Optimized Distribution Protection Using Binary Programming

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Abstract

The fundamental goal of an electric utility is to serve its customers with a reliable and low cost power supply. This goal has led to a number of standard protection engineering practices that ensure adequate service; however, with deregulation of the utility industry and increased competitive pressures, there is a desire to further improve service reliability and reduce costs. In this vein, this work proposes a binary programming optimization to identify type and location of the protective devices on a distribution feeder. The proposed algorithm uses engineering heuristics to minimize computational time. Numerical examples highlight the proposed approach.

Keywords: *Distribution reliability, distribution systems, integer programming, linear programming, protection design.*

1. INTRODUCTION

The fundamental goal of an electric utility has always been to serve its customers with a reliable and low cost power supply. Traditionally, the acceptable level of reliability and costs has been determined to a great extent by utility boards and similar commissions. Those guidelines have led to a number of standard protection engineering practices to ensure adequate service; however, with the deregulation of the utility industry and increased competitive pressures, there is a desire to further improve service reliability and reduce costs. These pressures require a fundamental improvement in the assessment of, and design for, reliability. In this vein, this paper formulates a binary programming problem to identify type and location of the protective devices on a distribution feeder. The objective of the optimization is to minimize the specific reliability measures that are impacted by protection device location while ensuring that all utility guidelines are satisfied.

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The change in the electric utility industry creates a need for a complete cost/benefit analysis of every expense, to define new indices for evaluating distribution reliability. Since distribution circuit contribute over 90% towards customer outage and supply unavailability [1-2], addressing distribution reliability is of paramount importance. There have been numerous studies for predicting the cost/benefit ratio associated with distribution feeder reliability [3-4]. The interruption energy assessment rate (IEAR) links customer outage cost to the service reliability indices in order to incorporate such costs in the reliability cost/benefit formulation [3]. In [4], it was proposed to select the most cost effective reliability improvement project based on the comparing the ratio of the various project costs to the associated changes in the reliability indices. These projects included replacing cables, installing protective devices, and other preventive or remedial actions. The System Average Interruption Frequency Index (*SAIFI*) and System Average Interruption Duration Index (*SAIDI*) were used in that work. In [5], the author developed a new analytical reliability assessment method (Hierarchical Markov Modeling) which finds the expected annual interruption frequency and the expected annual interruption duration for each customer experience. A new measure of reliability was developed which includes both utility and customer costs referred as, the Total Cost of Reliability (TCR). The protection system design was optimized based on these measures.

Utilities can improve distribution system reliability either through preventive measures or by appropriate remedial actions in response to a disturbance. Preventive measures include tree trimming on a regular basis, construction design modification, e.g., lightning arresters to prevent flashover, animal guards, and so on. Remedial actions capabilities include those provided by protective device response, fault locators and other sensors, and various distribution automation functions.

From a customer point of view an outage can be classified as momentary or permanent. A momentary outage usually lasts less than a few minutes, but a permanent outage requires repair and may be of several hours duration. On a *permanent outage* due to a fault, either a fuse blows or after several unsuccessful automatic reclosings an automatic sectionalizing device lockouts. Historically, momentary faults have been ignored both since they did not result in a reduction in energy supply and since utility commissions did not require momentary fault reports. Still, it is worth noting that today's electronic loads, such as, VCR's, digital clocks, microwaves and computers, are very sensitive to momentary faults. With the increase of these loads, customers have become less tolerant of such faults. Therefore, any reliability evaluation should include both permanent outages as well as momentary outages. This is included in the overall formulation of this work, but for brevity only permanent outages are shown in the development.

Today, most utilities have developed guidelines that give step by step procedures to select protective devices for specific applications. The number and types of protective devices to be installed on a particular feeder will depend upon the system impedance, the size and type of the load, the configuration of the circuit, and the exposure to hazards which may causes outages. Since these guidelines are limited in scope, engineering judgment still plays a major role in order to achieve a low cost and an acceptable level of service reliability. This paper proposes a more systematic approach.

2. DISTRIBUTION PROTECTION

This section presents background information on the distribution problem of interest.

2.1 Network structure

Distribution networks can be classified as either radial, spot or secondary. Radial systems are the most common and the focus of this study. Radial networks may consist of both overhead and underground lines using either a three wire or four wire scheme. On a four wire system, a ground neutral wire is run alongside the three phases, whereas on a three wire system, the neutral remains grounded at the substation. Laterals branching from the main three phase feeder can be single phase, two phase or three phase. In addition, most utilities design a system so two radial networks can pick up neighboring loads by tie switches during scheduled or unscheduled outages.

2.2 Protection devices

In general, protection of a distribution system consists of a circuit breaker at the substation with line reclosers, sectionalizers, interrupters and fuses along the main feeders and on the laterals. These protective devices must satisfy the following objectives:

- preventing safety hazards to the public by removing a fault circuit from the network.
- preventing or minimizing damage to equipment by clearing an abnormal condition.
- improving service reliability by removing a small section of the circuit for a given fault.

A feeder circuit breaker located at the substation and its protection scheme consists of phase, ground and automatic reclosing relays. A circuit breaker has fault interruption and automatic reclosing capabilities. A line recloser has fault sensing, fault interrupting, and automatic reclosing capability similar to those of a circuit breaker located at the substation. Importantly, line reclosers have the capability of automatically testing a line downstream from the recloser. The automatic scheme can be set to test energize the line once or twice at very high speed with several additional tests at a lower speed. The high speed tests are designed to enable the line recloser to check for a temporary fault without blowing load side fuses, thereby avoiding any unnecessary permanent outage for the customers downstream of the fuse. This capability is called a fuse saving scheme. An interrupter is similar to a line recloser, except that it does not have automatic reclosing capability. A sectionalizer is a device designed to isolate automatically a faulted line section after sensing the fault and waiting for a pre determined number of operations of a upstream breaker or line recloser. A sectionalizer does not have fault interruption or automatic reclosing capability, but can be used to switch load currents that fall within its continuous current rating.

A fuse is a low cost automatic sectionalizing device. It has fault sensing and interruption capabilities, but obviously lacks automatic reclosing capability so that momentary faults are treated the same as permanent faults. As mentioned earlier, problems with momentary faults can sometimes be addressed by using a fuse saving scheme. A fuse saving scheme allows a breaker or a line recloser to clear momentary faults before the fuse blows and thus, allows the fuse to operate only for permanent faults.

2.3 Protection design

Type and location of a distribution protective devices has been largely left to engineering judgment with limited guidelines. In general, a circuit breaker with phase and ground relays is installed at the substation. Line reclosers are installed on the main overhead feeder and on heavily loaded or long laterals. Due to cost limitations, only a limited number of these devices are installed on any given feeder. A typical feeder may have as many as three to six recloser locations. Location of these devices varies depending on the utility practices and the feeder configuration [6-7]. Some utilities break the feeder into sections based on the connected load (typically, 3-5 MVA per section) and others may use the number of connected customers (typically, about 500 customers per section) or distance to break the feeder into sections. Interrupters are used similar to line reclosers, except that they are used for underground circuits.

Sectionalizers are overhead line devices which must be used in conjunction with a line recloser or a breaker. If there is a location for which a line recloser should be installed but, coordination can not be achieved (with load and source side protection devices) then a sectionalizer can be used instead.

Fuses are used on both overhead and underground circuits. A fuse is low cost but comes at the great disadvantage of a long restoration time due to fuse replacement and because it treats momentary faults the same as permanent faults. At many utilities, economic considerations require a fuse to be installed on any lateral three or more spans long. Also, it is important to insure that fuses will coordinate with source and load side protective devices. Miscoordination between these devices may cause a fuse to blow for a fault outside its protection zone which will delay identifying the trouble section and hence increase outage duration.

2.4 Distribution reliability measures

A variety of reliability indices for a distribution system have been defined [8-9]. These indices can be divided into three categories.

- Single load point indices.
- Customer orientated indices.
- Load orientated indices.

Single load point indices which provide service reliability data from an individual customer viewpoint, are the average failure rate λ_s,

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{1}$$

the average outage duration r_s,

$$r_s = \frac{\sum_{i=1}^{n} \lambda_i \cdot r_i}{\sum_{i=1}^{n} \lambda_i} \tag{2}$$

and the average annual outage duration U_s,

$$U_s = \sum_{i=1}^{n} \lambda_i r_i \tag{3}$$

where n is the set of components whose failure results in an outage at the given load point, λ_i is the failure rate of component i and r_i is the outage time of component i.

A recent survey [9] indicates that the majority of the utilities use customer based indices to evaluate their service reliability, with the most commonly used indices given as System Average Interruption Frequency Index (*SAIFI*), System Average Interruption Duration Index (*SAIDI*), Customer Average Interruption Duration Index (*CAIDI*), Average Service Availability Index (*ASAI*) and Momentary Average Interruption Frequency Index (*MAIFI*).

2.5 Distribution reliability and Protective Devices

An important goal in designing and operating a distribution system is achieving and maintaining an acceptable level of service reliability. In this section, we discuss the effects of automatic, manual or remotely controlled line sectionalizing devices in *SAIFI*, *SAIDI*, *CAIDI*, *ASAI* and *MAIFI* indices which is summarized in Table 1.

	SAIFI	*SAIDI*	*CAIDI*	*ASAI*	*MAIFI*
Automatic	*x*	*x*	*x*	*x*	*x*
Manual		*x*	*x*	*x*	
Remote		*x*	*x*	*x*	

Table 1: The reliability impacts of sectionalizing devices (x indicates an impact)

Automatic line sectionalizing devices such as line reclosers, interrupters, sectionalizers and fuses will reduce the total number of customers affected for a single outage by automatically isolating the faulted section. They also reduce the frequency of outages for customers on the source side of these devices, and reduce the duration of outages by expediting the task of locating the faulted feeder section. In theory, the more automatic devices installed on a distribution feeder the better the service reliability. Still, there are some application limitations, such as, coordination between devices and the cost of the installation, maintenance and operation. Also, three phase line sectionalizing devices with automatic reclosing capabilities may worsen the *MAIFI* index.

Manual line sectionalizing devices, such as switches and disconnects, will reduce the duration of interruption by allowing faulted line sections to be manually isolated and permit service to be restored to customers on unfaulted sections of the feeder. The addition of manually operated *line sectionalizing* devices reduce the average annual customer minute outages but they do not have an affect on outage frequency.

Remote controlled sectionalizing devices or a distribution automation system will expedite service restoration. Remote controlled sectionalizing devices will allow a system operator to remotely identify a faulted section and operate certain switches to restore service to many of customers, further reducing the average annual customer minutes of outages but not affecting the outage frequency. A distribution automation system will perform this task automatically and has similar affects on the reliability indices.

3. PROPOSED ALGORITHM

3.1 Integer programming

Integer linear programming seeks to maximize or minimize a linear function of many variables subject to linear constraints and variables which must be integers. Any such problem can be approached by the following binary (zero-one) programming problem [10]

$$\min \sum_{i=1}^{n} c_i x_i \quad (4)$$

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.

Binary nonlinear programming problems can be reduced to linear problems by replacing any product terms by a variable x_{n+1} and adding the following $n+1$ constraints.

$$\sum_{i \in P} x_i - x_{n+1} \le p - 1$$
$$x_{n+1} - x_i \le 0 \ \forall \ i \in P \quad (5)$$
$$x_{n+1} \in \{0,1\}$$

where P is the set of product terms and p is the number of element in P. (For example, given $x_1 x_3 x_5$, then $P=\{1,3,5\}$ and $p=3$).

3.2 Formulation

The proposed method uses a binary programming optimization to identify type and location of the protective devices on a distribution feeder. The goal of this technique is to identify the type and location of the specific number of the protective devices on a distribution feeder in order to minimize the *SAIFI* index.

Consider a set of possible locations on the distribution feeder and sets of various protective devices. The optimization problem is to choose a subset of the locations at which to install a specific protective device in order to minimize the *SAIFI* index. Possible locations can be based on the number of the customers, the connected loads, the failure rates, the feeder configuration, specific utility practices, or for small feeders every single pole on the feeder.

A distribution feeder consists of a main section and several lateral taps. Depending on a utility practices, the lateral taps can be divided into various categories which we label one, two or 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 three spans, and will only be fused. 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* index 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* index level is constant unless a fuse saving scheme is applied.

Now, consider Fig. 1 which can be a main feeder or a category three lateral with n possible locations for installing protective devices. For a main feeder, a circuit breaker is located at location 1, and at other locations there may be line reclosers or sectionalizers for an overhead circuit and interrupters for a underground circuit.

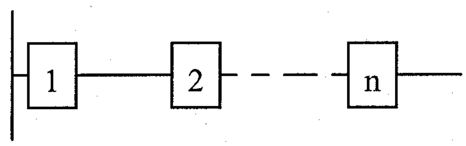

Fig. 1 A typical main or lateral feeder with several sections

Since effects of the reclosers, sectionalizers and interrupters are the same in the *SAIFI* index calculation, the proposed technique treats these three phase automatic sectionalizing devices identically. Subsequently (after determining an optimal solution), the type of three phase devices can be selected based on the type of the circuit (underground or overhead) and coordination concerns.

The following basic assumptions are used in the calculation of the *SAIFI* index which are representative of present practices.

- The feeder is operated as a radial feeder but can be connected as a loop through a normally open switch.
- The number and type of customers 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 and no fuses are allowed to be installed on the main feeder.

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

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T} \tag{6}$$

where 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

$$\sum \lambda_i N_i = \sum_{q=1}^{\alpha+\beta+1} A_q \tag{7}$$

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. The required calculation for each main feeder or lateral q is

$$\begin{aligned} A_q = & \sum_{i=1}^{q_n}\left(\lambda_{qi}+\gamma_{qi}\right)\sum_{j=i}^{q_n} N_{qj} - \sum_{i=1}^{q_n}\gamma_{qi}x_{qi2}\sum_{j=i}^{q_n} N_{qj} + \\ & \sum_{i=2}^{q_n}\lambda_{qi}\sum_{j=1}^{i-1} N_{qj}\prod_{k=j+1}^{i} x_{qk1}x_{qk2} + \\ & \sum_{i=2}^{q_n}\gamma_{qi}\sum_{j=1}^{i-1}\left(1-x_{qj2}\right)\sum_{k=j}^{q_n} N_{qk}\prod_{l=j+1}^{i} x_{ql1}x_{ql2} \end{aligned} \tag{8}$$

where q_n is the number of the possible 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, respectively, and N_{qj} is the number of customers for section j of q including all laterals connected to that section. Note, if there is a three phase device at location qk, then the variable $x_{qk1} = 0$, and otherwise $x_{qk1} = 1$. Here, the subscript 1 is used to represent a three phase device and the subscript 2 represents a fuse. These counter intuitive definitions for the variables x are used to simplify equation (8). Since the main feeder requires a three phase device at the substation and fuses are not permitted (8) reduces to

$$A_q = \sum_{i=1}^{q_n}\lambda_{qi}\sum_{j=i}^{q_n} N_{qj} + \sum_{i=2}^{q_n}\lambda_{qi}\sum_{j=1}^{i-1} N_{qj}\prod_{k=j+1}^{i} x_{qk1}, \quad q=1 \tag{9}$$

The calculation for the category two laterals can also be greatly simplified since a fuse will be installed at the tap and no other protective device will be installed on the lateral. Thus,

$$A_q = \sum_{i=1}^{q_n}\left(\lambda_{qi}+\gamma_{qi}\right)\sum_{i=1}^{q_n} N_{qi} \quad q \in \alpha+2\ldots\alpha+\beta+1 \tag{10}$$

Notice, that (10) is constant for a given feeder since the protection has been already determined. In this way, minimizing

$$z = \sum_{q=1}^{\alpha+1} A_q \tag{11}$$

is equivalent to minimizing the *SAIFI* index.

The constraints for this problem are coordination, design and application limitations, costs, and those due to the reduction of the non-linear binary programming problem to a zero-one linear programming problem. These are detailed in the following.

3.2.1 Coordination

If coordination between two protective devices at locations k and j can not be achieved, then a constraint must be added. For the coordination between two three phase devices,

$$x_{qk1} + x_{qj1} \geq 1 \tag{12}$$

for two single phase devices,

$$x_{qk2} + x_{qj2} \geq 1 \tag{13}$$

and for a combination of these

$$x_{qk1} + x_{qj1} + x_{qk2} + x_{qj2} \geq 3 \tag{14}$$

where x_{qk1} and x_{qj1} represent possible locations for a three phase device, x_{qk2} and x_{qj2} represent possible locations for a fuse at locations qk and qj respectively.

3.2.2 Design and application

For category three laterals, a three phase device or a single phase device must be installed at the tap points, so

$$x_{q11} + x_{q12} = 1, \quad \text{for } q \in \{2 \ldots \alpha+1\} \tag{15}$$

For any other locations only one type of the protective device may be installed, so

$$x_{qi1} + x_{qi2} \geq 1, \quad i \in \{2 \ldots q_n\} \text{ and } q \in \{2 \ldots \alpha+1\} \tag{16}$$

If at a location *qi,* due to a physical or other limitation, only a three phase device is allowed, then

$$x_{qi2} = 1 \tag{17}$$

or if only a single phase device is allowed, then

$$x_{qi1} = 1 \tag{18}$$

must be added as a constraint. If a fuse is installed at location *qi*, then a three phase device will not be allowed for any possible location on the load side of the fuse, so

$$x_{qi2} + x_{q(j+1)1} \geq 1, \; j \in \{i \ldots q_n - 1\} \text{ and } q \in \{2 \ldots \alpha+1\} \tag{19}$$

3.2.3 Cost limitations

Due to cost limitations, there may be a limited number of three phase (20) and single phase (21) devices allowed, so

$$\sum_{q=1}^{\alpha+1} \sum_{i=1}^{q_n} x_{qi1} \geq \sum_{q=1}^{\alpha+1} q_n - g_1 \tag{20}$$

$$\sum_{q=1}^{\alpha+1} \sum_{i=1}^{q_n} x_{qi2} \geq \sum_{q=1}^{\alpha+1} q_n - g_2 \tag{21}$$

where g_1 is the number of the available three phase devices for the entire feeder and g_2 is the number of the available single phase devices for the category three laterals.

4. TEST CASE

Consider the simple overhead radial system shown in Fig. 3 with seven possible protective device locations. The permanent and temporary failure rates, the number of customers and average connected load to each section are shown in Table 2.

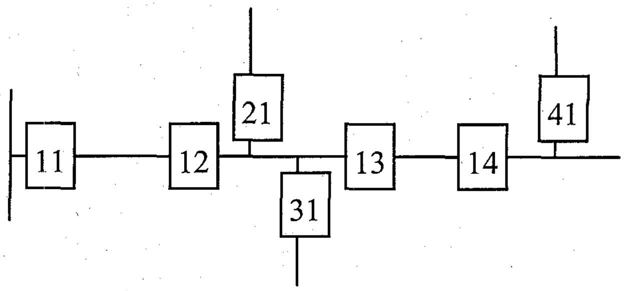

Fig. 3 Simple 7-load point radial system

In this example, the goal is to minimize the *SAIFI* index by identifying the type and location of protective devices. The following constraints are enforced:

- There are only two line reclosers available.
- There is no limitation on the number of the fuses which can be installed.
- A proper coordination between line reclosers in locations #13 and #14 is not possible.
- A fuse can not be installed on the main feeder.
- A fuse or a line recloser must be installed on all taps.
- There will be a breaker in location #11.
- All laterals are category three.

The above translate into a total of 15 constraints in the proposed formulation. Then the objective of this problem is to minimize

$$225x_{121} + 562.5x_{131} + 250x_{141} + 675x_{121}x_{131} + 500x_{131}x_{141} + 600x_{121}x_{131}x_{141} - 15x_{212} - 100x_{312} - 25x_{412} + 2637.5$$

After reducing to binary programming and removing the constants, then the objective reduces to

$$z = 225x_{121} + 562.5x_{131} + 250x_{141} + 675x_5 + 500x_6 + 600x_7 - 15x_{212} - 100x_{312} - 25x_{412}$$

Section	λ_{qi} *(f/yr)*	γ_{qi} *(f/yr)*	N_{qi} *(cust.)*	L_{qi} *(KVA)*
11	1.00	2.00	300	1200
12	0.75	1.75	250	550
13	2.25	5.50	125	200
14	2.00	4.75	200	450
21	0.25	0.75	20	30
31	1.00	2.00	50	100
41	0.50	2.50	10	15

Table 2 Reliability data for system of Fig. 3

Examples	Reclosers	Fuses	None	SAIFI
1	None	21,31,41	12,13,14	6.23
2	12	21,31,41	13,14	4.51
3**	13	21,31,41	12,14	3.56
4	14	21,31,41	12,13	4.69
5	13,14	21,31,41	12	3.27
6	12,14	21,31,41	13	3.66
7*	12,13	21,31,41	14	3.3

*where * is the optimal solution found by algorithm for case 1, and ** is for case 2.*

Table 3 SAIFI for Fig. 1 system

The optimal solution for this problem was found using a commercial mixed integer linear programming package and is seen to be example 7 in Table 3. This solution recommends installing line reclosers at locations 12 and 13, and fuses at locations 21, 31, and 41. Note that the *SAIFI* index is smaller for example 5, but due to the coordination problem, violates the specified constraints. Next, the problem was modified to allow only one line recloser. The optimal solution is 3.56 interruptions/customer year, example 3, which is around 4% less than example 6 with two line reclosers. These simple examples clearly indicate that selecting proper locations to install protective devices can greatly enhance their effectiveness.

5. CONCLUSION

This paper proposes a binary programming technique to improve the effectiveness of distribution protective design. The technique identifies type and location of the protective devices on a distribution feeder based on the objective of minimizing the *SAIFI*. Future work is focusing on computational issues, and addressing tradeoffs between load and customer based reliability indices as well as temporary and permanent fault considerations.

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BIOGRAPHIES

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