Performance Assessment for Normally Closed-loop Type Distribution Power Systems

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Abstract: The goal of this paper is to propose a performance assessment for normally closed-loop type distribution power systems. Pilot relaying systems have been successfully applied to the protection scheme for normally closed-loop distribution systems in the Taiwan Power Company (Taipower). This paper demonstrates that the proposed protection scheme is extremely well designed, such that both the number and the duration of interruptions caused by the faults can be minimized. The most significant advantage of this system is that the service is not interrupted when a fault occurs on the primary feeder. Finally, the reliability analyses of the primary distribution systems obtained using a generalized analytical approach are also considered.

Key-Words: Closed-loop, Distribution systems, Protection schemes, Pilot relaying, Reliability

1 Introduction

There are many distribution system configurations in the world, but the open-loop or radial type distribution system is the most popular. The common trait shared by both the open-loop and radial type networks is the power utility that provides electricity to customers via one source at the same time. In addition, the protection scheme always relies on the feeder overcurrent relay with inverse-time characteristics. Therefore, there is a service interruption when a fault occurs in the primary feeder system, and the duration of this interruption will be dominated by the protection scheme and alternative supply strategy.

Due to the rapid growth of high-technology industrial parks and the emergence of intelligent buildings, even temporary interruptions in the power supply can have significant costs. Therefore, the development of a reliable and high quality power supply is increasingly important. The open-loop or radial type distribution system, with the aid of distribution automation issues (such as supervisory control and data acquisition or SCADA), can reduce the duration of interruptions from a couple of hours to just a few minutes or less. However, the method of reducing the number of interruptions in the open-loop or radial type distribution system has been limited nowadays. Previously, although various experts have devoted themselves to related fields which are only subject to the optimal location of sectionalizers or the optimal policy of automatic restoration, the problem of the number of interruptions still has not been solved effectively [1-5].

In general, a normally closed-loop distribution system is designed so that no customers connected to the loop will be out of service when a fault occurs in the primary feeder system. To achieve this goal, the protection scheme and related facilities should also be upgraded significantly [6-7]. The faulty zone in the closed-loop network can be rapidly isolated within a short time, about six cycles, when the pilot relaying system is adopted. Up to now, it is not only Taipower that has adopted the normally closed-loop arrangement to serve its customers, but many other utilities in the world such as Florida Power Company, Hong Kong Electric Company, and Singapore Power Company, have done so as well [8-9].

Meanwhile, the reliability evaluation of electric power distribution systems has traditionally been an important part in the planning and operations of an electric power system. The reliability indices normally evaluated for distribution systems are the basic load point indices and the system performance indices. The comparison of distribution system reliability indices between closed-loop and open-loop arrangement is presented in this paper.

2 Normally Closed-Loop Distribution Systems

A normally closed-loop distribution system can be formed by tying the ends of two radial feeders together.

2.1 System configurations

There are three possible architectures, including up to four configurations, in forming a normally closed-loop distribution system, as shown in Figure 1. Figure 1(a) shows the two feeders fed from the same transformer and tied together to form a closed-loop type system. Figure 1(b) illustrates the two feeders fed from distinct transformers located in a substation, where the operation of a tie-circuit-breaker will result in two configurations. Figure 1(c) displays the two feeders fed from distinct transformers located in different substations. Owing to the possible transmission effects, the types of distribution systems displayed in Figure 1(b) and Figure 1(c) are not recommended [10-11].

For simplicity, a sample closed-loop distribution system with N (N=6) distribution nodes is proposed, as shown in Figure 2. Each node includes four-ways circuit breakers and associated intelligent electronic devices (IEDs). Generally, all of the protective devices of the switchgear are compacted in a feeder terminal unit (FTU), which consists of Feeder_IEDs with protection communication channels and Lateral_IEDs without protection communication channels. Meanwhile, two different types of switchgears may exist in a node, namely, the general distribution nodes with two feeder-ways and two lateral-ways and the transferring nodes with three feeder-ways and one lateral-way.

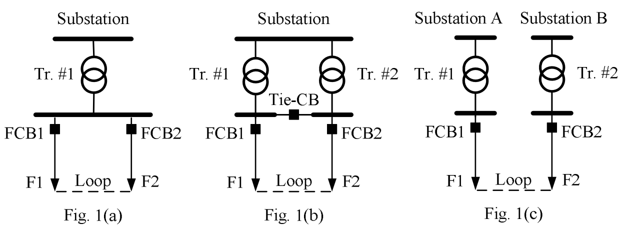

Fig.1 Three possible architectures for normally closed-loop distribution systems

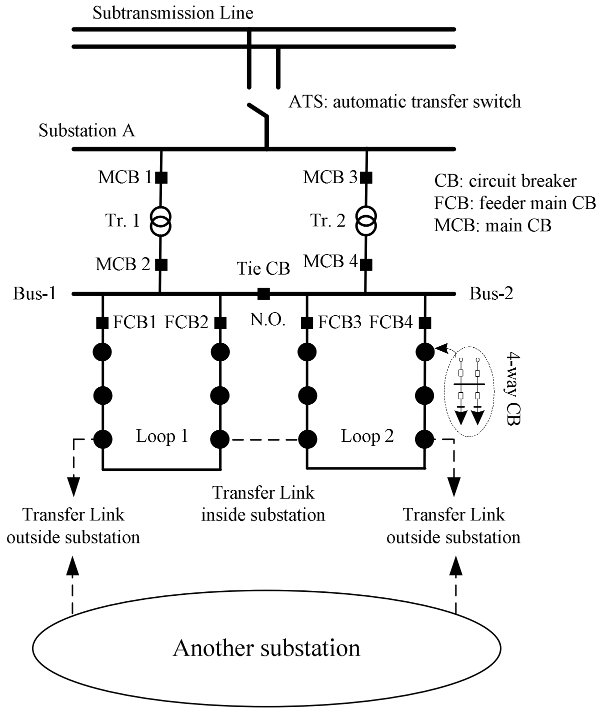

Fig. 2 Configuration of a sample closed-loop distribution system

2.2 Schemes of protection

Protection schemes for a normally closed-loop distribution system are primarily designed to prevent power interruptions, particularly those caused by an accident in the primary feeder. Therefore, power supply service will continue without a temporary interruption when a fault occurs along the feeder. The powerful ability of new generation IED allows the schemes of the pilot relaying system to fulfill the protection requirements, including both main protections and backup protections.

2.2.1 Pilot relaying systems

Pilot relaying is characterized by cooperating with a communication channel to identify the service conditions. Pilot relaying requires a reliable communication channel. The traditional type carrier relay starts or blocks the carrier depending on the protective schemes and carries out the protection function through various extra transmission mediums, such as power lines, microwaves, audios, and fiber-optics. However, such a sophisticated protection scheme can easily be implemented by an IED. It could be designed with the dedicated fiber-optic channel and the powerful programmable logic controller (PLC) function, which follows the IEEE Std. 61131-3, and can be described by an Instruction List, a Structured Text, a Sequential Function Chart, a Function Block Diagram, a Ladder Diagram, etc.

Each node includes four-ways circuit breakers and each channel can send and receive some logic bits (i.e., eight bits) or variables simultaneously. Thus, permission trip (PT), block trip (BP), and direct transfer trip (DTT) can be transmitted and received over the same channel, as shown in Figure 3. Meanwhile, the service condition of the fiber-optic channel is constantly monitored.

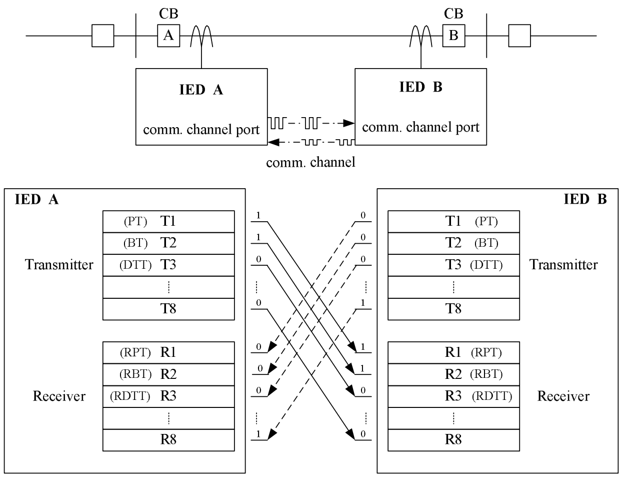

Fig. 3 Configuration of dedicated protection communication channel

The directional comparison is one of the protection schemes of pilot relaying systems. The directional overcurrent unit is used to identify the current flow direction. An internal fault exists if the directional units at both terminals of the protected line agree, such as a Permissive Overreaching Transfer Trip (POTT) and a Directional Comparison Blocking (DCB). Both directional units and distance units are available in the directional comparison relaying, but the latter is unsuitable for the normally closed-loop distribution system owing to the difficulty of distinguishing the different zone areas. Furthermore, both the instantaneous phase and ground directional overcurrent units are used to identify faults on the protected circuit.

2.2.2 Primary feeder system protection

There are three main protection zones in this protection scheme, namely, feeder protection, switchgear bus protection, and lateral protection. Those protection schemes can be described simply as follows:

. Feeder protection -- the combinational scheme of POTT and DCB.

. Switchgear bus protection -- the combination of output contacts of directional overcurrent units.

. Lateral protection -- the directional overcurrent relay (DOC).

. Backup protection -- breaker failure protection (BFP) or DTT or DOC.

The integral hierarchical protection scheme of the primary feeder system is shown in Figure 4 and the test results are summarized in Table 1 [10].

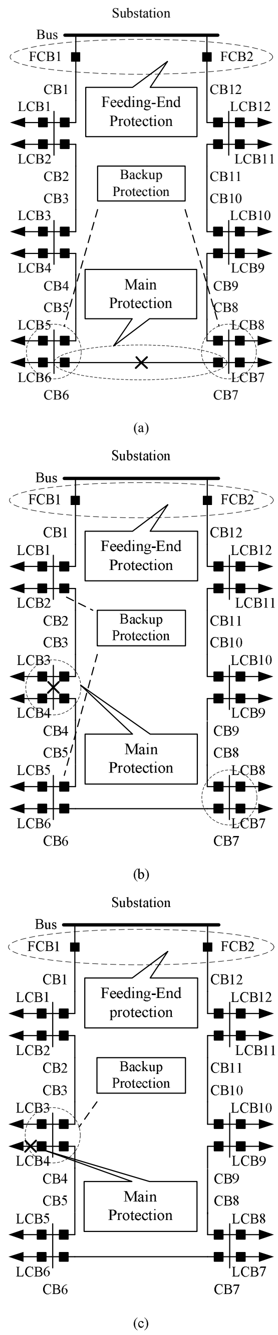

Fig. 4 The hierarchical protection schemes of the primary feeder system subjected to (a) feeder fault (b) bus fault (c) lateral fault

Table 1
Tripping Time (TT: Cycles) for Various Fault Conditions without Channel Failure

Locations of Fault		Main Protection / TT	Backup Protection / TT	Feeding_End Protection / TT
Feeder	Ring	POTT / 2	BFP / 9	DOC / 30
	Radial	Echo-Keying POTT / 4	BFP / 11	DOC / 30
Bus		Bus Protection / 3	DTT / 3.5	DOC / 30
Lateral		DOC / 3	BFP / 10	DOC / 30

3 Reliability Assessment of Electric Power Distribution Systems

The basic function of a modern electric power system is to provide electric power to its customers at the lowest possible cost and at acceptable levels of reliability. In general, the reliability adequacy assessment of the power system can be categorized in terms of three hierarchical levels (HL), as shown in Figure 5 [11]. Because the overall problem of HL3 evaluation can be very complex, the distribution functional zone is usually analyzed as a separate entity. However, HL3 indices can be evaluated by using the HL2 load-point indices as the input values of the distribution functional zone being analyzed.

Subtransmission circuits, distribution substation, primary feeders, distribution transformers, secondary circuits, and consumers' connection form different parts of what can generally be called a distribution system. The factors that mostly affect the reliability in a distribution system are the previously mentioned elements, the system protection scheme, the presence of automation, and system modification by means of devices such as fuses, sectionalizer, switches, and breakers. Meanwhile, the techniques of evaluating reliability indices for a radial distribution system are generally based on a failure-mode analysis including considerations of all realistic failure, restoration processes, and network reduction [12].

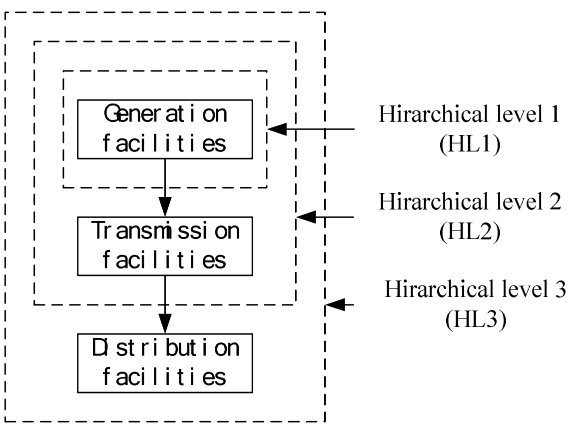

Fig.5 Hierarchical levels

3.1 Reliability indices calculation

The basic distribution system reliability indices are the three load point indices of the average failure rate λ, the average outage duration γ, and the annual outage duration U. These three basic indices are very important individual load point indices. A generalized analytical approach is used to evaluate the three load point indices [13]. The parameters are the average failure rate λ_j, the average repair time γ_j, and the average switching time s_j for a failed element j. Based on the failure-mode and effect analysis, the relative average failure rate λ_{ij} and average outage duration γ_{ij} of the load point i due to the failed element j are described as follows:

$$\lambda_{ij} = \lambda_j \prod_{k=1}^{N_{pr}} (1 - p_k) \quad (1)$$

$$\gamma_{ij} = t_a s_j + (1 - t_a)\gamma_j \quad (2)$$

where N_{pr} is the total effective number of breaker and fuses between the load point i and the failed element j. Meanwhile, p_k is the probability that breaker (or fuse) k operates successfully. The parameter t_a is the probability of being able to transfer load for a load point that can be isolated from the failed element. Therefore, the value of t_a is one for load points that can be isolated by disconnect switches (or breakers) from the failed element j. Finally, the formulas of the three load point indices are represented in Equations (3) to (5):

$$\lambda_i = \sum_{j=1}^{N_e} \lambda_{ij} \quad (3)$$

$$U_i = \sum_{j=1}^{N_e} \lambda_{ij}\gamma_{ij} \quad (4)$$

$$\gamma_i = \frac{U_i}{\lambda_i} \tag{5}$$

where N_e is the total number of elements in the distribution system.

3.2 System performance indices

Next, overall distribution system performance indices can be calculated from the three basic load point indices together with the number (N_i) of customers at load point i. The definitions and formulas for some of the more popular system performance indices are as follows:

. SAIFI-- System Average Interruption Frequency Index (interruption/system customer/yr)

$$SAIFI = \frac{\sum_{i\in\Omega} \lambda_i N_i}{\sum_{i\in\Omega} N_i} \tag{6}$$

where Ω is the set of load points in the system.

. SAIDI-- System Average Interruption Duration Index (hr/system customer/yr)

$$SAIDI = \frac{\sum_{i\in\Omega} U_i N_i}{\sum_{i\in\Omega} N_i} \tag{7}$$

. CAIDI-- Customer Average Interruption Duration Index (hr/system customer)

$$CAIDI = \frac{\sum_{i\in\Omega} U_i N_i}{\sum_{i\in\Omega} \lambda_i N_i} = \frac{SAIDI}{SAIFI} \tag{8}$$

. ASAI-- Average Service availability Index

$$ASAI = \frac{\sum_{i\in\Omega} 8760 N_i - \sum_{i\in\Omega} U_i N_i}{\sum_{i\in\Omega} 8760 N_i} \tag{9}$$

4 Numerical Examples

Figure 6 shows three simple configurations in a primary feeder system. Due to the assumption of perfect breakers, the major part of failed components is subject to a line component. The component data are given in Table 2. Assume that there are 400, 300, and 100 customers at load points A(D), B(E), and C(F) respectively, giving a total of 800 customers in a system. The substation supply bus and the alternate supply shown in Figure 6 are assumed to be available forever.

Table 2
Component reliability data for the numerical examples

Parameter / Component	λ_j/mile	γ_j	s_j
Feeder	0.1	3.0	-
Lateral	0.25	1.0	-
Manual switch	-	-	1
Automatic switch	-	-	0.1

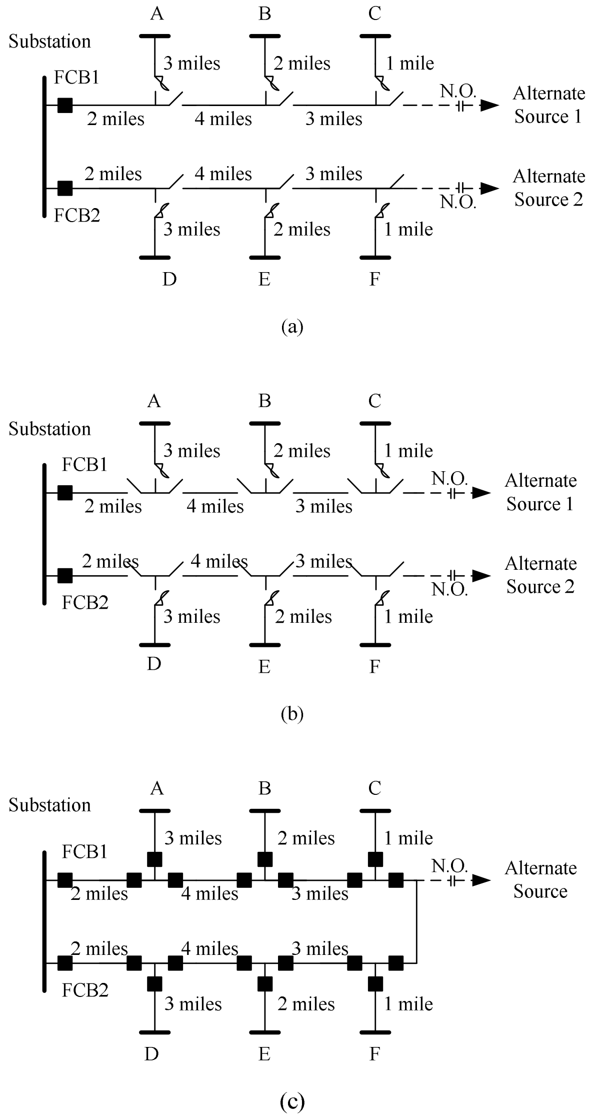

Fig.6 Three simple configurations in a primary feeder system (a) a radial type (Case#1) (b) a normal-open automatic distribution system (Case#2) (c) a normally-closed loop distribution system (Case#3).

In Case #1, the disconnect switch (DS) and the normal open switch are manual switches in a radial type. This procedure for Case #1 is illustrated in Table 3 and the results are summarized in Table 4.

In Case #2, the DS and the normal open switch are automatic switches in a normal-open automatic distribution system. This procedure for Case #2 is illustrated in Table 5 and the results are summarized in Table 6.

In Case #3, the DS are replaced by breakers in a normally closed-loop distribution system. This procedure for Case #3 is illustrated in Table 7 and the results are summarized in Table 8.

Table 3 Calculations for Case#1

Component	Load point A			Load point B			Load point C		
	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)
Feeder									
2 miles	0.2	3.0	0.6	0.2	1.0	0.2	0.2	1.0	0.2
4 miles	0.4	1.0	0.4	0.4	3.0	1.2	0.4	1.0	0.4
3 miles	0.3	1.0	0.3	0.3	1.0	0.3	0.3	3.0	0.9
Lateral									
3 miles	0.75	1.0	0.75	-	-	-	-	-	-
2 miles	-	-	-	0.5	1.0	0.5	-	-	-
1 mile	-	-	-	-	-	-	0.25	1.0	0.25
	1.65	1.24	2.05	1.4	1.57	2.2	1.15	1.52	1.75

Table 4 Calculated Indices for Case#1

Index	A (D)	B (E)	C (F)
λ (f/yr)	1.65	1.4	1.15
γ (hr/f)	1.24	1.57	1.52
U (hr/yr)	2.05	2.2	1.75
System Performance Indices SAIFI=1.4938 (interruptions/system customer/yr) SAIDI=2.0688 (hr/system customer/yr) CAIDI=1.3849 (hr/customer interrupted) ASAI=0.999764			

Table 5 Calculations for Case#2

Component	Load point A			Load point B			Load point C		
	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)
Feeder									
2 miles	0.2	0.1	0.02	0.2	0.1	0.02	0.2	0.1	0.02
4 miles	0.4	0.1	0.04	0.4	0.1	0.04	0.4	0.1	0.04
3 miles	0.3	0.1	0.03	0.3	0.1	0.03	0.3	0.1	0.03
Lateral									
3 miles	0.75	1.0	0.75	-	-	-	-	-	-
2 miles	-	-	-	0.5	1.0	0.5	-	-	-
1 mile	-	-	-	-	-	-	0.25	1.0	0.25
	1.65	0.51	0.84	1.4	0.42	0.59	1.15	0.3	0.34

Table 6 Calculated Indices for Case#2

Index	A (D)	B (E)	C (F)
λ (f/yr)	1.65	1.4	1.15
γ (hr/f)	0.51	0.42	0.3
U (hr/yr)	0.84	0.59	0.34

System Performance Indices
SAIFI=1.4938 (interruptions/system customer/yr)
SAIDI=0.6838 (hr/system customer/yr)
CAIDI=0.4576 (hr/customer interrupted)
ASAI=0.999922

Table 7 Calculations for Case#3

Component	Load point A			Load point B			Load point C		
	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)	λ (f/yr)	γ (hr/f)	U=λγ (hr/yr)
Feeder									
2 miles	-	-	-	-	-	-	-	-	-
4 miles	-	-	-	-	-	-	-	-	-
3 miles	-	-	-	-	-	-	-	-	-
Lateral									
3 miles	0.75	1.0	0.75	-	-	-	-	-	-
2 miles	-	-	-	0.5	1.0	0.5	-	-	-
1 mile	-	-	-	-	-	-	0.25	1.0	0.25
	0.75	1.0	0.75	0.5	1.0	0.5	0.25	1.0	0.25

Table 8 Calculated Indices for Case#3

Index	A (D)	B (E)	C (F)
λ (f/yr)	0.75	0.5	0.25
γ (hr/f)	1.0	1.0	1.0
U (hr/yr)	0.75	0.5	0.25

System Performance Indices
SAIFI=0.5938 (interruptions/system customer/yr)
SAIDI=0.5938 (hr/system customer/yr)
CAIDI=1 (hr/customer interrupted)
ASAI=0.999932

The comparisons of system performance indices between these cases are presented in Figure 7. In general, the index of SAIFI is similar in a system where the supply is only a single source at the same time, such as in Case #1 or Case #2. However, the index of SAIDI is dramatically reduced by the operations of the automation of transfer switches and disconnect switch in the two configurations. Meanwhile, both the indices of SAIFI and SAIDI in Case #3 are significantly influenced by the system configuration and the protection scheme.

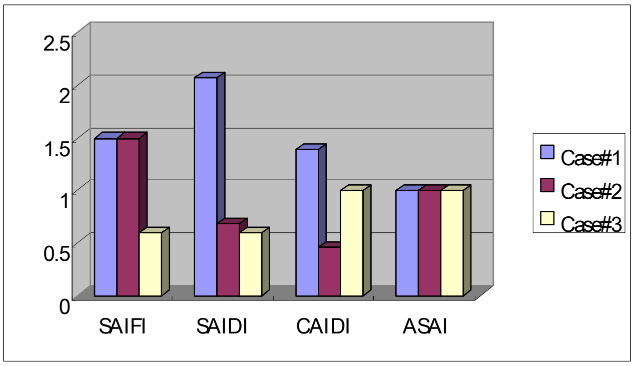

Fig.7 The comparisons of system performance indices between three cases.

5 Conclusion

This paper addresses the study of a distribution system management that aims to achieve a higher level of reliability. The pilot relaying protection scheme has played a significant role, especially in the normally closed-loop distribution systems. Thus, non-interrupted service can still be provided despite the occurrence of a fault on the primary feeder. The system performance indices have been significantly improved in Case #3, especially the index of SAIFI.

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