more than threshold value. Similarly from the same table it is observed that the average interruption duration ($r_{sys,q}$) at each LP is more than the threshold value (8 hrs) it is highest at LP five. Sensitivities $SC\lambda_k$ and SCr_k were evaluated for the three end points so as to satisfy the constraints on $\lambda_{sys,q}$ and $r_{sys,q}$. Since there are three path (1, 4, 5) and at the end path (1, 2, 6, 7) was selected to satisfy the constraints. Algorithm as explained in the Fig. 1 was implemented to evaluate desired final values of failure rates and repair times of each component. Table-1 also depicts the values of failure rates and repair times of each component. Table-3 gives the sensitivities as calculated finally using the $\lambda_{sys} = 0.5$ and $r_{sys} = 8$. Total penalty for improvement in failure rate of the component is 44.67 and total penalty for improving repair time is 18.387.

VII. CONCLUSION

A methodology has been developed for failure rate and repair time allocation to each segment of a radial distribution system. The methodology is based on sensitivity derivation of penalty cost function. The methodology is sub-optimal since sensitivities calculated for a specific decision variables are local and varies as the value of control variable changes. The method is easy to implement and failure rate/repair time may be quickly allocated based on the sensitivities.

Table 1: Failure rates and repair times along with reachable minimum values for sample distribution system.

Component No.	*Failure rates l_i^0/year*	*Repair time r_i^0 (hrs)*	*Minimum value of failure rate $l_{i,min/yr}$*	*Minimum value of repair time $r_{i,min}$ hrs*
1	0.40	10.00	0.20	6.00
2	0.20	9.00	0.05	6.00
3	0.30	12.00	0.10	8.0
4	0.50	20.00	0.10	8.00
5	0.20	15.00	0.15	7.00
6	0.10	8.00	0.05	6.00
7	0.10	12.00	0.05	6.00

Table 2: Initial and final failure rate ($\Lambda_{sys,Q}$) and repair time ($R_{sys,Q}$) for each load poin.

	Failure rate			*Repair rate*
LP	*Initial value $l_{sys,q}$*	*Final value $l^*_{sys,q}$*	*Intial value $r^*_{sys,q}$*	*Final value $r^*_{sys,q}$*
2	0.40	0.22	10.00	7.00
3	0.60	0.32	9.67	7.34
4	0.90	0.47	10.45	7.53
5	0.90	0.34	11.67	7.77
6	1.10	0.50	11.14	8.00
7	0.70	0.40	9.42	7.47
8	0.80	0.50	9.75	8.00

Table 3: Sensitivities $SC\Lambda_k$ and SCR_k with final solution and penalty costs.

Component K	*SCl_k*	*SCr_k*	*Penalty cost for each component*	
			$C_k(l_k)$	$C_k(r_k)$
1	–500.00	–1.00	9.00	3.00
2	–60.00	–3.80	2.00	0.52
3	–80.00	–1.71	3.00	1.025
4	–1000.00	–34.72	19.00	9.00
5	–500.00	–11.11	4.00	4.33
6	55.60	3.125	0.67	0.00
7	–20.00	–1.78	0.00	0.512

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