Towards Optimized Distribution Protection Design

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Abstract

Traditionally, distribution systems engineering has focused on simplified design criteria guided by individual utility practices and experience. These designs were not optimized but did satisfy specific regulatory goals for system performance. Two developments are invalidating this approach: deregulation of the industry and rapid improvements in technology. Deregulation forces utilities to more carefully consider the cost of providing reliable service and to be concerned with the customer cost of reliability. At the same time, microprocessor based devices have greatly expanded the capabilities of protection apparatus. Further, low cost high speed computers have rendered computer aided design tools feasible. In this paper, distribution feeder protection is formulated as a reliability problem. Distribution reliability indices appropriate for protection design are discussed. Indices which are impacted by protection design are identified. The authors propose a new approach to optimizing overall distribution system protection design.

1. INTRODUCTION

Deregulation and competition is forcing utilities to maintain an acceptable level of service reliability while carefully controlling capital and maintenance expenditures [1]. Costs may increase as a utility attempts to improve or maintain existing reliability levels. At the same time, the customer costs associated with outages can be evaluated [2]. In this environment, any reliability improvement project must be examined in terms of an overall cost/benefit ratio. The cost/benefit analysis relates capital and maintenance expenditures to the customer monetary losses and utility revenue losses associated with outages.

Reliability indices are one tool utilities use to prioritize capital and maintenance expenditures. A recent survey indicates that the most common indices used in the industry are customer based indices. These customer based indices are System Average Interruption Frequency Index (*SAIFI*), System Average Interruption Duration index (*SAIDI*), Customer Average Interruption Duration Index (*CAIDI*) and Average System Availability Index (*ASAI*) [3]. The usage of these indices varies by utility but the most common justifications are [4]:

- Furnish management with performance data regarding the quality of customer service on the electrical system as a whole.
- Identify substations and circuits with substandard performance and to ascertain the cause.
- Furnish management with performance data regarding the quality of customer service for each operating area.
- Provide reliability history of individual circuits for discussion with current or prospective customers.
- Satisfy regulatory reporting requirements.
- Provide a basis to establish service continuity criteria.
- Furnish management with performance data regarding the quality of customer service for each voltage level.
- Aid in the purchase decisions of replacement parts and new equipment.
- Provide data for an engineering comparison of electrical system performance among consenting companies.
- Obtain the optimum improvement in reliability per dollar expended for design, maintenance, and operating programs.

Note, some utilities use load based indices such as, Average System Interruption Frequency Index (*ASIFI*) and Average System Interruption duration Index (*ASIDI*). Since calculation of the *SAIFI* and *ASIFI* indices rely directly on the number, type and location of the protective devices, this paper will discuss optimization of the effectiveness of protective devices in order to minimize the *SAIFI* and *ASIFI* indices. The approach allows either a minimum cost solution to achieve a desired reliability goal or a maximized effectiveness given a cost constraint.

2. DISTRIBUTION PROTECTION

In general, protection of a distribution system consists of a circuit breaker with protective relays and an automatic reclosing relay at the substation, and a number of protective devices with various characteristics on the main feeder and laterals. The most commonly used devices are line reclosers, interrupters, sectionalizers and fuses. These devices provide various type of protection and are briefly discussed in the following.

A **circuit breaker** has fault interruption and automatic reclosing capabilities. Automatic reclosing ensures that following a temporary fault, service for the customers will be restored in less than a few minutes. Traditionally, protective and automatic reclosing devices are consist of three relays for phase faults, one relay for ground faults and one automatic reclosing relay. Today, a single microprocessor based relay allows traditional protection functions as well as advanced protection, control and monitoring functions. Fault locating and fault recording capabilities help to reduce restoration time during a permanent outage by identifying a faulted section on a timely manner.

A **line recloser** with fault interruption and automatic reclosing capabilities are overhead pole mounted or ground padmounted devices. Modern reclosers are controlled by a microprocessor based device. A line recloser will automatically restore customers for a temporary fault and can be set to save fuses for any temporary fault on the load side of the fuse. **Interrupters** are similar to line reclosers but do not have automatic reclosing capability. These devices are used for underground distribution circuits.

A **sectionalizer** is a protective device that automatically isolates faulted sections. Since a sectionalizer does not have a fault interruption capability, it must be applied in conjunction with a backup recloser or a breaker. A sectionalizer counts the number of the source side device operations after sensing a fault on its load side. After a predetermined number of counts, the faulted section of the circuit is isolated.

A **fuse** is the most inexpensive protective device available for overcurrent protection on a distribution circuit. Fuses have fault interruption capabilities but do not have automatic reclosing capabilities. In addition to traditional expulsion fuses, current limiting and electronic fuses provide additional capabilities. A current limiting fuse is a better choice if there is a concern for either grass fires in dry areas, noise generated during fuse operation, excessive fault duty or equipment damage due to high fault currents. An electronic fuse offers various time-current characteristic curves, provides current limitation for certain applications and has a higher continuos current rating capability.

3. DISTRIBUTION RELIABILITY

The primary causes of faults on a distribution circuit are lightning, tree contact, animals and equipment failure. A survey from thirteen utility companies over a two year period [5] indicates that 79% of the faults are phase to ground, 85% of the recorded faults are temporary and the outage rates on laterals are greater than the main feeder.

To prevent outages on a distribution feeders, utilities take various preventive actions, including installing lightning arresters to prevent flashover, tree trimming on a regular basis, installing animal guards and maintaining equipment on a regular basis. Still, preventive measures will not fully eliminate the occurrence of outages and thus, protective devices are installed to detect outages and to isolate sections of the distribution circuit. Protection devices prevent or minimize damage to equipment, allow greater safety measures and improve service reliability.

The reliability indices are sensitive to the number, type and location of protective as well as a utilities restoration practice. A circuit breaker or a line recloser will minimize number of the customer affected by a permanent outage and automatically restore power for a temporary outage. Some of the microprocessor based devices provide fault data which helps to locate and isolate a trouble section in a timely manner. The sectionalizer improves reliability indices only for permanent faults. Since a sectionalizer works in conjunction with a breaker or line recloser, customers on the breaker or a line recloser section will also experience a temporary outage for any temporary fault on the sectionalizer section. Interrupter impacts on reliability indices are essentially only on permanent faults since nearly all of the faults on underground circuits are permanent faults. Therefore, an interrupter does not have automatic reclosing capability. Finally, a fuse does not have automatic reclosing capability and thus, temporary faults are treated the same as permanent faults. The additional time required for replacing a blown fuse must be included in the restoration times.

In general, all of the above devices impact the customer interruption frequency and duration. Remote controlled sectionalizing and manual controlled sectionalizing devices will also decrease the interruption duration but do not have an effect on the interruption frequency.

4. PROTECTION IMPROVEMENTS

Utilities are continuously searching for novel design and operation practices to improve service reliability and reduce capital and maintenance expenditures. For example, increasing the distribution operation voltage allows longer feeder length and more customers on the feeder. Longer feeders with more customers will increase the interruption frequency and interruption duration which is normally addressed by installing a large number of protection devices. The formulation here and in our earlier work shows that poorly located protection devices may actually result in worse reliability [6].

Another practice to improve service reliability is to use a fuse saving scheme. A fuse saving scheme allows temporary faults on the load side of the fuse to operating a source side recloser or circuit breaker. This scheme improves permanent interruption frequency and interruption duration but the temporary interruption frequency will increase. Note as electronic loads increase, customers may be less tolerant of momentary faults. Using a single phase automatic protective device instead of a fuse improves permanent interruption frequency and duration. Single phase trips with three phase lockout will also improve temporary interruption frequency. While this last scheme has been proposed, there are some concerns that remain to be addressed with regards to backfeed and arc extinction. Recently many utilities have applied advanced supervisory control and data acquisition systems (SCADA) to the distribution system. Such a distribution automation scheme improves service reliability and will help better utilize the distribution system capacity.

5. PROPOSED METHODOLOGY

This section formulates the optimization problem. For a variation on this formulation see [6].

5.1 Optimization problem

The proposed technique formulates a binary programming optimization to identify type of the protective devices on a distribution feeder. The goal of this technique is to select the specific number of the protective devices to be installed at the predetermined locations on a distribution feeder either to minimize the *SAIFI* or *ASIFI* indices or to achieve a desired performance level in these devices. Locations can be selected based on specific utility practices, such as, number of customers, or based on engineering judgment and the feeder configuration.

A distribution feeder consists of a main section and several lateral taps. Depending on a utility's practices, the lateral taps can be divided into various categories which we label one, two and three. A category one lateral is short and has limited exposure (usually less than three spans). Due to cost, this type of lateral will not be fused. A category two lateral is usually longer than about three spans and will have a single fuse at the tap. A category three lateral is heavily loaded or long, and various types of protective devices can be installed on the tap or at other points.

In the *SAIFI* or *ASIFI* indices calculation, the category one lateral failure rate and the number of the customers can be treated as a part of the main feeder. The effect of category two laterals in the *SAIFI* or *ASIFI* indices level is constant unless a fuse saving scheme is applied. Consider Fig. 1 which can be a main feeder or a category three lateral with n predetermined locations for installing protective devices. For a main feeder, a circuit breaker is located at location 1. For other locations on the main feeder and category three laterals there may be line reclosers, sectionalizers or fuses for an overhead circuit and interrupters or fuses for an underground circuit. Since effects of the breakers, reclosers, sectionalizers and interrupters are the same in the *SAIFI* or *ASIFI* indices calculation, these are treated identically in the optimization.

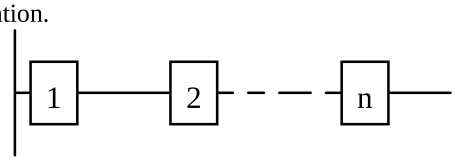

Fig. 1 A typical main or lateral feeder with several sections

The following basic assumptions are used in the calculation of the *SAIFI* or *ASIFI* indices which are representative of present utility practices.

- The feeder is operated as a radial feeder.
- The number and type of customers as well as total connected load are known for each individual section.
- Failure rate for a line section includes connected equipment failure rates.
- Multiple faults are not considered and all failures are repaired before the next fault occurs.
- All laterals have been assigned to be one of the three pre-defined categories.
- A breaker is located at the substation.
- Failure rate for underground sections are 100% permanent.

5.2 Binary programming formulation

Integer programming seeks to maximize or minimize a function of many variables subject to constraints including variables which must be integers. Any such problem can be approached by the following binary (zero-one) programming problem [6]

$$\min \sum_{i=1}^{n} c_i x_i \quad (1)$$

such that

$$\sum_{i=1}^{n} a_i x_i \le b_j \text{, for } j \in \{1 \ldots m\} \text{ and } x_i \in \{0,1\}$$

where c_i are cost coefficients, a_i and b_j are parameters describing the constraints, and m is the number of constraints.

The *SAIFI* index for a distribution feeder is defined as

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T} \quad (2)$$

where λ_i is the failure rate and N_i is the number of customers in section i, N_T is the total number of customers on the feeder. The numerator of (6) can be broken down into the contributions from the main feeder and each lateral as

$$\sum \lambda_i N_i = \sum_{q=1}^{\alpha+\beta+1} A_q \quad (3)$$

where α is the number of category three laterals, β is the number of category two laterals, and the first term, $q=1$, is the contribution from the main feeder. Then for each main feeder or lateral q

$$A_q = \sum_{i=1}^{qn} \lambda_{qi} \sum_{j=i}^{qn} N_{qj} + \sum_{i=1}^{qn} \gamma_{qi} x_{qik2} \sum_{j=i}^{qn} N_{qj}\,, \quad k \in \{1,2,3,4\} \quad (4)$$

where q_n is the number of the locations on the main feeder or lateral, λ_{qi} is the permanent failure rate and γ_{qi} is the temporary failure rate for section i of q, and N_{qj} is the number of customers for section j of q and if there is a fuse at location qi, then the variable $x_{qik2} = 1$. Note, the index k represents the type of the circuit, $k = 1$ is a three phase overhead, $k = 2$ is a single phase overhead, $k = 3$ is a three phase underground and $k = 4$ is a single phase underground circuit. For the category two laterals, a fuse will be installed at the tap with no other protective devices so

$$A_q = \sum_{i=1}^{q_n} \left(\lambda_{qi} + \gamma_{qi}\right) \sum_{i=1}^{q_n} N_{qi} \quad q \in \alpha + 2 \cdots \alpha + \beta + 1 \qquad (5)$$

Equation (5) is constant for a given feeder since the protection has been already determined, so minimizing

$$z = \sum_{q=1}^{\alpha+1} A_q \qquad (6)$$

is equivalent to minimizing the *SAIFI* index. For the *ASIFI* index, the above equations are modified by replacing the number of the customers with the connected kVA load on each section resulting in

$$A'_q = \sum_{i=1}^{qn} \lambda_{qi} \sum_{j=i}^{qn} L_{qj} + \sum_{i=1}^{qn} \gamma_{qi} x_{qik2} \sum_{j=i}^{qn} L_{qj}\,, \quad k \in \{1,2,3,4\} \quad (7)$$

$$A'_q = \sum_{i=1}^{q_n} \left(\lambda_{qi} + \gamma_{qi}\right) \sum_{i=1}^{q_n} L_{qi}\,, \quad q \in \alpha + 2 \cdots \alpha + \beta + 1 \qquad (8)$$

where L_{qi} is the connected load in section i of lateral q.

5.2.1 Constraints

The constraints for this problem are coordination, design and application limitations, and costs. These are summarized briefly in the following. The relevant details of the constraints can be found in [6].

Coordination between devices of the same type or different type must be assured. An analysis of the coordination restrictions is assumed to be completed in determining the device locations so that it is ensured coordination is possible for at least some combination of devices.

The design specifications require a breaker will be installed at the first location. Also only one type of the protective device may be installed at each location. Finally, if a fuse is installed at location *qi*, then a line recloser device will not be allowed for any possible location on the load side of the fuse. Finally, there may be situations where only a particular device may be installed.

5.2.2 Cost limitations and reliability objectives

With cost limitations, there may be a limited number of three phase and single phase devices which can be expressed as

$$\sum_{q=1}^{\alpha+1} \sum_{i=1}^{q_n} x_{qi11} \le g_1 \qquad (9)$$

$$\sum_{q=1}^{\alpha+1} \sum_{i=1}^{q_n} x_{qi31} \le g_2 \qquad (10)$$

$$\sum_{q=2}^{\alpha+1} \sum_{i=1}^{q_n} x_{qi21} \le g_3 \qquad (11)$$

where g_1 is the number of the available three phase line reclosers plus the breaker, g_2 is the number of the available three phase interrupters and g_3 is the number of the available single phase line reclosers.

Conversely, there may be a stated objective or goal for the *SAIFI* and/or *ASIFI* indices so that constraints are placed on these indices and then cost is minimized.

6. TEST CASE

Consider the simple overhead radial system shown in Figure 2 with eight protective device locations. The permanent and temporary failure rates, the number of customers and average connected load to each section are shown in Table 1. In this example, four different objectives are analyzed in identifying the type of the protective devices at eight locations. These objectives are: (a) minimizing *SAIFI*, (b) minimizing *ASIFI*, (c) minimizing cost based on achieving less than 3.0 for *SAIFI* (Cost #1) and (d) minimizing cost based on achieving less than 3.0 for the *ASIFI* (Cost #2).

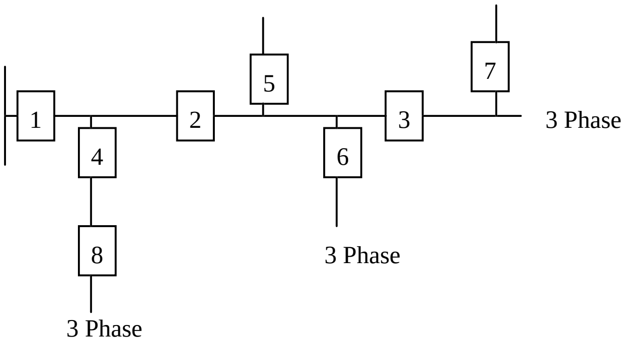

Fig. 2 Simple 8-load point radial system

Section	λ_i *(f/yr)*	γ_i *(f/yr)*	N_i *Customers*	L_i *(KVA)*
1	0.80	1.60	800	1500
2	1.10	1.80	1400	1100
3	1.00	2.00	1200	1000
4	0.90	2.00	500	2250
5	1.20	3.60	400	300
6	1.50	3.50	200	400
7	0.50	0.70	200	450
8	0.70	1.70	300	500

Table 1 Component data for the system

The system must satisfy the following constraints which translate into a total of 17 constraints in the proposed formulation:

- Fuses will be installed on any other locations for which a line recloser has not been selected.
- There will be a breaker in location #1.
- All laterals are category three.
- A line recloser will not be allowed on the load side of the fuse.
- There are no coordination problems.

The optimal solution for this problem was found using a commercial mixed integer linear programming package.

Table 2 shows the solutions for cases (a)-(d). Note, the values given for the objective in cases (c) and (d) are actually the *SAIFI* and *ASIFI* indices. The cost was calculated as single phase fuse was one cost unit, a three phase fuse was two cost units, a single phase recloser was three cost units and a three phase recloser was five cost units. The solutions for minimizing the *SAIFI* or *ASIFI* indices are identical with a breaker at location 1 and line reclosers at the other locations. For minimizing cost #1, the optimal solution is a breaker at location 1, line reclosers at locations 2, 3 and 5, and fuses at the remaining locations. For minimizing cost #2, the optimal solution is a breaker at location 1, line reclosers at locations 2 and 4, and fuses at the remaining locations.

Objective	*Value*	*CB*	*Reclosers*	*Fuses*
a) *SAIFI*	2.19	1	2,3,4,5,6,7,8	None
b) *ASIFI*	2.00	1	2,3,4,5,6,7,8	None
c) *SAIFI*	2.78	1	2,3,5	4,6,7,8
d) *ASIFI*	2.88	1	2,4	3,5,6,7,8

Table 2 Optimal Solutions

This numerical example shows clearly the additional costs necessary to achieve improvements in the reliability indices. If a particular index is more important for some feeder, then this will impact the optimal location. In general, selecting proper locations to install protective devices can greatly enhance their effectiveness.

7. CONCLUSION

This paper proposes a binary programming technique to improve the effectiveness of distribution protective design. The technique identifies type of the protective devices at the predetermined locations on a distribution feeder based on the objective of minimizing reliability indices, such as *SAIFI*, *ASIFI*, or by minimizing cost while achieving desired performance levels.

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