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Automated Sectionalizing Switch Optimization for Smart Grid Distribution Automation

S. CHOUHAN; H. INAN
Leidos Engineering, LLC
USA

SUMMARY

Determination of the optimum number and placement of sectionalizing switches in Distribution Automation (DA) feeders is a very challenging task. This is an important step in the feasibility process of DA projects and one has to consider the trade-off between reliability and economics to arrive at the answer. This paper presents a novel iterative approach based on the relative reduction in the normalized customer interruption costs for the optimal switch number and placement problem. An iterative algorithm is constructed which minimizes the total interruption costs at each step of the analysis to arrive at the solution. The proposed method has been successfully implemented to develop the DA system design for Guam Power Authority (GPA) Smart Grid Initiative project. As GPA's distribution system information is confidential, the proposed strategy is implemented on IEEE 34-bus and 123-bus test feeders to demonstrate the effectiveness of the proposed approach. The mathematical model is developed in Matlab and the results show the computational robustness and efficacy of the solution.

KEYWORDS

Distribution Automation (DA), Smart Grid, Switch Optimization, Optimal number and switch placement.

Sridhar.chouhan@leidos.com

I. INTRODUCTION

The problem of determining optimal number and placement switches has been studied by several authors with different approaches. Many works in literature formulated the problem as an optimization problem with various objective functions and computational algorithms. Authors in [1] proposed a genetic algorithm based approach to determine the best number of switches and their placement. A binary representation model, and reliability measure SAIDI calculated from the annual non-supplied energy were used in the approach. Authors in [2] also proposed a solution based on genetic algorithm to allocate switches, reclosers and fuses. The device allocation problem was modeled with non-linear integer programming models. Reliability index SAIFI was used as the objective function. A simulated annealing approach is proposed in [3] that considered the investment, maintenance and outage costs in a single global cost function to determine the optimal number and location of switches. A decomposition approach is presented in [4] and the solution is represented as a binary array of the possible location places for scandalizing switches. The problem complexity was reduced by using a polynomial-time partitioning algorithm to decompose the problem into a set of convex independent sub-problems to be solved independently.

Authors in [5] proposed an immune algorithm to solve the problem of optimal allocation of switches. The solution was to minimize the objective function which is sum of the customer interruption cost and the investment cost of installing switches. The immune algorithm based solution was used to design the DA system for a real distribution system in Taiwan Power Company. The work in [6] uses a reactive tabu search to find the optimal device allocation. The objective function was a sum of estimated interruption costs. Authors in [7] proposed the solution based on cost/worth approach and the best locations of switches are determined by Simulated Annealing algorithm. A trade off analysis between sectionalizing switch cost to the reliability worth was used in the solution. A particle swarm optimization approach was proposed in [8] to determine the optimum number and locations of two types of switches (sectionalizer and breakers) in radial distribution systems.

In this paper, an iterative algorithm based on the relative reduction in the normalized customer interruption costs to determine optimal switch number and location has been proposed [9]. The proposed approach is generalized and works for all kinds of switch types (such as load break switches, reclosers, fault breaking circuit breakers, etc.) with various levels of automation (manually operated, motor operated, remotely operated, etc.). Switch investments are isolated in the approach as these are dependent on switch type and manufacturer, and also vary from country to country. The proposed iterative algorithm does not rely on absolute customer interruption costs which are largely dependent on customer damage functions. Customer damage functions usually are derived based on various survey methods, and they vary greatly from one method of estimation to the other. This makes determination of optimal switch number and placement very subjective when the absolute values of customer interruption costs are used in the analysis. Also this may lead to unrealistic number of switches as the optimal solution. The proposed iterative algorithm isolates the impacts of such customer damage functions by employing an approach based on relative reduction in the normalized customer interruption costs.

II. MATHEMATICAL PROBLEM FORMULATION

The proposed iterative algorithm for the optimum switch number and placement problem makes use of customer interruption cost (CIC) [5]. CIC responds to the effects of system topology, interruption duration, load variations, and component random failures. It also recognizes various customer types and their nonlinear customer damage functions.

DA distribution feeder is divided into a set of Super Sections (SS). SS are formed by logically grouping a set of actual feeder line segments. Each SS will have load points and the equivalent load of SS is obtained by summing up individual loads in the SS. SS must be strategically selected in a way that the created zones of the feeder will have the ability to restore the power from adjacent feeders in the event of outages. The restoration of the power must not violate the system constraints such as thermal constraints (conductor or equipment loading limits) and voltage constraints (low and high voltage issues). DA feeders can be divided into SS with un-equal circuit lengths and loadings. Each SS is considered as a potential automated switch location in the analysis. A typical distribution feeder that is divided into SS is shown in Fig.1. CIC used in this study is expressed as:

$$CIC = \sum_{y=1}^{k} \mathrm{OC_y} = \sum_{y=1}^{k} \xi_y l_y \left(\sum_{z=1}^{k} \mathrm{C_{yz} P_z} \right) \tag{1}$$

$$C_{yz} = \left(Res_z * f_R(r_{yz}) + Com_z * f_C(r_{yz}) + Ind_z * f_I(r_{yz}) \right) \tag{2}$$

Where,

k : *Total number of Super Sections*
OC_y : *Interruption cost per year due to outages in SS-y*
ξ_y : *Outage rate (failure/mile-year) of SS-y*
l_y : *Circuit length in miles of SS-y*
C_{yz} : *Interruption cost ($/kW) of load at SS-z due to an outage at SS-y*
P_z : *Total load in kW of SS-z*
C_{yz} : *Integrated interruption costs of residential, commercial and industrial customers*
Res_z : *Load percentage of residential customers at SS-z*
Com_z : *Load percentage of commercial customers at SS-z*
Ind_z : *Load percentage of industrial customers at SS-z*
f_R : *Interruption cost function of residential customers*
f_C : *Interruption cost function of commercial customers*
f_I : *Interruption cost function of industrial customers*
r_{yz} : *Duration of service interruption of SS-z due to an outage at SS-y*

The integrated interruption cost framework given in (2) can be expanded to other types of customers as long as the customer damage functions are known. Customer interruption costs are heavily reliant on customer type and outage duration. For example, the interruption cost of residential customers is far less compared to industrial customers. The customers with high service priorities such as hospitals, police stations, fire stations, and tele communication data centers have high interruption costs as well.

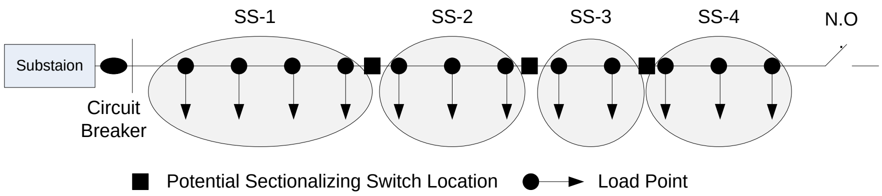

Figure 1: Typical Radial Distribution Feeder

III. ITERATIVE ALGORITHM FOR OPTIMAL SWITCH NUMBER AND PLACEMENT

The customer interruption cost (CIC) is calculated for all possible combinations of switch placements with different number of switches placed in the system. A generalized formula for total number of possible combinations the CIC is calculated for a feeder with "*n*" number of SS for placing "*r*" number of automated switches is given by,

$$\sum_{r=1}^{(n-1)} C_r^{(n-1)} = \sum_{r=1}^{(n-1)} \frac{(n-1)!}{r!\,(n-1-r)!} \tag{3}$$

However, the proposed approach significantly reduces the search space and the possible switch combinations for which CIC needs to be computed. The determination of optimal switch number and location is achieved by the iterative algorithm shown in Fig. 2.

IV. TEST SYSTEM AND RESULTS

The proposed iterative algorithm for optimal switch number and placement is tested on IEEE 34-bus test feeder, IEEE 123-bus test feeder, and on the real distribution system of GPA. GPA conducted a DA project through the Smart Grid Initiative program that will improve distribution system reliability and increase situational awareness. The project involved implementing the DA system on seventeen 13.8 kV distribution feeders. The design analysis using the proposed algorithm resulted in 24 load break switches and reclosers on the study feeders.

A. *Test System (IEEE 34-Bus System)*

The IEEE 34-bus test feeder is an actual feeder located in Arizona, with a nominal voltage of 24.9 kV. This is a lengthy feeder and assumed to have poor reliability which makes it a perfect candidate to implement the proposed solution. The data pertaining to feeder load (spot loads and distributed loads) and line segments (overhead and underground lines) are taken from [10]. The feeder has a total of 33 line segments with 6 spot loads and 19 distributed loads.

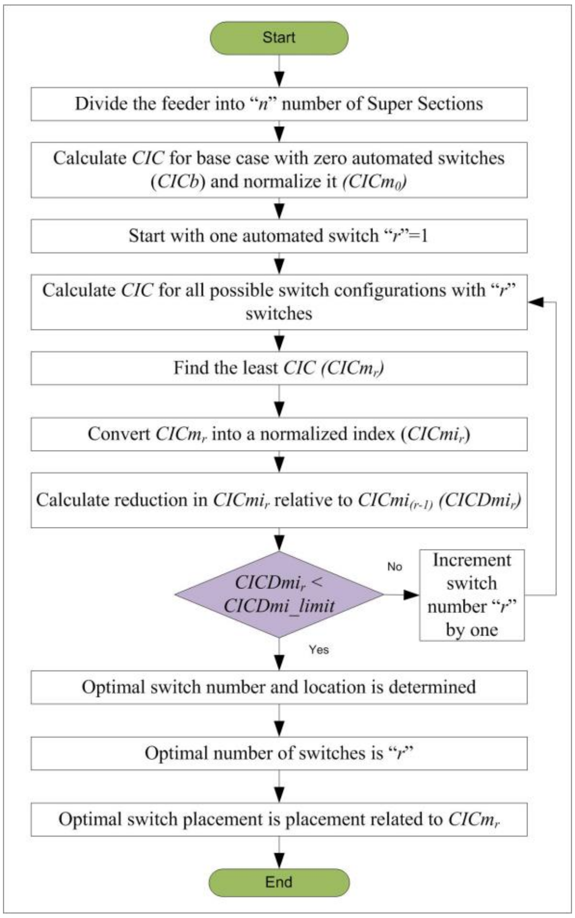

Figure 2: Iterative Algorithm for Optimal Switch Number and Placement

This feeder is strategically divided into seven SS as shown in Fig. 3. Circuit topography, customer distribution through the feeder, tie-points and switch locations were taken into account in the SS selection process. Each SS location is considered to be a potential location for sectionalizing switch. The information relevant to each SS is furnished in Table I. The information includes circuit length, load, and failure rate per annum per mile. The circuit length is different from the actual feeder length in the sense that circuit length is the actual conductor length of line segment. For example, a three phase line segment's circuit length would be three times the actual line segment's length. This helps to account the fault rate to each phase of the line segments within each SS. As the reliability data for this feeder is not available typical values shown in Table I are used in the analysis. Each SS is assumed to have a customer mix composed of 50% residential customers, 25% commercial, and 25% industrial customers. Average service duration of 240 minutes and automated switch operating duration of 1 minute are used in this study. The underlying assumption in the analysis is that each SS has back feed capability from an adjacent feeder to restore power to the interrupted customers in the event of outage. The customer damage functions for residential, commercial, and industrial customer classes shown in Fig. 4 [3] are used for this study.

TABLE I: IEEE 34-BUS AND 123-BUS TEST FEEDER SS DATA

	IEEE 34-bus system			IEEE 123-bus system		
Super Section ID	**Circuit Length (miles)**	**Load (kVA)**	**Failure Rate / year-mile**	**Circuit Length (miles)**	**Load (kVA)**	**Failure Rate / year-mile**
SS-1	21.86	80.08	0.06	1.17	335.41	0.59
SS-2	38.20	0.00	0.06	4.67	1406.16	0.59
SS-3	19.07	244.66	0.06	1.02	178.89	0.59
SS-4	37.25	61.37	0.06	1.23	449.38	0.59
SS-5	9.10	521.91	0.06	3.47	626.10	0.59
SS-6	6.61	712.50	0.06	0.31	438.21	0.59
SS-7	4.24	442.92	0.06	1.85	290.69	0.59
SS-8	N/A	N/A	N/A	1.06	268.33	0.59

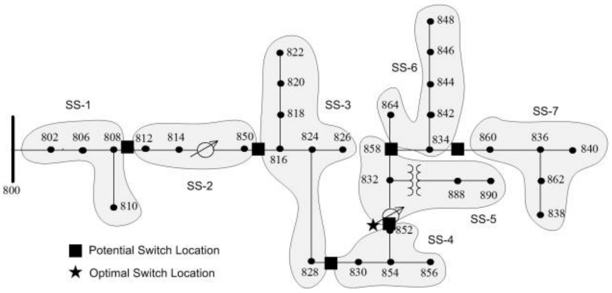

Figure 3: IEEE 34-Bus Test Feeder

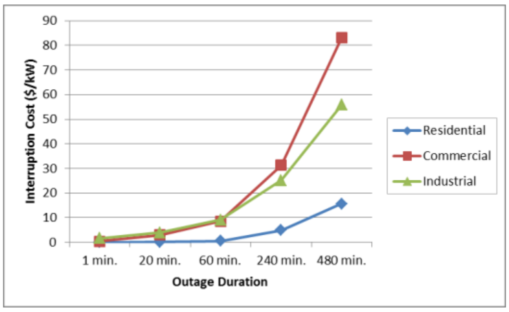

Figure 4: Customer Damage Functions

B. *Test System ((IEEE 123-Bus System)*

The IEEE 123-bus feeder is considered as a test system to be able to show the computational efficacy of the proposed solution on a more complicated network. The feeder operates at a nominal voltage of 4.16 kV and is characterized by overhead and underground lines, unbalanced loading with constant current, impedance, and power, four voltage regulators, and shunt capacitor banks. The data pertaining to feeder load and line segments are taken from [10]. This feeder is strategically divided into eight SS as shown in Fig. 5. The information relevant to each SS is furnished in Table I. Similar assumptions and data used for the prior test case are used for this test system.

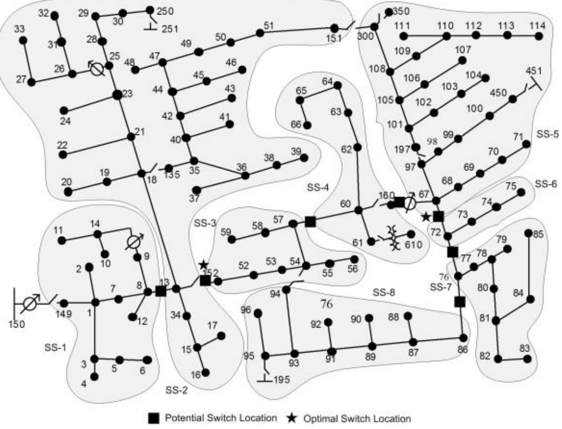

Figure 5: IEEE 123-Bus Test Feeder

C. *Results*

Fig. 6 and Table II furnish the optimal switch number and placement results for IEEE 34-bus and 123-bus test systems. Table-II lists least normalized customer interruption cost index $CICmi$ and relative reduction in normalized customer cost interruption index $CICDmi$ for switch numbers from “0” to “6”. Although all the indices shown in Table II are not necessarily required for the determination of optimal switch number and placement, these are shown to illustrate the working mechanism of the proposed algorithm. The iterative algorithm stops as soon as the $CICDmi$ index goes below the predefined threshold of “10”. The optimal number and placement solution for IEEE 34-bus system is “1” and “SS-4”. The optimal number and placement solution for IEEE 123-bus system is “2” and “SS-2, SS-5”. Increasing the number of switches beyond the optimal number found here would return minimal reduction in total customer interruption cost as shown in Fig. 6 and not worth exploring.

As per the solution provided by the proposed algorithm, installing one sectionalizing switch at SS-4 on IEEE 34-bus test feeder would reduce the total interruption cost by 69.9% compared to the base case with no switches. Similarly, installing two sectionalizing switches at SS-2 and SS-5 on IEEE 123-bus test feeder would reduce the total interruption cost by 63.2% compared to the base case. Increasing the number of sectionalizing switches beyond the optimal number would result in relative reduction of interruption costs less than 10%. The optimal placement of switches for IEEE 34-bus and IEEE-123 bus systems is marked on Fig. 3 and Fig. 5 respectively.

According to (3), there would be 63 and 127 possible combinations of switch placements on IEEE 34-bus and IEEE-123 bus systems respectively. The customer interruption costs have to be computed for all the possible combinations to arrive at a global optimal solution. However, the proposed approach limits the search space to 21 and 63 possible combinations for these test systems and arrives at an optimal solution that satisfies the defined criteria for minimum reduction in customer interruption costs. This greatly simplifies computational complexity of the problem and shows efficacy of the solution.

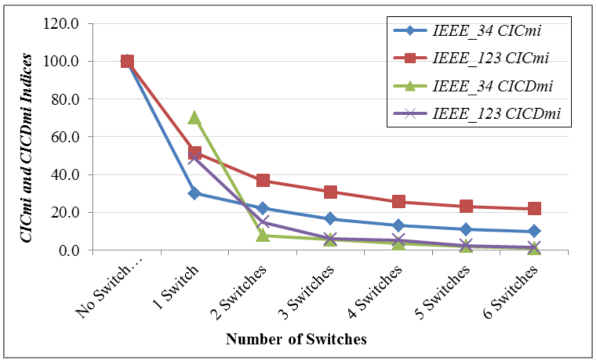

Figure 6: Calculated Indices for IEEE 34-Bus and IEEE-123 Bus Feeder

TABLE II: CALCULATED INDICES FOR IEEE 34-BUS AND IEEE-123 TEST FEEDER

# of Switch	**IEEE 34-Bus Feeder**			**IEEE 123-Bus Feeder**		
	CICmi	***CICDmi***	**Optimal Switch Location**	***CICmi***	***CICDmi***	**Optimal Switch Location**
0	100.0	N/A	N/A	100.0	N/A	N/A
1	**30.1**	**69.9**	**SS4***	51.6	48.4	SS3
2	22.2	7.9	SS2,SS4	**36.8**	**14.8**	**SS2,SS5***
3	16.6	5.6	SS2,SS4, SS5	30.9	5.9	SS2,SS4, SS5
4	13.0	3.5	SS2,SS3, SS4,SS5	25.6	5.3	SS1,SS2, SS4,SS5
5	11.0	2.0	SS2,SS3, SS4,SS5, SS6	23.3	2.4	SS1,SS2, SS4,SS5, SS6
6	9.9	1.1	SS1,SS2, SS3, SS4,SS5, SS6	21.9	1.3	SS1,SS2, SS4,SS5, SS6,SS7

* Optimal switch location determined by the proposed iterative algorithm.

V. CONCLUSIONS AND FUTURE WORKS

A key step in the DA project feasibility process is to determine the optimal number and placement of sectionalizing switches. A novel iterative algorithm is presented that is based on the relative reduction in the normalized customer interruption costs. The proposed approach isolates the impacts of varying switch investment and customer interruption data which is usually based on various survey studies. The proposed method is implemented on IEEE 34-bus, 123-bus test feeders, and GPA distribution system. The mathematical model is developed in Matlab and the results show the computational robustness and efficacy of the solution. The proposed technique significantly scales down the search space and simplifies problem complexity that requires minimal computational effort and time.

Although the proposed approach is demonstrated to find optimal number and location of automated sectionalizing switches, the method can easily be modified to accommodate other switching technologies such as reclosers and circuit breakers with various automation levels. The future work involves implementing the proposed technique to design the DA system for a real distribution system where certain operational considerations (such as back-feed capability without violating loading and voltage constraints) need to be incorporated in the model to arrive at the solution. The plan is to incorporate a distribution load flow solution in the process of finding the optimal number and placement of switches using the proposed approach.

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