Recloser and Sectionalizer Placement for Reliability Improvement Using Discrete Event Simulation

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***Abstract*—This paper presents a cost-effective strategy to place automatic reclosers and sectionalizers into electric distribution systems for reliability improvement using simulation and probability. Evaluation of reliability indices in the placement process is carried out via discrete event simulation that takes advantage of high performance parallel computing cluster. The requirements on probabilities evaluated from the empirical distributions of two reliability indices (SAIFI and CAIDI) are imposed as placement constraints or objectives, rather than the annual sample means used in the conventional placement problems. As a result, our placement solution is robust against the variability in model predicted SAIFI and CAIDI. The proposed placement strategy is illustrated through a Roy Billinton Test System (RBTS).**

***Index Terms*—Discrete Event Simulation, Distribution System Reliability, Reliability Evaluation, Switching Devices Placement**

I. Introduction

Reliability in power delivery is a matter of great importance to electric utility companies and their customers. Formalizing reliability consideration in the process of distribution system automation is a cost-effective way to achieve reliability improvement. One of the technologies being considered by the utilities is to install new switching devices that can be effectively coordinated to isolate faults and restore services to unaffected sections from alternative supplies. IEEE Std 1366-2012 [1] identifies several distribution reliability indices for evaluating the distribution systems, such as System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI). Utilities are required to report these indices to state public utility commissions.

Various solutions have been proposed to improve the distribution reliability by installing more switching devices, such as manual switches, circuit breakers, fuses, reclosers, and sectionalizers. A typical device placement problem is formulated as, minimizing the value of an objective function, subject to some constraints. The costs considered in the objective or constraints can include device cost and interruption cost. Ferreira and Bretas [2] formulated their placement problem by nonlinear binary programming (NLBP). They studied the operation of reclosers, and the impacts on reliability indices from both permanent and temporary faults. Bezerra et al. [3] proposed a two-stage placement without involving random variables such as failure rates and interruption durations of the system. However, all contingencies are given the same weight and no reliability index is analyzed. Abiri-Jahromi et al. [4] modeled their problem as mixed-integer linear programming (MILP) and used CPLEX to solve it. They also presented a sensitivity analysis on the effect of interruption cost (customer damage function), number of devices to be placed, customer type and load density. Falaghi et al. [5] used fuzzy multi-objective formulation to transform the objectives into a fuzzy environment. This formulation can be considered as using fuzzy membership functions to characterize the weights of the objectives. Moradi and Fotuhi-Firuzabad [6] considered the difference between the operations of circuit breaker and sectionalizer.

Placement solutions in the above papers typically used the observed sample means for random variables such as failure rates and interruption durations, without considering their variations. For example, if the required SAIFI must be smaller than a certain number, using the existing methods would lead to a solution where the mean SAIFI satisfies the requirement. However, this implies that a placement solution can suffer from a 50% chance of violation.

Discrete events simulation methods have been proposed to estimate the reliability indices. Goel and Billinton [7] compared contingency enumeration approach (analytical method) with Monte Carlo simulations. They showed that results from analytical method are close to simulation results. However, they still focused on the sample means. The reader is referred to [8]–[10] for more details. Balijepalli [11] reviewed the estimation of reliability indices with analytical methods and suggested that simulation methods would be preferred as they can provide more information on the variations of the indices. Through a large number of replications, the probability distributions of reliability indices can be estimated and the requirements on reliability are guaranteed with a certain probability.

Unlike the papers that used simulation for mean values estimation, in this paper, simulations also estimate the distributions of costs and reliability indices, which serve as placement criteria. The demand of significant computational power with the simulation-based placement is met by using high performance parallel computing cluster. In this paper, placement of reclosers and sectionalizer are evaluated with probability-based constraints and objective, which provides more robust solutions with any desired probability.

The remainder of this paper is organized as follows. The next section briefly discusses the backgrounds such as operation of reclosers and sectionalizers, reliability indices and cost

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functions. The optimal placement problem is formulated in Section 3. Section 4 discusses a simulation method to estimate the reliability indexes. Section 5 presents our placement solution using the RBTS.

II. Background

A. Operation of Reclosers and Sectionalizers

The focus on placement of reclosers and sectionalizers in this paper stems from the recent interest and investment of certain utilities. According to IEEE Std 1366-2012 [12], a recloser is a device that can automatically interrupt fault current and reclose. Reclosers, sectionalizers, fuses and other protective devices are coordinated to provide the desired protection function [13], [14]. Some advanced reclosers and sectionalizers also have the communication capability. This paper does not concern about the configuration details. It is assumed that reclosers and sectionalizers can isolate the fault and sectionalize distribution circuits under 5 minutes, which is in line with the finding in [15].

B. Reliability Indices

IEEE Std 1366-2012 [1] identifies a set of distribution reliability indices widely used in the industry and factors that affect their calculation. The definition of indices used in this paper is reproduce here:

$$\text{SAIFI} = \frac{\text{Total number of customers interrupted}}{\text{Total number of customers served}} \quad (1)$$

$$\text{CAIDI} = \frac{\sum \text{Customer Minutes of Interruption}}{\text{Total number of customers interrupted}} \quad (2)$$

According to IEEE Std 1366-2012 [1], momentary interruptions, of which the durations are less than a specific threshold (currently 5 minutes as defined by New York State) are not counted in calculating SAIFI and CAIDI. With reclosers, most interruptions caused by temporary faults are restored within 5 minutes and thus they are eliminated from the calculation of the indices. For a permanent fault, using reclosers and sectionalizers can reduce the switching time for partial restoration of service. Switching time is defined as the time to isolate the faulted section and restore power supply for the remaining part (unaffected sections) of the feeder. A permanent fault must be isolated before the feeder circuit breaker can be reclose to restore power supply. Without a recloser, the isolation could be done manually, which requires tens of minutes. With reclosers and sectionalizers, the switching time can be reduced to less than 5 minutes as mentioned above, which means some interruptions can be eliminated from SAIFI and CAIDI calculations according to IEEE Std 1366-2012 [1]. In [13], with a recloser installed at a substation, the improvements of reliability by using different midpoint devices are evaluated. A midpoint device can be a regular switch, a recloser, or a sectionalizer. The reliability also depends on how the devices and normally open switches are coordinated.

C. Cost Function

Cost of interruptions and devices has been considered as the objective function in optimal device placement problems [4], [6], [16]–[18]. To measure the interruption cost, Goel and Billinton suggested the concept of customer damage function [19], which measures how much a customer is willing to pay to avoid interruptions. A Berkeley Lab report [20] to the Department of Energy in 2009 summarized information on the value of reliable electricity service over 16 years in the US. For each customer sector, a simplified interruption cost per kWh can be defined as a piecewise linear function of interruption duration. The data points in Table I are used to construct piecewise linear cost functions for different sectors. Only two types (residential and non-residential) of customers are used in this paper. For interruptions longer than 8 hours, the rate of 8 hours is used.

Notice that the unit for the cost in Table I is per unserved kWh. The cost per kW load interrupted is calculated from the cost per kWh unserved. For each 1kW load interrupted, the interruption cost is calculated and shown in Table II and Fig. 1 as a function of interruption duration. The cost function increases with duration, and cost for non-residential users is much higher than that for residential users. The cost function here represents how customers value the service reliability. Utilities can develop their own damage functions for a preferred placement outcome. Nevertheless, the optimization and simulation method discussed in this paper does not depend on any particular cost function.

III. Problem Formulation

The existing work on switching devices placement problem all used mean values for reliability indices such as SAIFI and CAIDI. The main drawback of using a mean value is that

TABLE I
Customer Cost Data per Unserved kWh [20]

Duration	Momentary	30 mins	1 hour	4 hours	8 hours
Non-Res.	$1,604.1	$396.3	$282.0	$298.9	$296.1
Residential	$16.8	$3.5	$2.2	$1.2	$0.9

TABLE II
Interruption Cost per 1kW Load

Duration	Momentary	30 mins	1 hour	4 hours	8 hours
Non-Res.	$53	$198	$282	$1,196	$2,369
Residential	$0.56	$1.75	$2.20	$4.80	$7.20

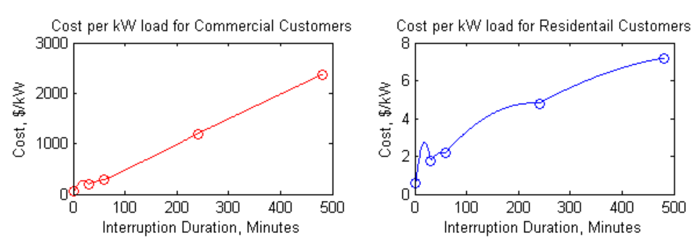

Fig. 1. Cost per kW average load for customers

no information about the variation is given. In such cases, violations of reliability requirements measured in probabilities could be as high as 50%. To avoid this problem, a more restrict requirement should be used in the constraints.

In this paper, simulation is utilized to evaluate the reliability indices. An empirical probability distribution along with its mean and variance can be estimated for each random variable, including the cost and reliability indices. The reliability requirements are imposed by certain percentiles for the random variables. Such formulation also quantify the uncertainties of the placement solution. Suppose 90th percentile is used, then SAIFI and CAIDI fall below the prescribed levels with a 90% probability. To be more specific, One of several alternative placement problems is stated as follows:

$$\text{Minimize: } k \tag{3}$$

$$\text{Subject to: } \mathbf{P}(\sum_i \sum_j L_j f(T_{ij}) < k) > 0.9 \tag{4}$$

$$F_{\text{SAIFI}}(s) = \mathbf{P}(\text{SAIFI} < s) > 0.9 \tag{5}$$

$$F_{\text{CAIDI}}(c) = \mathbf{P}(\text{CAIDI} < c) > 0.9 \tag{6}$$

$$\text{Number of Reclosers} < N_R \tag{7}$$

$$\text{Number of Sectionalizers} < N_S \tag{8}$$

where, T_{ij} is the interruption duration for interruption i at load point j; $f(T_i)$ is interruption cost function (per kW load) defined by the customer damage function summarized in Fig. 1; Lj is the average power load at load point j; F_{SAIFI} and F_{CAIDI} are cumulative distribution function of SAIFI and CAIDI; $\mathbf{P}(\text{SAIFI} < s)$ is the probability of SAIFI less than a prescribed number s; $\mathbf{P}(\text{CAIDI} < c)$ is the probability of CAIDI less than a prescribed number c; N_R and N_S are the affordable numbers of reclosers and sectionalizers.

The objective in this formulation is to minimize the annual cost k. Since such a cost is also a random variable, it is expressed in the same way as the constraints for SAIFI and CAIDI. Any one of them can be switched with the objective to form an alternative placement problem. With this formulation, three random variables need be estimated: annual cost, SAIFI and CAIDI. Simulation is used to obtain their 90th percentile estimations from their empirical probability distributions. In this paper, k, s and c are approximated by the 90th percentiles of the corresponding random variables.

IV. Simulations

A. Simulation Method

For each component subject to failure, time to failure (TTF), time to repair (TTR) and time the switch (TTS) are all random variables, for which the distributions are to be assumed. One of the major advantages of simulation-based method is the freedom of choosing the most suitable distributions for TTF, TTR, and TTS. The example in this paper uses exponential distributions for these three variables. Also, each element operates as good as new after each repair. The simulation method discussed in [8], [9] is used with a slight modification. The operation of each element is individually considered as a Markov process to generate time sequence.

During the simulation, the number of failures and failure durations at each load point are recorded. For each sample period, yearly sample values of SAIFI, CAIDI and annual cost are calculated based on the failure rates and failure durations of the load points. The simulation is run for a long time to collect a large number of samples. The 90th percentiles are calculated for system performance evaluation.

B. Simulation and Optimization Program

A MATLAB simulation program is developed to assess the reliability indices for different placement of switching devices. In the program, a distribution system is represented by a graph. Each connection can be a line or a line with device such as recloser, switch, fuse, etc. An integer number is used to indicate the device installed with the connection line. The placement problem is basically finding the optimal set of integers for all the connections under the constraints. Generally, the simulation process is as follows: 1. Generate TTF for each element; 2. Find the element with minimum TTF; 3. Advance the simulation time to minimum TTF; 4. For element with minimum TTF, generate TTR and TTS; 5. With this element failure, find the affected load points; 6. Record the interruption time and calculate cost; 7. Advance the simulation time with TTR; 8. Generate a new TTF for the repaired element; 9. Check if any other element fails before this element is repaired, if so, rollback the simulation to failure time of the other element; 10. Go back to step 2 until specified simulation time is reached. Noted that only sustained interruptions over 5 minutes are counted.

V. Placement for RBTS

The Roy Billinton Test System (RBTS) [21], [22] is used by many authors [3]–[6], [18] for switching device placement. This paper uses part of the system to demonstrate our method of recloser/sectionalizer placement. Fig. 2 shows Bus 2 of RBTS, which consists of 4 feeders and 22 load points. All lines are overhead lines. Regular circuit breakers and manual switches are installed as shown in Fig. 2.

In this system, each lateral feeder is equipped with a fuse, which is not shown in the Fig. 2. Since no temporary failure rate for the system is given, only permanent failure is considered in this paper. Also the power supply to the feeders is assumed to be 100% reliable and fuse blowing scheme is used. Two kinds of failures are considered in this case: transformer failure and line failure. The failure rate, switching time and repair time of these two kinds of failures are given in [21]. Table III reproduces the given data and calculated the mean time to failure (MTTF) of each element.

A. Verification of the Simulation Program

For the system shown in Fig. 2, the settings of case (A) in [21] is used to verify our simulation program. In this case, breakers and manual switches are as shown in the figure; a fuse is installed at each lateral feeder; an alternative supply

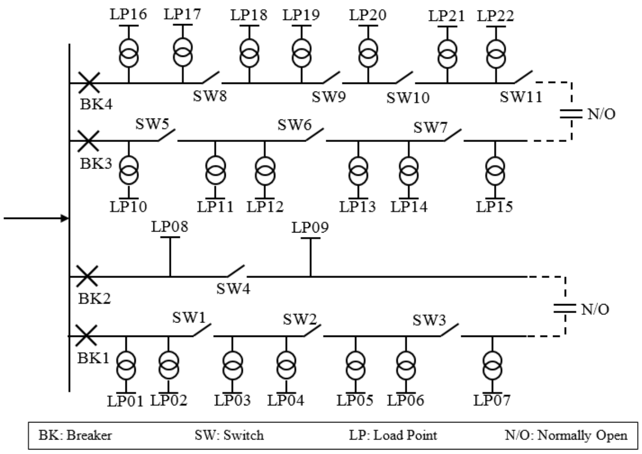

Fig. 2. Bus 2 of RBTS [8], [21], [22], Base Case

is provided for each feeder; transformers are repaired after failure. Reliability indices and load point indices (e.g., failure rate, annual failure duration) for case (A) obtained by an analytical method are given in [21]. Simulation results with another simulation method for the same case are also given by [10]. These values (basically mean values) are used to verify our simulation program.

The system is simulated for 1 million years. Since the system is small and the MTTF is very large, it is very likely that no component fail in a year for this small system. Calculating reliability indices yearly generally yields results of high variations. To emulate a large system, average yearly reliability indices are calculated every 100 years. Therefore, there are a total of 10,000 samples of SAIFI, CAIDI and cost, respectively. The empirical distributions obtained by this method are similar to those from a system of 100 times larger. It should be noted that this example is intended to show qualitative effects of variations on SAIFI, CAIDI and cost.

Table IV shows the statistics of SAIFI, CAIDI and cost. Compare to the mean values, 90th percentiles provide more conservative evaluations. Such variations should be paid attention to even for a large system. As reliability of the system is concerned, the conservative evaluations should be more suitable than mean values. The mean values of SAIFI and CAIDI are compared in Table V with results from other papers. The close match of results validates our program for simulation-based evaluation of SAIFI and CAIDI.

B. Device Placement Results

For device placement, the candidate locations for placement considered are limited to replacement of feeder circuit breakers at substations by reclosers, and manual switches by automatic sectionalizers in Fig. 2. In addition, automatic sectionalizers are only installed on feeders with reclosers, and the normally open switches are assumed to be coordinated to operate with reclosers and sectionalizers. With $N_R = 2$ and $N_S = 4$ in (7) and (8), there are a total of 48 possible placement options.

TABLE III
TRANSFORMER AND LINE RELIABILITY DATA

Component	Failure Rate	MTTF	Switching Time	Repair Time
Transformer	0.015	584,000	1.00	200
Line	0.065	134,769	1.00	5

Failure rates are per year per km. Time unit is hour.

TABLE IV
STATISTICS OF SAIFI, CAIDI AND COST FOR BASE CASE (A)

	Mean	Std. Deviation	90 percentile
SAIFI	0.247	0.026	0.281
CAIDI	14.64	4.527	20.75
Cost	4.830	1.510	6.836

TABLE V
COMPARISON OF RELIABILITY EVALUATION RESULTS

	Method	SAIFI	CAIDI	SAIDI
This paper	Simulation	0.247	14.64	3.59
Allen91 [21]	Analytical	0.248	14.55	3.61
Goel00 [10]	Simulation	0.249	14.54	3.62

TABLE VI
STATISTICS OF SAIFI, CAIDI AND COST FOR BASE CASE (E)

	Mean	Std. Deviation	90 percentile
SAIFI	0.247	0.026	0.280
CAIDI	3.092	0.354	3.557
Cost (M$)	1.055	0.147	1.274

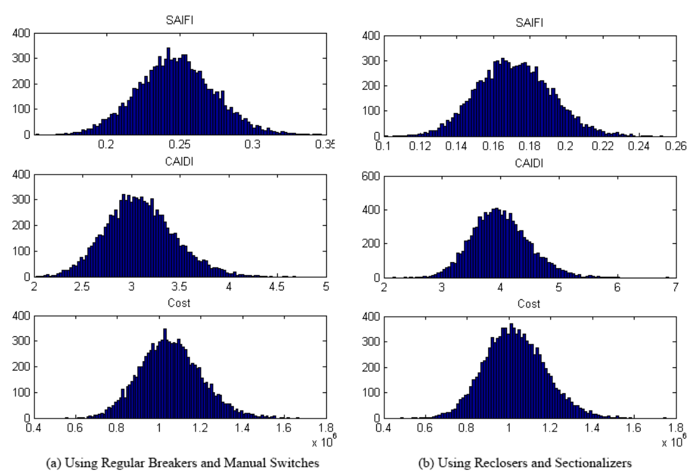

Fig. 3. Histogram of SAIFI, CAIDI and Cost

Setting for case (E) in [21] is used instead of case (A) with the same simulation setup, the only difference is the repair time of transformers. In case (E), transformers are replaced by a new one, thus reducing the repair time to 10 hours. Simulation result without reclosers and sectionalizers is shown in Table VI and Fig. 3(a). If the requirements for SAIFI is $s = 0.21$ in (5) and for CAIDI is $c = 4.8$ in (6), there are a total of 24 feasible placements. Within these feasible locations, the simulation result shows that the optimal placement is to replace breakers 1, 3 by reclosers, and switches 1, 2, 6, 7 by sectionalizers. With this placement, the 90th percentile of SAIFI is 0.197, which is about 20% of improvements. The histogram of the improved system is showed in Fig. 3(b).

From the simulation result, we see the improvement is significant for the example system. The use of 90th percentiles takes into consideration of the variations of the random variables and provides a more robust placement than the existing placement results that rely on the indices calculated from mean values only.

It should be noted that reclosers and sectionalizers generally reduce the switching time for partial restoration with alternative power supply. When the switching time becomes very small (e.g. less than 5 minute), such interruptions are considered as momentary. Thus they are not counted into SAIFI and CAIDI. Since long interruptions requiring repairs still remain, the average interruption time in a sustained interruption for each customer (i.e. CAIDI) appears to be higher. However, such increase of CAIDI, as a result of eliminating short interruptions, is due to the practical calculation method. If all the momentary and sustained interruptions were considered, the average interruption duration would have been smaller after the device placement.

VI. CONCLUSIONS

This paper has shown that discrete event simulation allows us to obtain the distributions of SAIFI, CAIDI and interruption cost. Device placement formulation described by probability-based objectives and constraints allow us to obtain placement solutions satisfying the requirements with any desired probability. This innovative formulation provides a measurement for the uncertainty on the solutions. Using 90th percentiles instead of mean values for reliability assessment yields more robust solutions with respect to the variability of the reliability constraints, whereas the previous solutions are not. The cost function used in this paper provided an example of how to assess interruptions from the perspective of various classes of customers. Such cost studies can be extended to include many more aspects of the cost incurred in interruptions, including those concerned by utility companies.

Since the RBTS is a relatively small problem, all possible solutions are enumerated to find the optimal one. In general, for large systems, randomized search algorithms such as particle swarm optimization can be used to find a good solution more efficiently. In the simulation of RBTS, yearly sample for a random variable is obtained from each 100-year simulation in order to emulate a large system. In practice, samples should be obtained from each 1-year simulation for a large system. It should be noted that, the variances of SAIFI, CAIDI and cost tend to be smaller for larger system. Therefore, utilities with larger service area tend to have smaller variances. According to the simulation program, the computational complexity for the simulation-based reliability index evaluation is generally $O(n)$, where n denotes the number of elements subject to failures in the system.

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