Protective Devices Allocation Optimization for Electrical Distribution System

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Abstract: Most of electric distribution utilities have their reliability performance measured by reliability indices such as SAIFI and SAIDI to evaluate customer satisfaction. Adding protective devices in electrical distribution system can increase the system reliability by protecting public customers from local faults. In large-scale distribution system, it is difficult to determine the positions of these protective devices, which can efficiently protect customers within utilities' investment. In this paper, we propose an optimization technique to identify types and positions of protective devices to minimize SAIFI and SAIDI indices according to system requirement constraints.

1. Introduction

There are many reliability indices used in electrical distribution system, known as *electric power distribution reliability indices* [1]. The most common indices used by electrical utility providers are *System Average Interruption Frequency Index (SAIFI)* and *System Average Interruption Duration Index (SAIDI)*, to measure the impact of the utility outage, in terms of the number of interrupted customers and interruption durations, respectively. Consequently, protective devices play an important role in reducing the number of interrupted customers.

Most of researches tend to use optimization techniques in operational field, while a few researches are on the optimization of reliability indices and investment costs[5]. Soudi et al. [2, 3] presented a technique to minimize SAIFI considering protective device allocation. They used reclosers and fuses as protective devices to minimize the number of interrupted customers.

In this paper, we present a technique to minimize both SAIFI and interruption durations or SAIDI considering device allocation using breakers, reclosers, disconnecting switches, and fuses.

2. Electrical Distribution Power System

2.1 Protective Devices Configuration

There are many types of protective devices and each type performs different function from one another. A typical configuration of distribution system is illustrated in Figure 1, having one main feeder, and multiple branches.

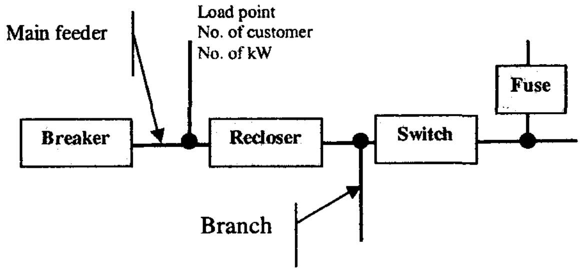

Figure 1. Protective Devices Configuration

Breaker, recloser and fuse, shown in Figure 1, are automatic protective devices installed in substation, distribution feeders and branches, respectively. Disconnecting switches are manual protective devices used to separate fault out of the network. Moreover, recloser can trip and reclose while fuse can only perform open-circuit.

2.2 SAIFI and SAIDI indices

Both SAIFI and SAIDI indices are the most frequently used indices to measure the system reliability and performance. SAIFI and SAIDI are used 70% and 80% by electrical utility providers. Definitions of the indices are mathematically written as

$$SAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum \lambda_i N_i}{N_T} \quad (1)$$

$$SAIDI = \frac{\text{Total customer interruption durations}}{\text{Total number of customers served}} = \frac{\sum \mathrm{U}_i N_i}{N_T} \quad (2)$$

where N_i is the number of customers in section i, N_T represents the total number of customers on the feeder, λ_i and U_i represent failure rate and unavailability of section i, respectively.

3. Research Methodology

3.1 Model Formulations

In this paper, similar to paper [2], feeders are divided into branches as shown in Figure 2. Each block represents a load point, which is a possible location to install a protective device.

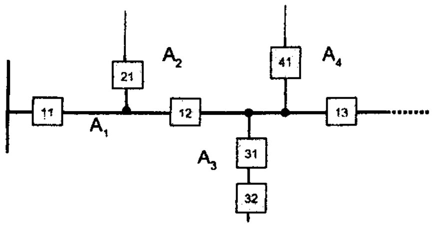

Figure 2. Divided Feeders for Optimization Approach

The SAIFI, and SAIDI indices can be optimized according to equations (3) and (4), respectively.

$$\sum \lambda_i N_i = \sum_{q=1}^{\alpha+1} A_{fq} \tag{3}$$

$$\sum U_i N_i = \sum_{q=1}^{\alpha+1} A_{dq} \tag{4}$$

where A_{fq} and A_{dq} represent total number of customer interruptions and total customer interruption durations for every q. α is the number of tap-point locations in branches where fuse is installed. q = 1 represents the installation at the main feeder. The first load point (block 11) has q=1 only, since a breaker has to be installed. Branches in the network with no fuse will be included as load points in the main feeder. Our research aims to optimize the number of protective devices by minimizing the number of interrupted customers and the customer interruption durations caused by sustained faults. Protective device failure rate is assumed to be neglected when compared to the failure rate of each block in Figure 2. Model formulations for the number of interrupted customers, and the customer interruption durations are presented in equations (5) and (6), respectively.

$$\begin{aligned} A_{fq} = {} & \sum_{i=1}^{q_n} \lambda_{qi} \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} \sum_{j=1}^{i-1} N_{qj} \prod_{k=j+1}^{i} x_{qk1} x_{qk2} \\ & + \sum_{i=1}^{q_n} \gamma_{qi} (1 - x_{qi2}) \sum_{j=1}^{q_n} N_{qj} + \sum_{i=1}^{q_n} \gamma_{qi} \sum_{j=1}^{i-1} (1 - x_{qj2}) \sum_{k=j}^{q_n} N_{qk} \prod_{l=j+1}^{i} x_{ql1} x_{ql2} \end{aligned} \tag{5}$$

$$\begin{aligned} A_{dq} = {} & \sum_{i=1}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} \prod_{k=j+1}^{i} x_{qk1} x_{qk2} x_{qk3} \\ & + \sum_{i=2}^{q_n} \lambda_{qi} r_s \prod_{k=j+1}^{i} x_{qk1} x_{qk2} (1 - x_{qk3}) + \sum_{i=1}^{q_n} \gamma_{qi} r_r (1 - x_{qi2}) \sum_{j=1}^{q_n} N_{qj} \\ & + \sum_{i=1}^{q_n} \gamma_{qi} r_r \sum_{j=1}^{i-1} (1 - x_{qj2}) \sum_{k=j}^{q_n} N_{qk} \prod_{l=j+1}^{i} x_{ql1} x_{ql2} \end{aligned} \tag{6}$$

where q_n is the number of load points in the main feeder or branches, i represent section covering each block of A, λ_{qi} is the permanent failure rate and γ_{qi} is the momentary failure rate for section i of q, and N_{qj} is the number of customers in section j of q including all branches connected to that section. Note that, if there is a three-phase device (recloser) at location qk, then the variable $x_{qk1} = 0$, or otherwise $x_{qk1} = 1$. Here, the subscript 1 is used to represent a three-phase device, the subscript 2 represents a fuse and the subscript 3 represents a disconnecting switch. For outage duration notations, r_r is the repair time and r_s is the switching time for section i.

3.2 Optimization Techniques

We use optimization software from LINDO Software Inc [6], LINGO. The LINGO software is a linear, non-linear, and integer programming solver with a mathematical modeling language.

We aim to determine protective device allocation subject to SAIFI and SAIDI indices. Recloser and disconnecting switch are devices on the main feeder only, therefore we revise our objective functions for the main feeder shown in equations (7) and (8), and branches shown in equations (9) and (10).

$$A_{fq} = \sum_{i=1}^{q_n} \lambda_{qi} \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} \sum_{j=1}^{i-1} N_{qj} \prod_{k=j+1}^{i} x_{qk1} \tag{7}$$

$$\begin{aligned} A_{dq} = {} & \sum_{i=1}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} \prod_{k=j+1}^{i} x_{qk1} x_{qk3} \\ & + \sum_{i=2}^{q_n} \lambda_{qi} r_s \prod_{k=j+1}^{i} x_{qk1} (1 - x_{qk3}) \end{aligned} \tag{8}$$

$$\begin{aligned} A_{fq} = {} & \sum_{i=1}^{q_n} \lambda_{qi} \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} \sum_{j=1}^{i-1} N_{qj} \prod_{k=j+1}^{i} x_{qk2} \\ & + \sum_{i=1}^{q_n} \gamma_{qi} (1 - x_{qi2}) \sum_{j=1}^{q_n} N_{qj} + \sum_{i=1}^{q_n} \gamma_{qi} \sum_{j=1}^{i-1} (1 - x_{qj2}) \sum_{k=j}^{q_n} N_{qk} \prod_{l=j+1}^{i} x_{ql2} \end{aligned} \tag{9}$$

$$\begin{aligned} A_{dq} = {} & \sum_{i=1}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} + \sum_{i=2}^{q_n} \lambda_{qi} r_r \sum_{j=1}^{q_n} N_{qj} \prod_{k=j+1}^{i} x_{qk2} \\ & + \sum_{i=1}^{q_n} \gamma_{qi} r_r (1 - x_{qi2}) \sum_{j=1}^{q_n} N_{qj} + \sum_{i=1}^{q_n} \gamma_{qi} r_r \sum_{j=1}^{i-1} (1 - x_{qj2}) \sum_{k=j}^{q_n} N_{qk} \prod_{l=j+1}^{i} x_{ql2} \end{aligned} \tag{10}$$

4. Case Study

We collect actual distribution system data from substation 1 of Navanakorn industrial estate [7], which Provincial Electricity Authority (PEA) of Thailand provides 22 kV electric energy. PEA's policy tends to decrease SAIFI and SAIDI particularly in the industrial estate because part of the PEA's main profit comes from this industrial sector. We choose one of feeders from the total 10 feeders, which covers major number of customers and highest profit as our case study. The feeder serves 2285 customers with the total load of 5,720 kW. There are 7 load points in the main feeder and 4 branches, as depicted in Figure 3.

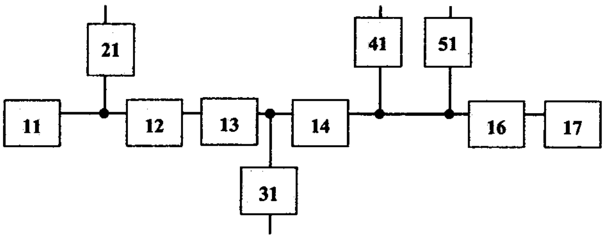

Figure 3. Configuration of One Feeder [7]

The collected data shown in Table 1 includes the number of the customers served, permanent and momentary failure rates, etc. Sufficient actual data collected during 1998-2001 by PEA is used to provide SAIFI and SAIDI information in our analysis.

Average repair time (r_r) and switching time (r_s) of the feeder in Figure 3 are 55.2 minutes and 26.2 minutes, respectively. Complexity of the problem depends on many parameters including the size of the feeder, types of allocated components and the number of component allocations. In this case study, there is one main feeder and four branches (q=5) for each of A_{fq} and A_{dq}. Each of the load points can have a recloser installed or a disconnecting switch installed, or else neither of the devices are installed. However the number of fuses installed at tap points A_2-A_5. can be as many as the number of load points in the corresponding branches.

Table 1. Actual Average Data Collected from Navanakorn Industrial Estate [7]

Load point q_n	Failure rate λ_I (failures/ year)	Momentary fault γ_i (failures/year)	N_i
11	0.405333	0.324267	888
12	0.533333	0.426667	355
13	2.122666	1.698133	703
14	1.066666	0.853333	339
15	0.512000	1.101000	138
16	0.123000	0.491000	527
17	0.256000	1.024000	662
21	0.469333	0.375467	354
22	0.224000	0.179200	289
23	0.426667	0.341333	209
31	0.512000	0.409600	42
32	0.746667	0.597333	65
33	0.320000	0.256000	34
41	0.042667	0.034133	90
51	0.906667	0.725333	124
52	0.213333	0.170667	26
53	0.266667	0.213333	7
54	0.853333	0.682667	87

5. Optimization Result

We consider each independent A_q and with LINGO solver, we obtain an optimal solution for each A_{fq} and A_{dq}. We assume disconnecting switch having zero failure rate, and therefore has no effect on SAIFI index. We fix the number of disconnecting switches and vary the number of reclosers in order to determine the optimal number of both devices. Including the number of customer interruptions and the number of customer interruption durations impacted from fuse, our optimization results are shown in the graph in Figures 4 and 5. The optimal solutions for fuse installation are presented in Table 4.

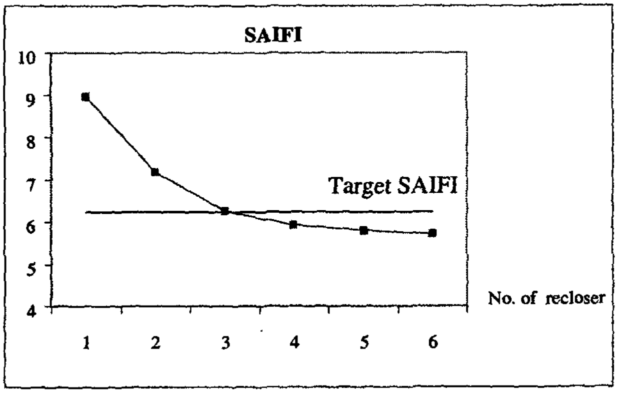

Figure 4. Optimal SAIFI and Targeted SAIFI at Different Number of Reclosers Installed

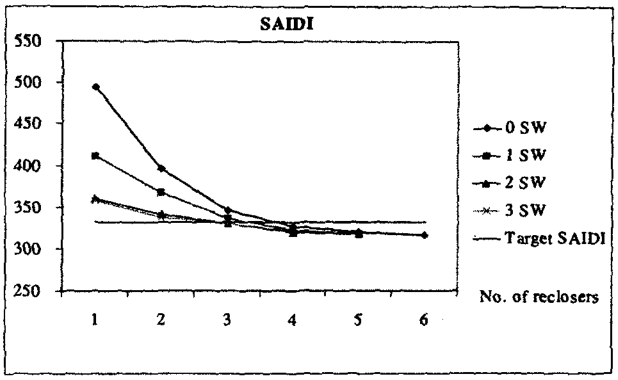

Figure 5. Optimal SAIDI and Targeted SAIDI at Different Number of Disconnecting Switches Installed

No. of Reclosers	Positions of Reclosers	Positions of Disconnecting Switches	SAIFI
0	-	-	8.9595
1	12	-	7.1666
2	12,14	-	6.2601
3	12,13,14	-	5.9304
4	12,13,14,15	-	5.7982
5	12,13,14,15,17	-	5.7237

Table 2. SAIFI and Optimal Recloser Allocations

No. of Reclosers	Positions of Reclosers	Positions of Disconnecting Switches	SAIDI
0	-	-	494.57
1	12	-	395.59
2	12,14	-	345.56
3	12,13,14	-	327.36
4	12,13,14,15	-	320.06
5	12,13,14,15,17	-	315.95
0	-	14	411.20
1	12	15	367.53
2	12,14	13	336.06
3	12,13,14	15	322.06
4	12,13,14,15	17	317.51
0	-	13,14	359.69
1	13	12,14	341.49
2	12,14	13,15	330.77
3	**12,13,14**	**15,17**	**319.51**
4	12,13,14,15	14,17	317.70
0	-	13,15,17	357.77
1	13	12,14,16,	337.32
2	12,14	13,15,16	330.18
3	12,13,14	15,16,17	321.19

Table 3. SAIDI and Optimal Disconnecting Switch Allocations

A	Position	SAIFI	SAIDI
A=2	21,22	1.6038	88.53
A=3	31,32	2.4476	135.11
A=4	41	0.0768	4.24
A=5	51,52	2.5633	141.50

Table 4. SAIFI, SAIDI and Optimal Fuse Allocations

The Number of reclosers and disconnecting switches can be determined for targeted SAIFI and SAIDI. The Targeted SAIFI and SAIDI information can ease the electrical utility providers make decision including the suitable number of reclosers, disconnecting switches installed and their locations in a main feeder. In this case study, we choose targeted SAIFI = 6.30 interruptions/ customer/year and targeted SAIDI = 323 min./customer/ year. The graph in Figure 4 demonstrates that using three reclosers is the optimal solution, while satisfying the targeted SAIFI. From graph in Figure 5, we can determine the optimal number of disconnecting., indicated that none or one disconnecting switch is insufficient to satisfy the targeted SAIDI. Therefore, we choose two disconnecting switches as the optimal design solution. Finally the optimal solution is to install reclosers at the load points 12,13,14 and disconnecting switching at the load points 15,17, as shown in Table 3. However, the utility providers should consider another solution that is to install reclosers at the load points 12,14 and disconnecting switch at 13,15. The utility providers may use just two reclosers, while the obtained SAIFI is close to the targeted SAIFI. This is because the price of one recloser is about 5,000-8,500 US$. They may choose to spend less or within budget, if the SAIFI requirement is not critical or can be less.

In general, the more reclosers installed on the main feeder, the more reliability benefit can be obtained.
This statement is not true for fuse, since fuse is vulnerable to momentary fault. Therefore, more fuses installed might increase (worsen) the values of SAIFI and SAIDI.

4. Conclusion

This research aims to help decision maker in providing appropriate protective device allocations in the electrical distribution system. We apply our optimization technique with a non-linear solver, LINGO.

In electrical distribution system, reliability field data can be modeled and measured by several optimization methods. The methods can solve several special problems efficiently even with the large-scale systems. However, one important factor in optimization is on data collection, which is often a cumbersome or tedious task. With reliable data, the right decision-making can be obtained from appropriate optimization techniques.

In our future work, we plan to add into our optimization model the cost of protective devices, cost of outage of electrical utility, customer costs including interruption cost and duration cost.

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