Optimal Switch Insertion for Power Loss Reduction and Reliability Enhancement in the Nigeria Conventional Distribution Networks: A Case Study

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ABSTRACT

This paper seeks to analyze the potentials of optimal switch insertion and relocation of the existing ones in the Nigeria conventional distribution network for reliability enhancement and power loss minimization. Maximizing customers' satisfaction and enhancement of service reliability of the distribution network isa critical thing to utility and how to achieve it is also a major concern? Optimal switch insertion can enhance the network operation, minimize power losses in the lines, increase service restoration to blackout areas and improve the electric power supply to customers in the distribution network and increase the system reliability. The impact of optimal insertion of sectionalizing switches and optimal relocation of the existing ones for reliability enhancement and power loss reduction in real-time distribution network has been investigated.Additionally, the research examined the history of frequent power interruptions in the network and their cost implication on the system and customers alike, and as well as the benefits of eliminating frequent outages in the Nigeria distribution networks as a case study. Also, feeder ranking based on reliability indices, customer damage function (CDF), capital investment and their correlations were analyzed and established. Conclusively, the results depicted that the reliability of the network can be affected by the number of sectionalizing switches introduced by an optimal relocation of the existing ones and their locations as well as its capacity of power loss reduction in the network.

Keywords: Conventional distribution network, optimal switch insertion, capital investment, reliability indices,power loss reduction, ECOST

INTRODUCTION

Reliable power supply is key to nations' socioeconomic drive and development. In recent time, the frequent outages in the distribution networksof the Nigeria power systems became worrisome and this is due to scheduled and unscheduled outages that are rampant in the Nigeria distribution networks. According to Akpojedje et al. (2018) frequent power interruptions in the Nigeria electric power distribution networks have become a recurrent decimal and it is tagged as one of the biggest obstacles to be tackled in the distribution section of the Nigeria power systems. It is on record from customer interruptions data that the distribution system failures are responsible for 80% of the consumer outages in the power systems (Allen et al., 1991). Therefore, the need to operate electricity distribution networks in the Nigeria power systems with high reliability and efficiency while minimizing associated costs remains a challenge for utilities and the network planners (Alabdullah and Ebadi, 2017). Ensuring a reliable, economical and quality power supply to customers are the primary objectives of electric power supplier (utilities) (Akpojedje, 2021). According to Tippachan and Rerkpreedapang (2009) and Abiri-Jahromi et al. (2012) who opined that the main challenge is that increasing levels of reliability require greater capital and operational expenditure. Hence, optimization is to find a balance between reliability and cost. Also, according to Abiri-Jahromi et al. (2012) the major challenge facing decision makers in the distribution network is how to achieve the most possible return on the project(s) while minimizing the costs. Optimizing cost in engineering while maximizing the reliability of a system is a key to optimization in power engineering. Tools should have the capacity to perform cost/benefits analysis and the reliability assessment of the system. According to Gholizadeh et al. (2022) who asserted that the higher levels of reliability are associated with greater capital and operational costs. There areincreasing needs for reliable power supply by consumers which put pressure on utility engineers to explore all options in improving reliability of the distribution systems without appreciable commensurate cost increase. According to Hariri et al. (2020) who opined that increasing need for reliable and continuous power supply to electricity customers has led to the development of quantitative analysis of the distribution systems reliability worth and its application such as value-based reliability optimization in the past few years. Often time, optimal switch insertion or placement problem is conducted to maximize profit while considering switch deployment financial risks. Also, the optimal switch deployment tries to reduce customers' outages in the network thereby improving the reliability of the network. According to Jalilian et al. (2019) who opined that sectionalizing switches are the main components of any restoration scheme in fault situation in power distribution systems. Also, according to Abiri-Jahromi et al. (2012) who reported that in an automated distribution network, automatic and remote-controlled switches play a fundamental role such as reducing the time required to detect and locate faults, increasing the speed of isolating faulted equipment and provide faster load restoration above and below a faulted feeder zone. The optimal placement or insertions of switches have serious effect on the quality of services rendered to customers in the distribution network especially in terms of outage duration, reliability and availability of electricity supply. Assessing optimal insertion of switch is necessary to see its effects on the network. Therefore, this paper proposes a mixed-integer nonlinear programming (MINLP) to find the optimal insertions (placement) of switches in the distribution network by taking number of customers' outages, outages duration, device installation, capital investment, annual operation and maintenance cost into account for optimal performance of the systems.

MATERIALS AND METHODS

This section presents the materials and methods adopted in this research. The materials used are presented in section 2.1 and the methods adopted are described in section 2.2.

Materials

The materials used for this research include simulation software, remote controlled switches (RCS), optimization tool and input data.

Input Data

Historical data required for the research were collected from the injection substation under investigation such as the customers' outages in the network, outage duration, frequency of outages, number of customers and types in the various feeders of the network.

Methods

The analytical method was implemented using the mixed integer nonlinear programming (MINLP) model to find the optimum switch insertion in the presence of dynamic load operation mode and financial loss due to frequent interruption of electricity supply to customers.

Problem Formulation

The locations of the switches are represented by binary logical decision variable which is defined in equation 1:

$$Q_{S,f} = \begin{cases} 1 & \text{Switch present at location‘s’ of the feeder ‘f.’ Otherwise} \\ 0 & \end{cases} \quad 1$$

Objective Function

To ascertain the reliability of the distribution system under investigation, various customer oriented indices can be used such as SAIDI, SAIFI, CAIDI, ECOST, etc. In this study three customer oriented indices were deployed to determine the reliability of the electricity supply to consumers, this because it characterizes both customer interruption cost and the network reliability. The customer outage cost can be evaluated using ECOST (customer oriented reliability indices) which is one of the best index since it can account for the effect of the topology of the network, interruption duration, equipment failure probability, customer types and their damage function, equipment investment required to reach and maintain an adequate reliability level of the system. The objective function is as follows;

$$\text{Minimize } Obj_{ECOST} = C^{s} + C^{in} + C^{m} + C^{o} \quad 2$$

Optimal Insertion of Switch Modeling

The mixed integer nonlinear programming (MINLP) formulation for optimal switch insertion in the distribution network was based on analytical method. In contrast, the MINLP guarantee converges to global optimum compared to heuristic approaches. Mathematically, optimization problem is to choose optimal number of switches and their locationsin order tominimize the expected customer interruption thereby increasing the reliability and minimizing the total cost. Modeling the optimal switch insertion in this research,is based on the work of Abiri-Jahromi et al. (2012), the ECOST is taken into consideration as follows:

$$ECOST = \left[\sum_{t}^{T} \sum_{f}^{N_f} \sum_{i}^{N_{flf}} \sum_{j}^{N_{LPf}} \sum_{k}^{CT_f} \lambda(f,i,t) * AL(f,j,k) * (1+\varphi)^{t-1} * C^{D_{ij}}(f,,i,j,k) * (1+\theta)^{-t} \right] +$$
$$\left[\sum_{f=1}^{N_f} \sum_{s=1}^{N_S} (CIC_s + IC_s) * X(s,f) + \sum_{t=1}^{T} \sum_{f=1}^{N_f} \sum_{s=1}^{N_s} AMC_{s,t} * X(s,f) * (1+\theta)^{-t} \right] \quad 3$$

From equation 2, the first term is related to the interruption cost (IC), the load growth rate of the feeders (φ) and the annual interest rate (θ) has been taken into consideration. The second term of the equation contained the capital investment cost (CIC) where t = 1 and the annual maintenance cost (AMC). T, N_f , N_{fL_f} , N_{Lp_f} and CT_f are the life time of the switch (T), number of feeders in the network (N_f), number of fault location in the feeders (N_{fL_f}), number of load points in the feeder (N_{Lp_f}) and number of customer type in the feeder (CT_f). Also, x(s,f) is the binary decision variable which is equal to 1 if a switch is installed in the s^{th} location of the feeder f, in the distribution network and λ(f, i, t) is the failure rate of component I in feeder f at time , t. AL(f, j, k) is the average load of the k^{th} type customer located at the j^{th} load of the feeder f, and it’s subjected to the following constraints (Mohammed et al., 2017):

$$\sum_{f=1}^{N_f}\sum_{s=1}^{N_s}\left(CIC_s + IC_s\right) * X(s,f) \le \overline{CI} \quad 4$$

$$C^{D_{ij}}\left(i,j,k,f\right) \ge CDF^{D_{ij}^{sw}}\left(i,j,k,f\right) \quad 5$$

$$C^{D_{ij}}\left(i,j,k,f\right) \ge CDF^{D_{ij}^{RP}}\left(i,j,k,f\right) * \left(1 - \sum_{s-si}^{sj} X\left(s,f\right)\right) \quad 6$$

The $CDF^{D_{ij}^{sw}}\left(i,j,k,f\right)$ and $CDF^{D_{ij}^{RP}}$ are customer damage function value for outage duration equal to switching time and customer damage function value for the outage duration equal to the fault clearance time of a faulted component or device. Therefore, in terms of customer oriented index, the equations become:

$$D\left(f,i,j\right) \ge D^{sw}\left(f,i,j\right) \quad 7$$

$$D\left(f,i,j\right) \ge D^{RP}\left(f,i,j\right) \quad 8$$

$$\sum_{f=1}^{N_f}\sum_{i=1}^{N_{fl}}\sum_{j=1}^{N_{lpf}} \frac{\left[\lambda\left(f,i,t\right) * D\left(f,i,j\right)\right]}{NC} \le \overline{SAIDI\left(t\right)} \quad 9$$

$D\left(f,i,j\right)$is the outage duration, $D^{sw}\left(f,i,j\right)$ and $D^{RP}\left(f,i,j\right)$ are the switching time and repair time of each component respectively of the network.

Customers Damage Function Characteristic

Customers interruption in the network need to be modeled and different customers have different interruption cost in the network. Hence, the customer damage function (CDF) characteristic in the network need to be determined and define the behavior of the various customer type interruption cost. The different customer interruption cost characteristic was obtained from the numerical data gotten from the network under investigation. Utilizing the customers interruption cost characteristic in the network, the polynomial equations in the work of Mohammed et al. (2017) was adopted for the various types of customers in the network as follows:

Residential Customer

$$CDF_R(D) = -0.0000004xD^3 + 0.00008xD^2 + 0.0032xD \quad 10$$

Commercial Customer

$$CDF_C(D) = 0.0000005xD^3 - 0.0002xD^2 + 0.1545xD \quad 11$$

Industrial Customer

$$CDF_I(D) = 0.0000008xD^3 - 0.0005D^2 + 0.183D \quad 12$$

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Numerical Analysis of the Distribution Network

The proposed formulation was applied to real-time distribution network connected to one hundred and fifty nine (159) buses out of which one hundred and forty-two (142) buses were in service as at time of data measurement with four (4) feeders. The Ugbowo 2x15 MVA, 33/11 kV distribution network is situated in the Ugbowo metropolis. The required data are component failure rate, average load, number and type of customers on each feeder, etc. The capital investment and installation cost of switch is considered at $4700, the annual operation and maintenance cost of a switch is taken to be 2% which is $94. While the lifespan of a switch is assumed to be 15 years. Also, the forecasted load growth rate is taken to be 3%.

Brief Description of the Ugbowo Network and Analysis

The Ugbowo injection substation is located at the Ugbowo town in Ovia North Local Government Area of Benin City; Edo State, Nigeria with it geographical coordinates of $6^0$24’0’’ North, $5^0$36’0’’ East. The Ugbowo 2x15 MVA, 33/11 kV injection substation consist of four (4) feeder and ten (10) appropriate location of existing sectionalizing switches in the proposed locations of 15, 16, 19, 33, 42, 52, 64, 104, 105 and 131. At first scenario, the objective function with the existing sectionalizing switches was estimated. At second scenario, some of the existing sectionalizing switches were optimally relocated within the network and the objective performance of the network was estimated. By optimally relocating the existing switches, 22.54% improvement was achieved as shown in Table 1 and the total cost saved was improved.Figure 1 depicts a single line diagram of the network under investigation. The two 15 MVA, 33/11 kV transformers comprises of the first 15 MVA transformer which is called transformer T_1 comprises of FGGC and Uselu feeders while the second 15 MVA transformer is called transformer T_2 comprises of Eguaedaiken feeder and the Ugbowo feeder. A feeder is an outgoing or incoming conductor used to transport electric power to the desired destination and it can either be an overhead or underground conductor.

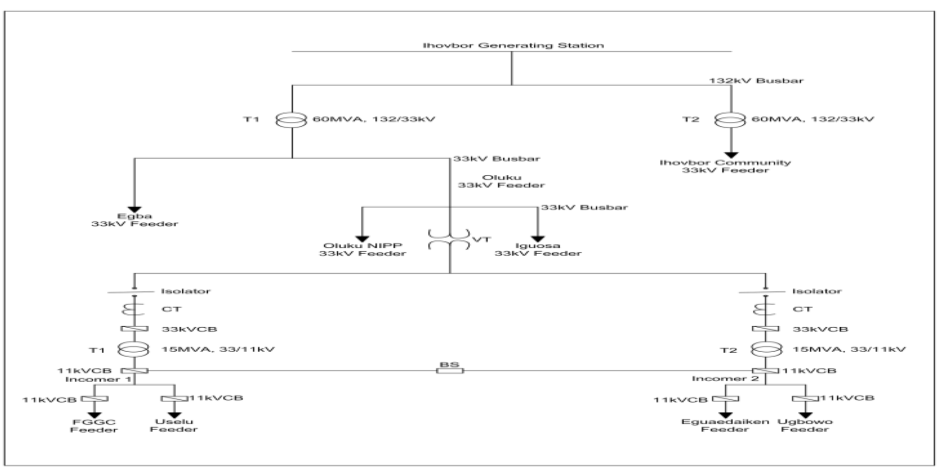

Figure 1: Single Line Diagram of the Ugbowo 2x15 MVA, 33/11 kV Distribution Network Feeders and 132/33 kVSupply from Ihovbor Generating Station (Akpojedje and Osho, 2022).

Table 1: Optimal Relocation of Existing Switches and Addition of Five New Ones to the Network

S/N	Scenarios	Number of Switch	Location of Switches	Power Loss (MW)	% of Power Loss Reduction	SAIFI (Hrs)	SAIDI (Inter/ Cust.)	CAIDI (Hrs)	Interruption Cost in Naira	Total Cost in Naira
1	Existing Switches	10^{old}	15, 16, 19, 33, 42, 52, 64, 104, 105, 131	3.606	Nil	1.29	7.25	5.62	411,510,000	412,310,000

2	Optimal Relocation of Existing Switches	10^{old}	15, 16, 33, 42, 52, 104, 105, 131, 142, 163	1.527	42.34%	1.01	6.56	6.50	289,150,000	291,230,000
3	Investing on New Five Additional Switches	10^{old} + 5^{new}	1, 16, 33, 41, 42, 52, 83, 104, 105, 111, 129, 131, 142, 162, 163	0.867	56.78%	0.34	2.71	7.97	163,010,000	164,200,000

Investing on Five (5) Additional Sectionalizing Switches in the Network

Enhancing the reliability of the network, the existing sectionalizing switches were introduced and optimally placed in the network. The existing switches relocated and the introduction of new once and their location is shown in Table 1. The capital investment for purchasing five additional new switches in the network is equal to $23,500. The optimal insertion of new switches and their optimal locations in the network and the impact of optimally relocating the existing ones in the network on customer oriented indices have been established in Table 1. The reliability improvement in relation to customer or load point behavior, interruption cost, total cost and the percentage of power loss reduction in the network is depicted in Table 1 as well.

Sensitivity Analysis of the Network

Assessing the effects of optimally relocating the existing and introduction of new sectionalizing switches in the network for reliability enhancement in relation to customers' satisfaction (interruption cost and number of outages per customer), sensitivity analyses are conducted on the system as follows:

Enhancement of Reliability Indices versus Capital Investment

The optimal insertion of five new sectionalizing switches and optimally relocation of the existing ones has greatly impacted the network performance. Assessing the effect of capital investment on reliability indices such as SAIDI, SAIFI and CAIDI, the sensitivity analyses were conducted on the network. Increasing the capital investment to proportional level on sectionalizing switches in the network increases the reliability indices value on the network. Figure 2 show the relationship between capital investment and reliability indices on the network.

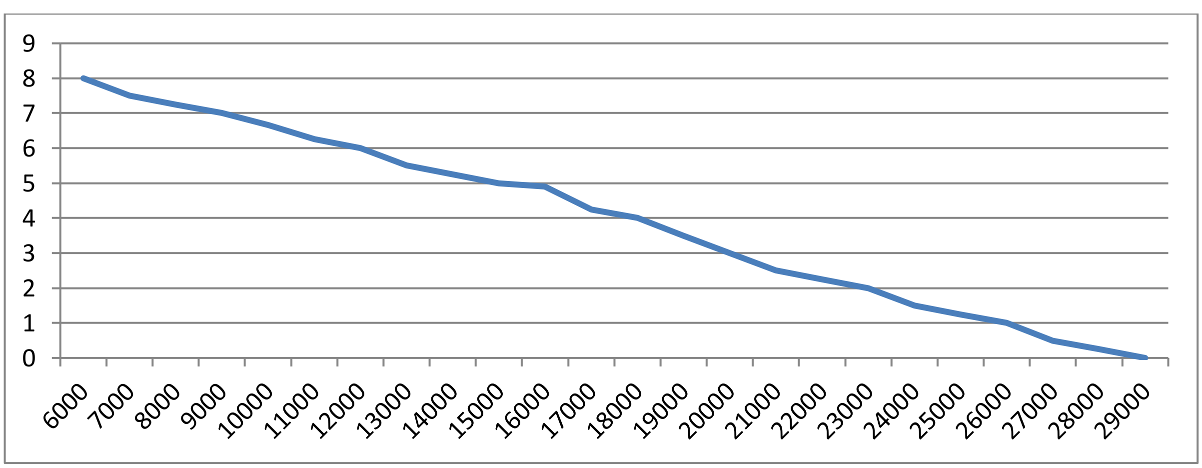

Figure 2: Enhancement of Reliability Indices versus Capital Investment

Optimal Switch Insertion versus Customer Damage Function

The variation of the customer damage function (CDF) in relation to optimal switch insertion on the network was evaluated and analyzed. Figure 3 shows the relationship of optimal number of sectionalizing switches and the customer damage function. In Figure 3, as the number of sectionalizing switches increase, so the customer damage function increases but in a nonlinear form and this is indicating that a higher level of reliability is required in the network. Also, the nonlinearity of Figure 3 curve depicts the complexity of the network and the nonlinear connections between the customer damage function, duration of outage, topology structure of the network, frequency of outage, etc.

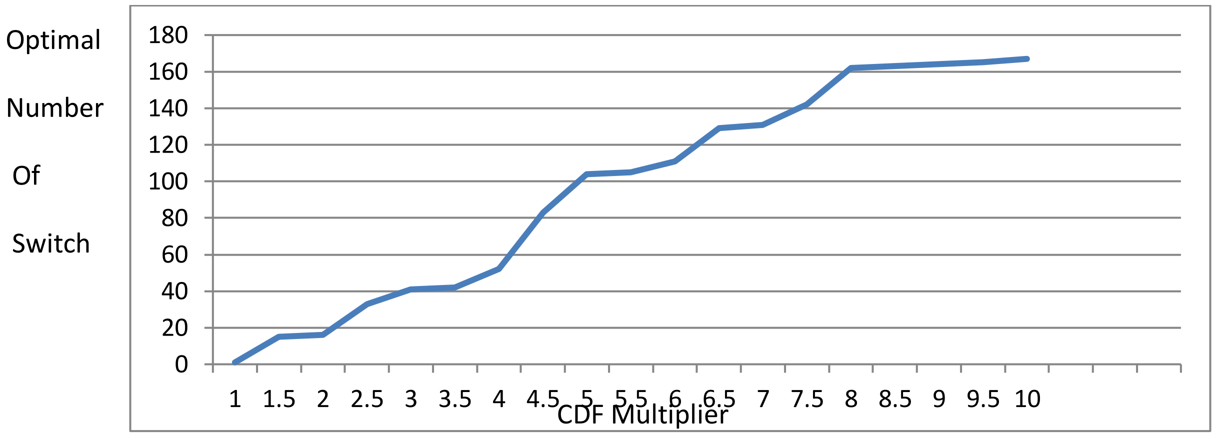

Figure 3: Optimal number of sectionalizing switches installed versus the customer damage function (CDF) variation

Feeder Ranking Base on Reliability Indices

The ranking of feeders in the network is based on the reliability analysis conducted in the system. The supply availability in the feeders' dependence on some criteria which determine the importance and the criticality of the feeder and its impact on the SAIDI index. These criteria are number of momentary and sustained outages, failure rate, number of customers in the feeder, criticality of the feeder load, required time for repair of the feeder, length of the feeder, etc. From Table 2, it is observed that the FGGC feeder has the highest availability followed Uselu feeder, Equadaiken feeder and Ugbowo feeder have the lowest availability in the network with highest load and the longest feeder length. These factors greatly affect the reliability of the feeder causing fluctuation of electricity supply in the feeder with high line losses.

Table 2: Annual Reliability Indices of the Network Feeders

Feeder	Annual Failure Rate (λ)	SAIDI	SAIFI	CAIDI
FGGC	0.1996	8.07	1.48	5.49
Uselu	0.2236	2.24	0.37	6.05
Equadaiken	0.2862	1.96	0.35	5.60
Ugbowo	0.3004	1.81	0.302	6.03

CONCLUSION

This paper investigated the effect of optimal insertion of sectionalizing switches and its enhancement on reliability indices using conventional distribution network in the Nigeria grid as a case study. The existing sectionalizing switches were optimally relocated within the network and five additional new sectionalizing were introduced in the network to determine its impact on the network reliability. The complex problem of the switches was formulated as a mixed integer nonlinear programming and it was solved with one of the commercial large scale solvers. The numerical and sensitivity analyses carried out have revealed the enhancement capability and efficient performance of the method in real-time distribution network. The results indicated that the reliability of the distribution network can be affected by the number of sectionalizing switches and their location in the network.

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