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ORIGINAL ARTICLE

The Optimal Impact of Feeder Impedance on the Status of Disconnection of Photovoltaic System under Single Short-circuit Fault in Asymmetric Low Voltage Distribution Network

Ali Ghanei ardakan[a*], Alireza Sedighi Anarki[b], Davoud Abootorabi Zarchi[c], Faride behdad[d]

[a] Ph.D. Candidate, Department of Electrical Engineering, Yazd University, Yazd, Iran.
[b] Associate Professor, Department of Electrical Engineering, Yazd University, Yazd, Iran.
[c] Associate Professor, Department of Electrical Engineering, Yazd University, Yazd, Iran.
[d] Yazd Electrical distribution company, Yazd, Iran.

[*]Corresponding Author E-mail Address: agha73@yahoo.com
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Abstract

This paper presents an analysis of the feeder voltage profile and the status of the disconnection of photovoltaic systems after a single-phase short circuit fault in a 400 V low voltage feeder. The paper aims to evaluate and discuss the feeder impedance on the status of the disconnection of photovoltaic systems in a real asymmetric distribution network with 100% penetration level. The analysis was intended to figure out the conditions under which systems in the feeder may fail to disconnect after a single-phase short circuit fault or keep feeding the network. Simulations were carried out in the DIgSILENT software environment and the results were reported and analyzed. The results indicate that the change in the absolute value of the feeder impedance does not affect the system disconnection. Still, the change in the resistance ratio to the reactance of the feeder impedance affects the system disconnection status in some phases.

Keywords: Asymmetric Distribution Network, Feeder impedance, photovoltaic systems, single-phase short circuit, voltage profile.

1. Introduction

Nowadays, the use of photovoltaic systems and their connection to local distribution networks as distributed production systems has become very common. Among the reasons for using photovoltaic systems as distributed production, for producers and consumers, we can mention the reduction of line losses, improvement of voltage profile, reduction of emission of polluting gases, improvement of network security and reliability (Atwa et al., 2011). Along with the advantages of connecting photovoltaic systems to the grid, these sources may also have destructive effects on power quality, protection, and control of distribution systems (Zhengrong et al., 2011). Today, the connection of photovoltaic systems to the distribution network has increased in many countries of the world.

With the increase of systems connected to the network, their dynamic behavior in the state of voltage drop has a great impact on the reliability and security of the network. References (Shahnia et al., 2011), (Shahnia et al., 2014) have investigated technical problems such as voltage increase and voltage imbalance due to the high penetration of photovoltaic systems in weak pressure distribution networks; they have also provided solutions to reduce problems. On the other hand, reference (Tonkoski et al., 2012) has investigated the effect of feeder impedance and other parameters on voltage increase in a distribution network.

Hadi Hosseinian and his colleagues have researched single-phase and three-phase short-circuit faults in the distribution system, and the effect of various parameters such as fault location, fault impedance, network grounding type, and the production capacity of photovoltaic systems on voltage changes. As a result, they have determined the time and

sequence of disconnection of the systems when the fault occurs and have pointed out that the current protection system does not guarantee the disconnection of the systems (Yengejeh et al., 2015, 2016).

In (de Almeida et al., 2024), the effects of high penetration of small-scale single-phase grid-connected systems on the protection of distribution systems were studied. The results obtained show that the effects of high penetration of single-phase photovoltaic systems on the protection systems for single-phase short-circuit faults commonly seen in distribution networks can be easily managed. However, the increasing penetration of distributed generation in distribution systems for high impedance faults is one of the most important challenges for distribution companies.

In (Bracale et al., 2025), a mixed Taguchi-based method is proposed for probabilistic short-circuit analysis of unbalanced networks. This method uses mixed orthogonal arrays. It returns the probabilistic characteristics of the fault current and voltage with reduced computational load and acceptable accuracy compared to the traditional Monte Carlo method. For evaluation, the proposed method is compared with traditional Monte Carlo methods, a non-mixed Taguchi-based method, and point estimation method in an unbalanced distribution network.

However, no research has been done on the effect of feeder impedance on the voltage value and the state of interruption of photovoltaic systems after a short circuit fault. Therefore, in this article, we investigated the effect of feeder impedance on the state of disconnection of systems when the penetration coefficient of the systems (the ratio of the power produced by the systems to the total power of the network) is 100%, and occurs a single-phase short circuit (the most common type of fault in the distribution network), in the extended model of asymmetric distribution network.

In the second part, the scientific bases used are presented. In the third part, the studied network is introduced, and the simulation and analysis of its results are examined in the fourth part, and The conclusion is given at the end of this article and in the fifth part.

2. Scientific Basics

For short circuit calculations, it is first necessary to derive the general network model used in short circuit calculations. Consider a 20 kV medium voltage feeder feeding a 20/0.4 kV three-phase distribution transformer as shown in Fig. 1 This transformer feeds small residential and commercial loads through a 3-phase, 4-wire overhead line. Due to the differences in the amount of electricity subscribers and the distribution of photovoltaic systems in all three phases and at different nodes, distribution networks generally have an asymmetric configuration, which is valid for calculating all types of faults.

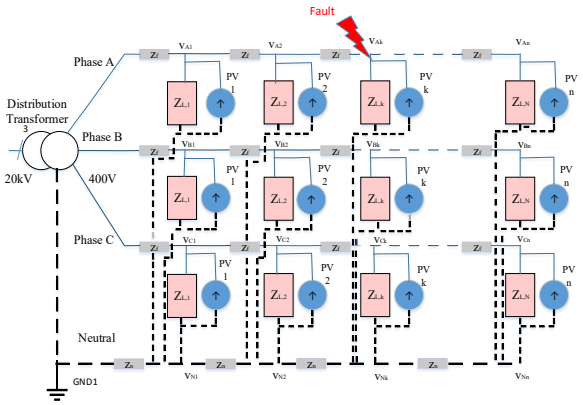


Fig. 1. General distribution model (Yengejeh et al., 2014)

The network model must be obtained based on consecutive networks to perform asymmetric short-circuit calculations. The impedance between the two adjacent nodes in the low-voltage network feeder is represented by the impedance matrix and 1:

$$\left[Z_{Fault}^{LV}\right]_{ABC} = Z_f . I_{3*3} \quad (1)$$

Where z_f is the phase impedance between the two adjacent buses, and I_{3*3} is the unit matrix. Similarly, the average impedance of the voltage feeder is equal to:

$$\left[Z_{Fault}^{MV}\right]_{ABC} = Z_f^{'} . I_{3*3} \quad (2)$$

Where z'_f is equal to the impedance of a medium voltage feeder, likewise, the impedance of the distribution transformer is equal to:

$$\left[Z^{trans}\right]_{ABC} = Z_{trans} . I_{3*3} \quad (3)$$

Where z_{trans} is equal to the impedance of each distribution transformer phase, feeder impedance for modeling consecutive networks is defined by 4:

$$\left[Z_f^{LV}\right]_{012} = [A]^{-1}\left[Z_f^{LV}\right]_{ABC}[A] \quad (4)$$

Where,

$$[A]=\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} \qquad a=1<120^\circ$$

Consecutive networks for the medium voltage feeder and transformer impedance are calculated similarly using 2 and 3.

In addition, since the systems are single-phase, the current of their output consecutive networks must be obtained. The output current matrix of photovoltaic systems connected to phases A, B, and C in bus i is as follows:

$$\left[I_i^{PV}\right]=\left[I_A^{PV}\, I_B^{PV}\, I_C^{PV}\right]_i^T \tag{5}$$

Where T is the matrix transpose function, and the components of the consecutive output current of the systems are calculated as follows:

$$\left[I_i^{PV}\right]_{012}=[A]^{-1}\left[I_i^{PV}\right]_{ABC} \tag{6}$$

Fig. 1 shows an asymmetric fault in the kth bus of a network with n buses. Consecutive equivalent networks are modeled by Fig. 2. Next, the network needs to be simplified using the Thevenin-Norton method to find the equivalent circuit from the fault point. The simplification process is performed separately for the downstream and upstream systems, as Fig. 3 shows (Yengejeh et al., 2014).

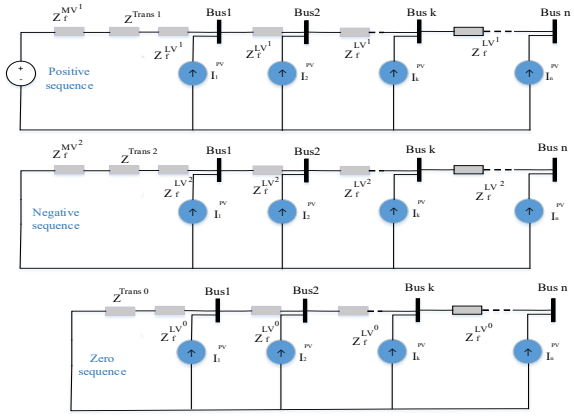


Fig. 2. Equivalent sequence distribution considering photovoltaicsystems
(Yengejeh et al., 2014)

For downstream fault systems, their output currents have been summed up as presented in 7 and summarized based on the Norton equivalent circuit; likewise, for upstream systems, the Thevenin equation has been expressed as presented in 8 to 10.

$$I_{no}^{j}=\sum_{i=k}^{n} I_i^{PV\,j} \qquad j=0,1,2 \tag{7}$$

$$V_{th}^{'1}=1+\sum_{i=k}^{k-1} I_i^{PV^1}\left(Z_f^{MV^1}+Z^{trans^1}+iZ_f^{LV^1}\right) \tag{8}$$

$$V_{th}^{'2}=\sum_{i=k}^{k-1} I_i^{PV2}\left(Z_f^{MV2}+Z^{trans2}+iZ_f^{LV2}\right) \tag{9}$$

$$V_{th}^{'0}=\sum_{i=k}^{k-1} I_i^{PV0}\left(Z^{trans0}+iZ_f^{LV0}\right) \tag{10}$$

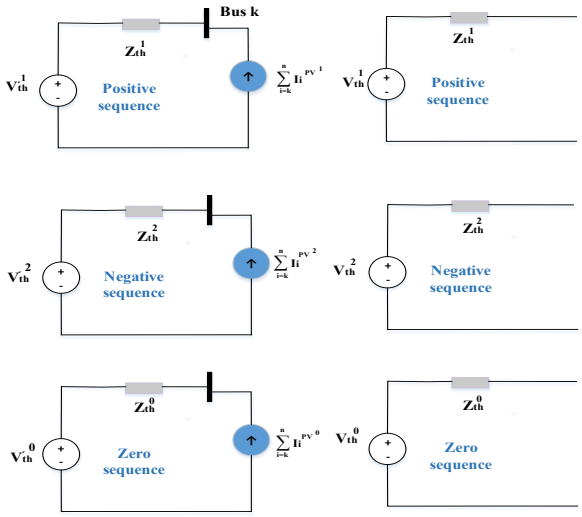


Fig. 3. Thevenin and Norton equivalent circuit
(Yengejeh et al., 2014)

In addition to the impedance of the sequences, the voltages of positive, negative, and zero sequences have been calculated due to the asymmetry of photovoltaic systems in the phases by the simplification of prior Thevenin-Norton equations.

$$\begin{aligned} Z_{th}^1 &= Z_f^{MV^1}+Z^{trans^1}+iZ_f^{LV^1}\\ Z_{th}^1 &= Z_{th}^2\\ Z_{th}^0 &= Z_{th}^{trans^0}+iZ_f^{LV^0}\end{aligned} \tag{11}$$

$$\left[V_{th}\right]_{012}=\left[V_{th}^{'}\right]_{012}+\sum_{i=k}^{n}\left[I_i^{PV}\right]_{012}+\left[Z_{th}\right]_{012} \tag{12}$$

In addition, using the information provided by some studies (Grainger & Stevenson, 1994; Gogen, 2009) about different types of short circuits, the current and voltage of negative, zero, and positive sequences of faults could be calculated when photovoltaic systems are connected to the network.

Single-phase-to-ground short circuit is the most common type of short circuit. In this fault, for example, phase A is connected to ground by Z_{Fault} impedance. In this state, consecutive networks are arranged serially with each other and with $3Z_{Fault}$ (Ghanei Ardakan et al., 2024). In addition, their

consecutive current in the fault conditions is as shown in 13:

$$I_{a0} = I_{a1} = I_{a2} = \frac{V_{th}^{0} + V_{th}^{1} + V_{th}}{Z_{th}^{0} + Z_{th}^{1} + Z_{th}^{2} + 3Z_{Fault}} \quad (13)$$

With the obtained currents, the negative, zero, and positive sequence voltages are expressed as follows:

$$V_{aj} = V_{th}^{j} - Z_{th}^{j} I_{aj} \qquad j = 0,1,2 \quad (14)$$

Phase voltages are obtained by equation 17:

$$[V_{Fault}]_{abc} = [A][V_a]_{012} \quad (15)$$

3. An introduction to the studied network

As demonstrated in Fig. 4, the case study system is a 178-bus real LV distribution system located in Yazd province, Iran. This system is connected to a 20 kV system by a 20 kV / 0.4 kV transformer while feeding 137 nonlinear residential loads. In the sub-system, the transformer, two single-phase PV systems labeled as PV1 and PV2, each with the capacity of 5 kW, are located at the end of the feeder connected between phase A and neutral. It should be noted that other single-phase photovoltaic systems will be added to the network as the study continues. The values of the loads are based on the number of meters installed in houses and in the location of other consumers. In addition, the active power of each phase has been shown in Table 1. To distribute the load, the same type of bases that the photovoltaic system is connected to, PQ is considered because the power generation level of these systems is not to the extent that they can be modeled as PV bases.

According to the information collected from the network level, the loads are considered as single-phase and constant power, and each one is connected to one of the phases.

TABLE 1. The amount of active power per phase

Phase	*A*	*B*	*C*
Active Power(KW)	*19.6*	*35.2*	*14*

According to the IEEE 929 standard, photovoltaic systems installed on roofs act as a single-phase constant power source and have a unit power factor. Also, this standard recommends limits for normal and abnormal operating voltage for the operation of photovoltaic systems (IEEE, 2000). According to this standard, if the power supply voltage of photovoltaic systems is lower than 88% of the nominal voltage, the systems must be disconnected from the feeder and stop providing energy. Likewise, the voltage of the healthy phases should not increase by more than 10% of the rated voltage. The maximum system cut-off time also depends on the amount of voltage drop or increase, so the cut-off time of the systems will be different, because they see different voltages. Table II shows the maximum system disconnection time.

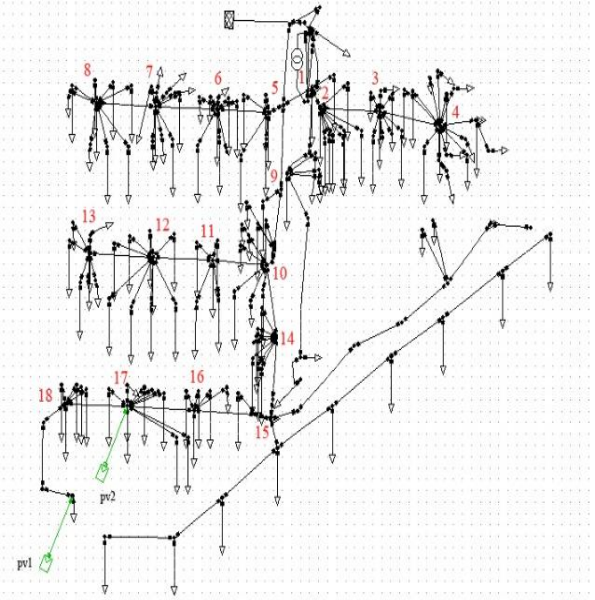


Fig. 4. The Distribution Test

Table 1. Maximum disconnection time of PV in response to feeder voltages

Condition (PU)	Maximum tripping time (cycle)
V< 0.5	6
0.5 ≤ V≤ 0.88	120
0.88 ≤ V≤ 1.1	Normal
1.1 ≤ V≤ 1.37	120
1.37 ≤ V	2

4. Simulation and results

The impedance of the feeder plays a decisive role in increasing the voltage of the feeder. To investigate the impact of this feature, two states are investigated. In the first case, the absolute value of the impedance of the feeder is different, and in the second case, the ratio of the resistance to the reactance of the feeder (K=R/XL) is different, while the impedance size is constant.

4.1. The impact of the absolute value of the impedance

To analyze the impact of the absolute value of the impedance of the feeder on the voltage profile during the feeder and the time of disconnection of the systems, a single-phase short-circuit fault with a resistance of 2m ohm is applied in the middle node (node 10) of phase A. However, the value of the impedance of the feeder is variable, as shown in Table 3.

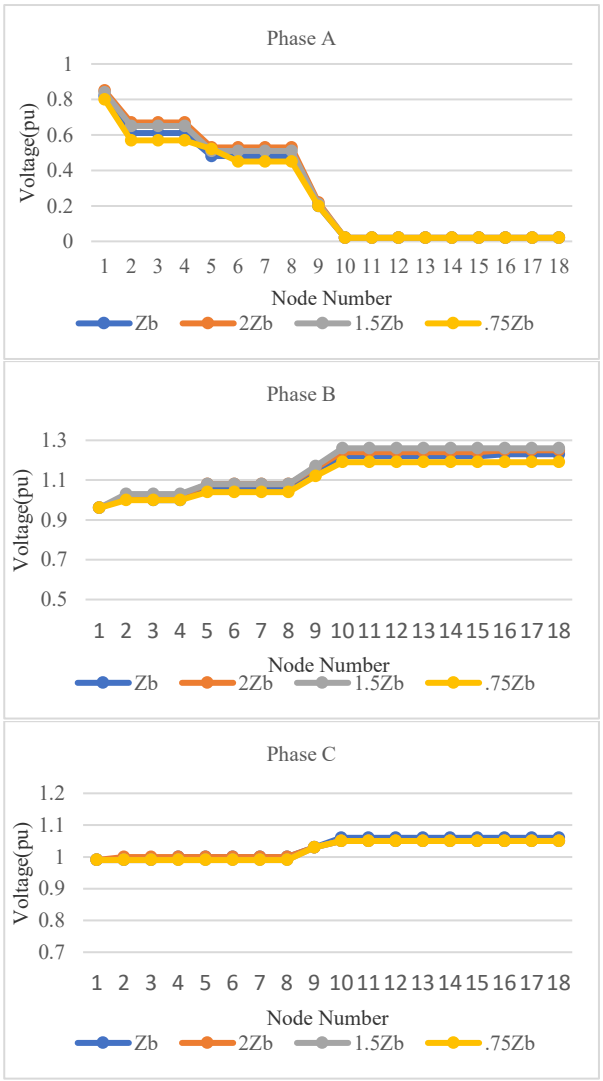


Fig. 4. The voltage profile along the feeder for different Z

The voltage profile along the feeder for different impedances is shown in Fig. 5. This figure shows that for all other sizes, the node voltage in phase A is less than 88% of the nominal value with little variation. After-fault voltage of the nodes in phase B is higher than 110% of the nominal value, and for phase C, the voltage of the nodes is close to each other and within the normal range. Therefore, it can be said that changing the size of the impedance of the feeder does not affect the disconnection status of the systems.

Table 3. The value of resistance and reactance for different Z

		positive and negative, sequences (Ω/km)		zero (Ω/km) sequences	
		35mm²	25mm²	35mm²	25mm²
Z_b	R	0.57768	0.81929	1.02861	1.25029
	X_L	0.24629	0.25725	1.30800	1.46372
$2Z_b$	R	1.15536	1.63858	2.05722	2.5005
	X_L	0.49258	0.5145	2.616	2.92744
$1.5Z_b$	R	0.86652	1.22893	1.54291	1.87543
	X_L	0.36943	0.38587	1.962	2.19558
.75Zb	R	0.43326	0.61446	0.77145	00.93771
	X_L	0.18471	0.19293	0.981	1.09779

4.2. Impedance ratio ($K=R/X_L$)

To analyze the effect of changing the impedance ratio on the voltage profile along the feeder and the state of disconnection of the systems, a single-phase short-circuit fault with a resistance of 2 milliohm is applied in the middle node (node 10) of phase A. However, the value of the impedance ratio of the feeder is variable. The reviewed items are shown in Table 4. The voltage profile along the feeder is shown in Fig. 6. This figure shows that for all considered ratios, the node voltage in phase A is very close to each other and less than 88% of the nominal value. For phase B, the voltage values of the nodes are close to each other. And in the nodes after the fault location, it reaches more than 110% of the nominal value. But for phase C, the voltage value of the nodes after the fault location will be different.

Table 4. The value of resistance and reactance for different K_b

		positive and negative, sequences (Ω/km)		zero (Ω/km) sequences	
		35mm²	25mm²	35mm²	25mm²
K_b	R	0.57768	0.81929	1.02861	1.25029
	X_L	0.24629	0.25725	1.30800	1.46372
$2K_b$	R	0.5988	0.84729	1.3961	1.67
	X_L	0.13	0.135	0.9	0.95
$3K_b$	R	0.62162	0.85387	1.5166	1.79323
	X_L	0.09	0.09	0.7	0.7
$.5K_b$	R	0.48426	0.73123	0.60737	0.80199
	X_L	0.4	0.45	1.55	1.75
.33K	R	0.3264	0.61417	0.4570	0.53207
	X_L	0.54	0.6	1.6	1.85

According to the change of the impedance and reactance value of the sequences, the relations and calculations of section 2 also confirm the same curves. Therefore, according

to the obtained results, if the impedance ratio of the feeder is different, the voltage value of the nodes in phases A and B is close to each other, and it will be different in phase C. Therefore, there is no change in the state and time of system disconnection in phases A and B, but for phase C, because the voltage value for the nodes after-fault location has changed, there is also a change in the state of system disconnection.

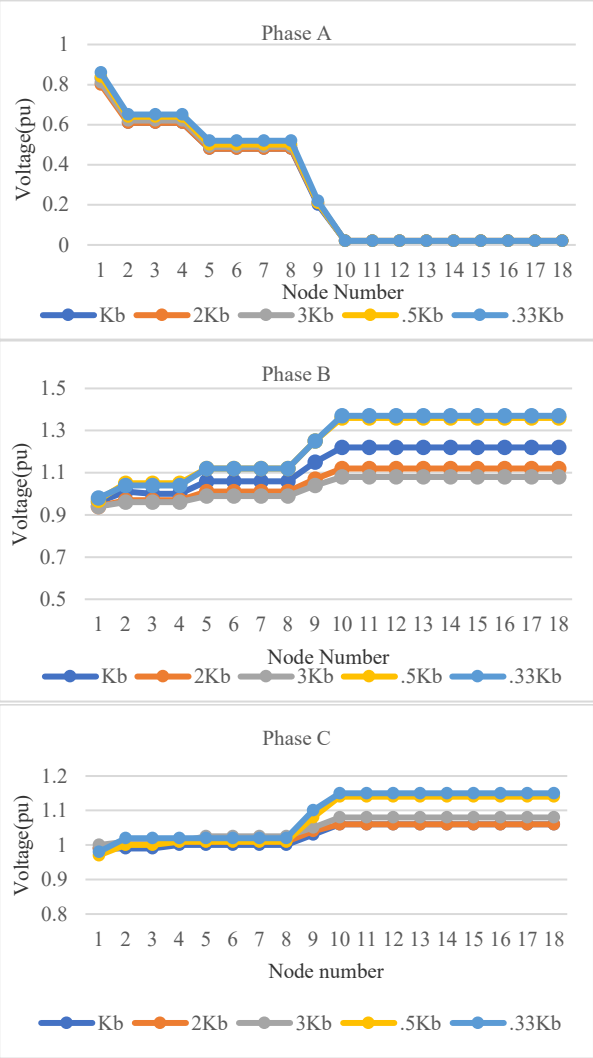


Table 5. The voltage profile along the feeder for different K

5. Conclusions

This article investigates the state of disconnection of single- Phase systems after a single-phase short-circuit fault to the ground, in the weak pressure feeder of an asymmetric distribution network. In this article, the effect of feeder impedance on the state of disconnection of systems has been investigated. Phase systems after a single-phase short-circuit fault to the ground, in the weak pressure feeder of an asymmetric distribution network. In this article, the effect of feeder impedance on the state of disconnection of systems has been investigated. Analyses show that the value of the after-fault voltage in the faulty phase is less than 88% of the nominal value. Hence, all systems connected to this phase will be cut off, and changing the absolute value and impedance ratio on the cut-off condition will not change. For healthy phases, changing the absolute value of the impedance of the feeder will not affect the voltage of the nodes and the disconnection status of the system. By changing the ratio of the impedance of the feeder in one of the healthy phases in the node's voltage, there is no change in the state of disconnection of the systems. But the after-fault location voltage will be changed in one of the phases, and there is a change in the disconnection status of the systems. Therefore, the impedance of the feeder can be one of the parameters that affect the system disconnection status.

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