Reliability Evaluation of a Radial Feeder with the Placement of Both Shunt Capacitors and a Fault Passage Indicator

G. Kirankumar[1], E. Vidya Sagar[2]

[1]*Assistant Professor, Department of Electrical Engineering, University College of Engineering, Osmania University, Telangana. India.*
[2]*Professor, Department of Electrical Engineering, University College of Engineering, Osmania University, Telangana. India*

Abstract - *The reliability of a radial feeder depends on its component's average failure rate and restoration time. High current is one of the causes of the failure of line sections. This current consists of real and reactive components. The placement of shunt capacitors reduces the reactive current and results in a reduction of the average failure rate, hence increasing reliability. Further, the restoration time of the system is reduced by placing the fault passage indicator (FPI). In this work, first, the optimal location and rating of the shunt capacitors placement are determined based on the minimum total cost (which includes energy loss cost and capacitor costs) using the particle swarm optimization method (PSO). Second, the optimal placement of FPI on the radial feeder is considered based on the feeder reliability using the failure mode effects analysis (FMEA) method. Further, the feeder reliability is evaluated by placing both shunt capacitors and a single FPI.*

Key Words: Radial Feeder, Shunt Capacitor, PSO, FPI, Reliability and FMEA.

1. INTRODUCTION

The main function of the power system is to supply quality, quantity, and reliable power to the customers connected to the system. The reliability of the power system is affected by two factors, those are a). Components failure rate and b). Power restoration process. Reducing components failure rate and faster power restoration will improve the reliability of the radial feeder.

The shunt capacitors are placed to improve the voltage profile, reduce power losses, and also to reduce the component failure rates by reducing the reactive current passing through them. During the peak load conditions operating temperature of the feeder sections increases due to high currents and causes high failure rates. The placement of shunt capacitors on the radial feeder supplies a part of the required reactive current. Hence, it reduces the operating temperature as a result reduces the failure rate of feeder equipment and sections [5, 8].

The process of power restoration time consists of (i) crew traveling time, (ii) fault location identification time, and (iii) fault clearing time by repair or replacement, or switching action of that faulty component. The FPI is a device that enables a quick solution to reduce the fault location identification time [4, 7].

In this paper, both component failure rates and power restorations are considered to improve the radial feeder reliability with the placement of the shunt capacitors and a single FPI.

The following section describes the placement of the shunt capacitor and a single FPI on the radial feeder.

2. OPTIMAL PLACEMENT OF SHUNT CAPACITORS ON RADIAL FEEDER USING PSO METHOD

The objective of the shunt capacitor placement in the radial feeder for minimizing the total cost (which includes energy loss cost, capacitor purchase and installation cost) and maximizing the savings is subjected to satisfy the constraints of bus voltage and the number of capacitors placed. The mathematical expression of the above objective function is described in equation 1.

$$F_{obj.} = K_p P_L^T + K_C Q_c^T \quad (1)$$

Where $F_{obj.}$ is the total costs in \$/yr. K_P is the annual cost per unit of power loss in \$/kW-yr. K_C is the total capacitors purchase and installation cost in \$/kVAR. P_L^T & Q_C^T are the total active power losses and capacitors reactive power respectively [9].

The annual total cost of capacitors can be calculated as:

$$Total\ Capacitors\ Cost = \frac{K_C Q_c^T}{LifeExpectancy} \$/yr. \quad (2)$$

2.1 Bus Selection for the Placement of Capacitors

The best location of capacitor placement on the radial feeder is identified using the loss sensitivity index (LSI). These indices predict the buses that will experience thegreatest reduction in losses with capacitor placement and will reduce the capacitors usage in number. Hence, the cost of purchase, installation and maintenance is less. The indices are given by equations 3 and 4.

$$LSI_1 = \frac{\partial P_{Lk}}{\partial V_{i+1}} = -2 \times R_k \times \left(\frac{P_{i+1}^2 + Q_{i+1}^2}{V_{i+1}^3}\right) \quad (3)$$

$$LSI_2 = \frac{\partial P_{Lk}}{\partial Q_{i+1}} = \frac{2 \times Q_{i+1} \times R_k}{V_{i+1}^2} \quad (4)$$

Where LSI_1 and LSI_2 are the first and second loss sensitivity indices respectively. P_{Lk} and R_k are the active power flow and resistance in the k^th line between i and i+1 bus respectively, P_{i+1} & Q_{i+1} are the effective active and reactive powers beyond the receiving node i+1.[10]

2.2 Optimization method

The PSO method is used to optimize the objective function. It begins with an initial population of random solutions or particles and searches for optima by updating various properties of the individuals in each generation. The particles change their positions by flying around a multi-dimensional search space until a relatively unchanged position has been encountered [11]. At each step time, changing the velocity of each particle flying towards its best position (pbest) and best position of the group (gbest) by updating the current position, a new velocity of particle 'i' for k+1 iteration is given by [12]

$$V_i^{k+1} = \omega V_i^k + (C_1 rand_1 (pbest_i - x_i^k)) + (C_2 rand_2 (gbest_i - x_i^k)) \quad (5)$$

Where V_i^k is the velocity of particle 'i' at k^{th} iteration, C_1 and C_2 are weight factors, ω is the inertia weight parameter, $rand_1$ and $rand_2$ are the random numbers between 0 and 1.

The change in the position for k+1 iteration is given by

$$x_i^{k+1} = x_i^k + V_i^{k+1} \quad (6)$$

Where x_i^{k+1} indicates the change in the current position.

3. PLACEMENT OF A SINGLE FPI ON RADIAL FEEDER LOCATIONS

An FPI is an economical, smart device and easy to install in a radial feeder to determine the fault location time for quick power restoration from faulty conditions. After the occurrence of the sustained fault, the Power restoration may be due to the repair/replacement of components or switching of appropriate disconnecting switches. The fault location time is determined is as follows: The FPI placement on the radial feeder is shown in figure 1. Assume the average fault location time of the feeder without FPI is T_0 hour. With the installation of an FPI, the fault location time for part 1 of the feeder is T_1 and for part 2 is T_2 and are given by

$$T_1 = T_0 \times \frac{X_1}{L} \quad hr \quad (7)$$

$$T_2 = T_0 \times \frac{X_2}{L} \quad hr \quad (8)$$

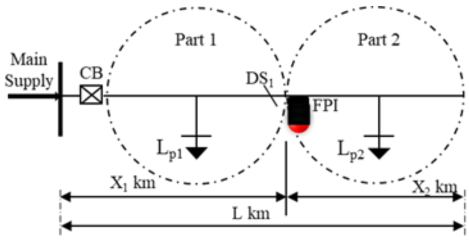

Fig -1: Radial Feeder with a single FPI

The following section describes the reliability evaluation with the placement of shunt capacitors and a single FPI on the radial distribution system. [4]

4. RELIABILITY EVALUATION

The load point indices such as average failure rate (λ_{LP}), average repair time (r_{LP}) and annual outage time (U_{LP}) are obtained from the following equations given by [2, 3]

$$\lambda_{LP} = \sum_i \lambda_i \quad \text{failure/year} \quad (9)$$

$$U_{LP} = \sum_i \lambda_i r_i \quad \text{hours/year} \quad (10)$$

$$r_{LP} = \frac{U_{LP}}{\lambda_{LP}} \quad \text{hours} \quad (11)$$

Where λ_i and r_i are respectively i^{th} component average failure rate and average repair time.

System performance indices such as system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) and energy not supplied (ENS) are calculated by using equations 12, 13 and 14 respectively.

$$SAIFI = \frac{\sum \lambda_{LPi} N_{LPi}}{\sum N_{LPi}} \quad \text{Interruptions/customer-year} \quad (12)$$

$$SAIDI = \frac{\sum U_{LPi} N_{LPi}}{\sum N_{LPi}} \quad \text{Hours/customer-year} \quad (13)$$

$$ENS = \sum Ld_{avg(LPi)} U_{LPi} \quad \text{kWh/year} \quad (14)$$

Where λ_{LPi}, U_{LPi}, $Ld_{avg(LPi)}$ and N_{LPi} respectively, average failure rate, annual outage time, average load and number of customers connected to i^{th} load point ($_{LPi}$).

The following section describes the failure rate modelling with the placement of a shunt capacitor and power restoration with a single fault passage indicator.

4.1 Failure Rate Modeling with the Placement of Shunt Capacitor

The failure rate modeling of capacitor placement on feeder sections is as follows: For the i^{th} feeder section, before the placement of the shunt capacitor section failure rate is considered as an uncompensated failure rate and is indicated with λ_i^{UC}. After the shunt capacitor placement, if the reactive current across the feeder section is fully compensated then the section failure rate is considered as fully compensated (85% of λ_i^{UC}) and indicated with λ_i^{C}. In case of moderate levels of reactive current compensation, the resultant section failure rates (λ_i^{new}) are computed as given by [5]

$$\lambda_i^{new} = C_c \times \left(\lambda_i^{UC} - \lambda_i^{C}\right) + \lambda_i^{C} \qquad \text{failure/year} \qquad (18)$$

Where C_c is the compensation coefficient and is given by

$$C_c = \frac{I_r^{UC}}{I_r^{C}} \qquad (19)$$

Where I_r^{UC} and I_r^{C} are the reactive currents passing through the feeder sections before and after the capacitor placement.

The optimal placement of the shunt capacitor on the radial feeder results in new reduced/moderated section failure rates, which are used to determine the feeder load point and performance reliability indices.

4.2 Power Restoration with the Placement of a Single FPI

The average restoration time with the FPI placement on the radial distribution feeder is determined as: [4]

i) If the fault clearance is associated with repair action, then the average restoration time is determined as the sum of the average repair time and fault location time.

ii) If the fault clearance is associated with switching action, then the average restoration time is determined as the sum of the switching time and fault location time.

If the average repair time and average switching time of the feeder sections are r_s and s_s respectively. When a sustained fault in part B of the shown in figure 1. Then the restoration time of load points in part A due to switching action (s_n) and in part B due to repair action (r_n) are given by

$$s_n = s + T_1 \qquad \text{hr} \qquad (17)$$

$$r_n = r + T_2 \qquad \text{hr} \qquad (18)$$

The following section describes the data and assumptions considered for the reliability evaluation of a radial feeder.

5. RELIABILITY DATA

Feeder 1 of Roy Billiton Test System 2 (RBTS2) and corresponding data are considered for reliability evaluation [1]. The feeder is configured with fuses and disconnecting switches. The feeder with FPI placement is shown in figure 3 and the feeder section length data is shown in Table 1.

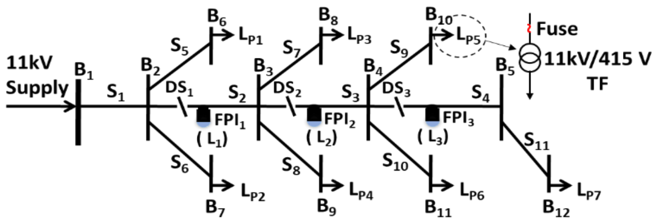

Fig -2: Feeder 1 of RBTS2 with FPI arrangement.

In the above figure, S indicates feeder sections, DS indicates disconnecting switch, TF indicates the distribution transformer and L_P indicates the load point.

Table -1: Feeder Sections Length Data

Length (km)	Feeder Sections
0.60	S4, S5, S8
0.75	S1, S2,S3, S10
0.80	S6, S7, S9, S11

Load data of peak load, type and the number of customers connected to each load point are shown in Table 2.

Table -2: Load Data

Load Point	Peak Load (MW)	No. of Customers	Type of Customers	Power factor
Lp1,Lp2, Lp3	0.8668	210	residential	0.80
Lp4,Lp5	0.9167	1	institutional	0.75
Lp6,Lp7	0.7500	10	commercial	0.86

Component reliability data of average failure rate, average repair time, and switching times are shown in Table 3.

Table -3: Component Reliability Data

Component	λ	r hr	s hr
Feeder Section	0.065f/km-yr.	4.75	0.25
Distribution Transformer	0.015f/yr.	199.25	-

The average fault location time is taken as 0.75 hr. [4]. Resistance and reactance data of feeder sections are shown in Table 4. [6]

Table -4: Feeder Section Impedance Data

Feeder Section	R (Ω)	X (Ω)
S1, S2,S3, S4	0.2712	0.2464
S5, S6,S7, S8, S9, S10,S11	0.2733	0.2506

The assumptions considered for reliability evaluation are (a). Supply from the mains is assumed to be 100% reliable. (b). Fuses are 100% reliable and can successfully isolate load point failures from sections so there is no effect of one load point failure on others. (c). FPI operation is 100% reliable and placed next to the disconnecting switch on the feeder. (d). No alternative supply. The reliability of RBTS2 Feeder 1 is evaluated for four different case studies and those are

i. Case A: Feeder configuration without considering shunt capacitor and FPI placement.

ii. Case B: Feeder configuration considering shunt capacitor placement.

iii. Case C: Feeder configuration considering a single FPI placement.

iv. Case D: Feeder configuration considering both Shunt Capacitors and a single FPI placement.

The following section discusses the case studies and results.

6. RESULTS AND DISCUSSIONS

6.1 Case A

Case A is considered as the base case. The load point indices are calculated using equations 9 to 11 and the results are shown in Table 5. Feeder performance indices are calculated using equations 12 to 14 and results are shown in Table 6.

Table -5: Load Point Indices of Feeder

Load Point	λ f/yr	U hr/yr	r hr
LP1	0.239	3.58	14.94
LP2	0.252	3.64	14.43
LP3	0.252	3.84	15.20
LP4	0.239	3.77	15.76
LP5	0.252	4.03	15.98
LP6	0.249	4.01	16.12
LP7	0.252	4.19	16.60

Table -6: Performance Indices of Feeder

	SAIFI	SAIDI	ENS
Feeder 1	0.248	3.70	14054.7

6.2 Case B

In case B, the shunt capacitor placement locations for peak load conditions are obtained by following the concept presented in section 2. The PSO simulation results with shunt capacitor placements are shown in Table 7.

Table -7: PSO Simulation Results on Feeder Parameters

Parameters	Before capacitor placement	After capacitor placement
Total active power losses (kW)	195.88	160.38
% Power loss reduction	-----	18.12
Capacitor location and size (kvar)	-----	B_{10} (498), B_{12} (468)
Cost of power losses ($/yr)	32908	26944
Cost of capacitors ($/yr)	-----	483.21
Minimum voltage(pu)	0.957	0.963
Net savings ($/yr)	-----	5481

The reactive currents in feeder sections before and after the shunt capacitor placement are shown in Table 8. New failure rates of feeder sections are calculated using equations 18 and 19 respectively and are shown in the same Table 8.

Table -8: Reactive Currents, Compensation Coefficient and New Failure Rates of Feeder Sections

Section	Reactive currents (A)		C_c	λ_i^{new} f/yr
	Without Capacitor	With Capacitor		
S1	264.11	209.61	0.80	0.0631
S2	194.34	139.80	0.73	0.0624
S3	114.98	60.38	0.54	0.0606
S4	35.38	13.32	0.28	0.0580
S5	34.87	34.87	1.00	0.0650
S6	34.89	34.89	1.00	0.0650
S7	35.39	35.39	1.00	0.0650
S8	43.96	43.96	1.00	0.0650
S9	44.29	11.70	0.39	0.0553

S10	35.30	35.30	1.00	0.0553
S11	35.38	13.32	0.28	0.0553

Using the new feeder section failure rates, the load point indices and performance indices are calculated and the results are shown in Table 9 and Table 10 respectively.

Table -9: Load Point Indices of Feeder with Shunt Capacitor Placement

Load Points	λ_{LP} f/yr	U_{LP} hr/yr	r_{LP} hr
LP1	0.226	3.55	15.74
LP2	0.237	3.61	15.23
LP3	0.240	3.80	15.82
LP4	0.227	3.73	16.44
LP5	0.240	3.99	16.63
LP6	0.230	3.94	17.17
LP7	0.232	4.09	17.59

Table -10: Performance Indices of Feeder with Shunt Capacitor Placement

	SAIFI	SAIDI	ENS
Feeder 1	0.234	3.66	13878.7

Comparing case B with case A, the percentage reduction of load points outage time in the feeder is shown in figure 3.

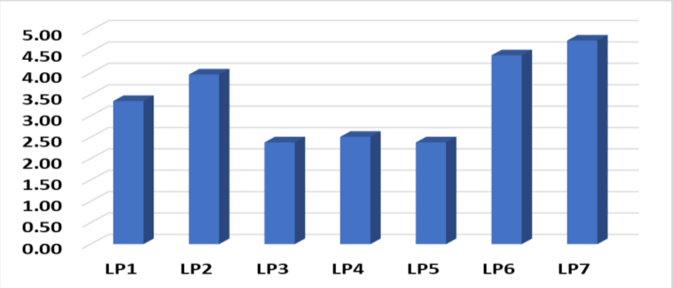

Fig -3: Percentage reduction of the failure rate in load points with shunt capacitors placed on the feeder

6.3 Case C

In case C, the placement of a single FPI means only one FPI at a time in different locations (L1, L2 and L3) on the feeder is considered. Using the concept discussed in section 3, the fault location times in part 1 and part 2 for a sustained fault on the feeder with FPI placement are determined using equations 7 and 8 respectively and the restoration time of load points in part 1 and part 2 are calculated from equations 17 and 18 respectively. Load point and performance indices are calculated and the results are shown in Table 11 to Table 16.

Table -11: Load Point Indices of Feeder with FPI Placement on Location L_1

Load Points	λ_{LP} f/yr	U_{LP} hr/yr	r_{LP} hr
LP1	0.239	3.48	14.54
LP2	0.252	3.54	14.02
LP3	0.252	3.75	14.85
LP4	0.239	3.69	15.40
LP5	0.252	3.94	15.63
LP6	0.249	3.93	15.77
LP7	0.252	4.10	16.24

Table -12: Performance Indices of Feeder with FPI Placement on Location L_1

	SAIFI	SAIDI	ENS
Feeder 1	0.248	3.60	13726.2

Table -13: Load Point Indices of Feeder with FPI Placement on Location L_2

Load Points	λ_{LP} f/yr	U_{LP} hr/yr	r_{LP} hr
LP1	0.239	3.50	14.63
LP2	0.252	3.56	14.12
LP3	0.252	3.76	14.90
LP4	0.239	3.70	15.45
LP5	0.252	3.94	15.62
LP6	0.249	3.92	15.76
LP7	0.252	4.10	16.24

Table -14: Performance Indices of Feeder with FPI Placement on Location L_2

	SAIFI	SAIDI	ENS
Feeder 1	0.248	3.62	13754

Table -15: Load Point Indices of Feeder with FPI Placement on Location L_3

Load Points	λ_{LP} f/yr	U_{LP} hrs/yr	r_{LP} hr
LP1	0.239	3.56	14.87
LP2	0.252	3.62	14.36
LP3	0.252	3.82	15.13

LP4	0.239	3.75	15.68
LP5	0.252	4.01	15.90
LP6	0.249	4.00	16.05
LP7	0.252	4.13	16.36

Table -16: Performance Indices of Feeder with FPI Placement on Location L_3

	SAIFI	SAIDI	ENS
Feeder 1	0.248	3.68	13968.2

Comparing with case A, the percentage reduction of annual outage time of load points with FPI placement on the feeder locations of L1, L2 and L3 in case C are shown in figure 4.

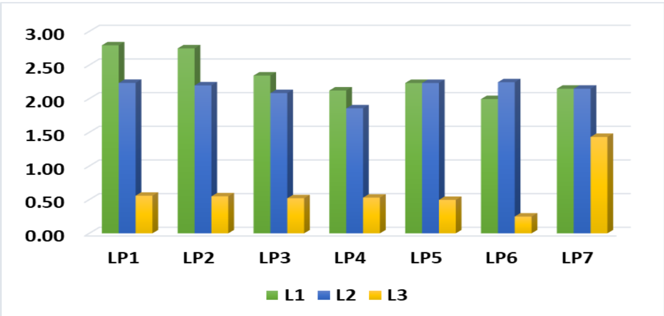

Fig -4: Percentage reduction of annual outage time of load points

6.4 Case D

The placement of both shunt capacitors and a single FPI are considered. Based on the feeder's minimum values of SAIDI and ENS, the optimal location of FPI on feeder sections is considered as L_1. The load point and performance indices are calculated and the results are shown in Table 17 and Table 18 respectively.

Table -17: Load Point Indices of Feeder with the placement of both shunt capacitors and a single FPI

Load Points	λ_{LP} f/yr	U_{LP} hr/yr	r_{LP} hr
LP1	0.226	3.55	15.74
LP2	0.237	3.61	15.23
LP3	0.240	3.80	15.82
LP4	0.227	3.73	16.44
LP5	0.240	3.99	16.63
LP6	0.230	3.94	17.17
LP7	0.232	4.09	17.59

Table -18: Performance Indices of Feeder with the placement of both shunt capacitors and a single FPI

	SAIFI	SAIDI	ENS
Feeder 1	0.230	3.55	13511

The percentage reduction of load point annual outage times in case D compared with case C and case A are shown in figure 3 and figure 5 respectively.

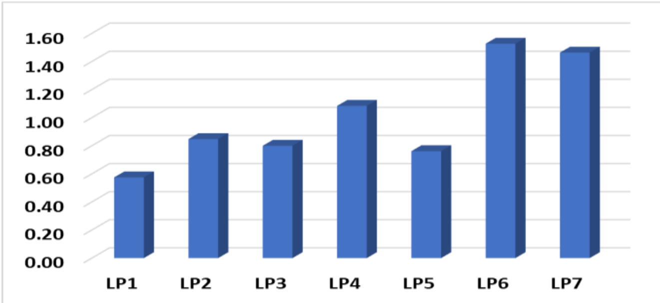

Fig -5: Percentage reduction of annual outage time of load points in case D when compared with case C

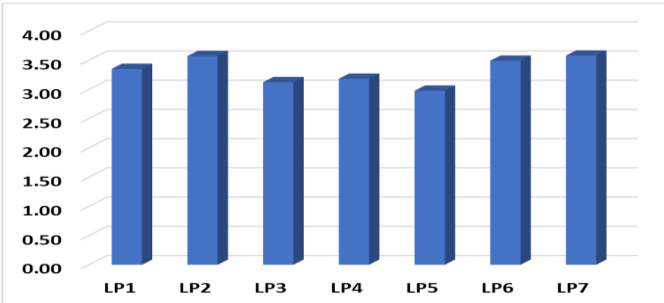

Fig -6: Percentage reduction of annual outage time of load points in case D when compared with case A

7. CONCLUSIONS

The reliability of feeder 1 of RBTS 2 is evaluated for four diffident case studies and presented in the above section. The numerical results clearly showing the impact of the individual and combined placement of the shunt capacitor and FPI operations on feeder reliability. The placement of both the shunt capacitor and a single FPI are reducing both component failure rates from the peak load conditions and power restoration time from the sustained fault conditions which results in the system having better reliability operations. The percentage reduction of SAIFI, SAIDI and ENS in case D over case A are 7.26, 4.05 and 3.87 respectively.

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