

IEEE Recommended Practice for Fault Diagnosis and Protection in Smart Distribution System

IEEE Power and Energy Society

Developed by the
Transmission and Distribution Committee

IEEE Std 2748™-2023

STANDARDS

IEEE Recommended Practice for Fault Diagnosis and Protection in Smart Distribution System

Developed by the

Transmission and Distribution Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

Abstract: The fault diagnosis and protection schemes and application cases for smart distribution systems from ac 6 kV to 20 kV are provided by this recommended practice, covering security requirements, architectures, and configuration, as well as basic functions and technical indexes of software systems and hardware terminals and requirements of information exchange. Schemes provided in this document are adaptable to various operation modes, control patterns, equipment conditions, and reliability requirements of distribution systems. This recommended practice is mainly based on engineering practices in the voltage range of 6 kV to 20 kV. The proposed fault location, isolation, and service restoration (FLISR) schemes can also be used in the voltage range of 2.4 kV to 38 kV as specified in ANSI C84.1 after an evaluation of communication conditions and cost analysis. Phase (three-phase and phase-to-phase) faults, ground (three-phase-to-ground, two-phase-to-ground, and single-phase-to-ground) faults and conductor-broken faults are covered by the fault types. Changes and needs brought by the connection of distributed generators are considered, and schemes empowered by information and communication technologies are also introduced.

Keywords: centralized scheme, communication-assisted scheme, fault diagnosis and protection, IEEE 2748™, non-communication-based scheme, smart distributed scheme, smart distribution system

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Introduction

This introduction is not part of IEEE Std 2748-2023, IEEE Recommended Practice for Fault Diagnosis and Protection in Smart Distribution System.

This recommended practice focuses on the configurations and schemes of fault diagnosis and protection corresponding to different grid operation modes, control patterns, equipment conditions, and reliability requirements in smart distribution grids. With the development of information and communication technology (ICT), diverse and abundant data in monitoring and control systems for distribution grids exist. And due to the connection of distributed energy resources and electric vehicles, the distribution grid becomes more variable and complex. Considering different distribution grid conditions and requirements, this recommended practice provides valuable practices relevant to the fault diagnosis and protection strategies including operation requirements, architecture of fault diagnosis and protection configuration, basic functions and technical indexes of software systems and hardware terminals, the realization modes of fault diagnosis and protection, relevant information exchange demand, and so forth. The fault types cover phase (three-phase and phase-to-phase) faults, ground (three-phase-to-ground, two-phase-to-ground, and single-phase-to-ground) faults and conductor-broken faults. This recommended practice applies to distribution systems from 6 kV to 20 kV since the recommendations are mainly based on engineering practices in the voltage range of 6 kV to 20 kV. The proposed fault location, isolation, and service restoration (FLISR) schemes can also be used in the voltage range of 2.4 kV to 38 kV as specified in ANSI C84.1 [B1] after an evaluation of communication conditions and cost analysis.⁶

⁶The numbers in brackets correspond to those of the bibliography in Annex B.

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IEEE Recommended Practice for Fault Diagnosis and Protection in Smart Distribution System

1. Overview

1.1 Scope

This recommended practice focuses on the configurations and schemes of fault diagnosis and protection corresponding to different grid operation modes, control patterns, equipment conditions, and reliability requirements in smart distribution network. With the development of information and communication technology (ICT), there is diverse and abundant data in monitoring and control systems for the distribution network. And due to the connection of distributed energy resources (DERs) and electric vehicles, the distribution network becomes more diversified and complex. Considering different distribution network conditions and requirements, this recommended practice provides valuable practices relevant to the fault diagnosis and protection strategies including operation requirements, architecture of fault diagnosis and protection configuration, basic functions and technical indexes of software systems and hardware terminals, the realization modes of fault diagnosis and protection, relevant information exchange demand, and so forth. The fault types cover phase (three-phase and phase-to-phase) faults, ground (three-phase-to-ground, two-phase-to-ground, and single-phase-to-ground) faults and conductor-broken faults. This recommended practice applies to distribution systems from 6 kV to 20 kV.

1.2 Purpose

In view of the fact that a single fault diagnosis and protection strategy cannot adapt to various configurations of smart distribution networks, an effective fault diagnosis and protection method should be able to adjust with changes of the monitoring and operating conditions, network topology, and reliability requirement of smart distribution networks. Therefore, schemes for fault diagnosis and protection according to the operation modes, control patterns, equipment conditions, and reliability requirements in smart distribution grids are needed.

This recommended practice provides valuable experience for planners and operators in the matter of fault diagnosis and protection configuration. It is intended to provide preferred strategies of fault handling according to different grid situations and user requirements.

The implementation of this recommended practice will help enhance security and the normative operation for smart distribution networks.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

1.4 Limitations

The recommendations in this document are not mandatory requirements. This recommended practice is developed to be compatible with other related IEEE guides, recommended practices, and standards to the extent possible; also observe the following:

- Equipment failures such as distribution transformer faults and switch faults are not discussed in this recommended practice.
- The fault diagnosis and protection schemes for dc or ac-dc hybrid distribution systems are not covered in this recommended practice.
- This recommended practice is mainly based on engineering practices in the voltage range of 6 kV to 20 kV. The proposed fault location, isolation, and service restoration (FLISR) schemes can also be used in the voltage range of 2.4 kV to 38 kV as specified in ANSI C84.1 [B1]⁹ after an evaluation of communication conditions and cost analysis.

1.5 Technology status and schema

The rapid development of telecommunication technology, digitization, and intelligent technology is promoting the technical innovation of fault diagnosis and protection for distribution grids. Exploiting the advantages of traditional relay protection technologies adequately while superposing advanced communication methods and information processing methods effectively to achieve fast, reliable, and accurate troubleshooting is a topic that still needs to be discussed in-depth and verified in practice.

In addition, the growing integration of DERs is reshaping current distribution grids with more complex topological structures, more varied and complex operation modes and performances. The traditional distribution grid is usually a radial system with a single power source (SO), and, therefore, the traditional FLISR scheme is designed for unidirectional power flow. With the integration of DER, both the topology of the distribution grid and the characteristics of the fault current (amplitude and distribution) are changed, which also affect the existing FLISR scheme mainly from the following aspects:

- a) The changeability of the fault location and DER connection location has increased the complexity and changeability of the amplitude and distribution of voltage and current upon faults. The location and power of the DER may impact the fault current, and the higher the penetration of the DER, the more significant the impact is. See 5.2.5, 5.3.5, and 5.4.2.5 for more details about the DER impacts of different fault types.

⁷The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

⁹The numbers in brackets correspond to those of the bibliography in Annex B.

- b) If a fault occurs at DER upstream, the DER feed-in current may sustain arc burning, leading to reclosing failure and reducing the reliability of power supply.
- c) The neutral point of the distribution grid has multiple grounding modes, such as direct grounding, non-grounding, impedance grounding, and resonant grounding, which will affect the distribution of fault characteristics. With DER connected, the DER grounding method will also impact the fault characteristics, which should be fully considered.

DERs considered in this standard are ac/dc inverter type and ac rotating generator type. The main contents covered by this recommended practice are shown in [Figure 1](#).

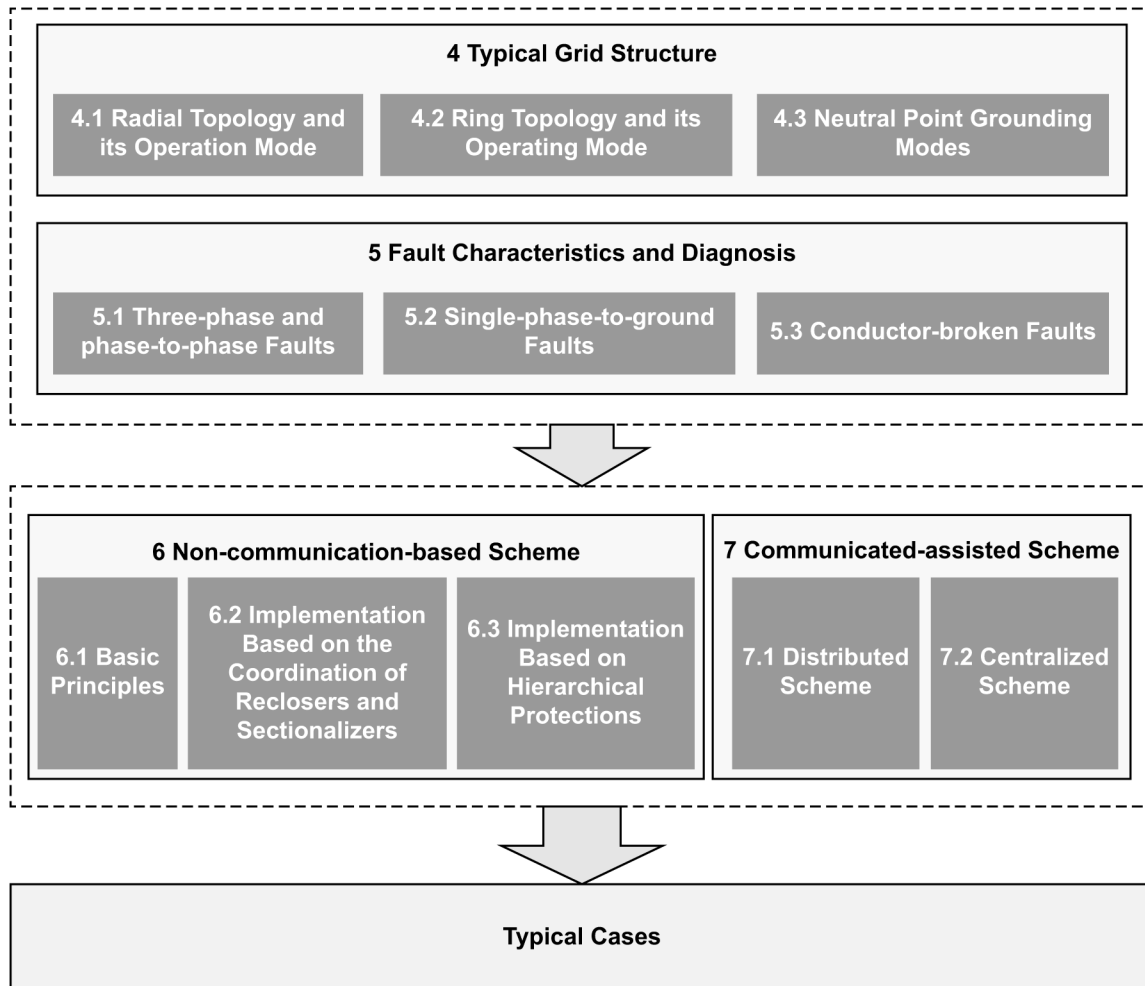


Figure 1—Main contents covered by this recommended practice

The standard has eight clauses; the first three clauses are conventional, and the others are as follows:

- **Clause 4** describes the typical network topologies, the radial and loop topologies, and the corresponding operation modes, as well as the common neutral grounding modes. As these factors have direct impacts on the fault features, the document set this clause before discussing the specific fault types and FLISR schemes.
- **Clause 5** describes the common fault types—including the three-phase, phase-to-phase, single-phase-to-ground, and conductor-broken—and the corresponding diagnosis methods. The impacts brought by DER connections on fault characteristics and diagnosis methods are also considered. This clause identifies the key objects of the document and provides the methodology foundation for the FLISR schemes provided in the following clauses.
- **Clause 6** provides the non-communication-assisted FLISR scheme, covering the two typical applications of reclosers and sectionalizers coordination and the hierarchical protections.
- **Clause 7** provides the communication-assisted FLISR scheme, covering the schemes of the distributed mode realized by the smart FA system and the centralized scheme by the central stations. Particularly, this clause discusses how the DER connection may influence the FLISR scheme and provides improvement measures and criteria.
- **Annex A** provides four application cases including the smart distributed fault diagnosis and protection scheme, the centralized fault diagnosis and protection scheme, the fault process for closed-loop distribution grids, and the coordinated non-communication-assisted fault diagnosis and protection scheme.

In this recommended practice, the impact of DER connection is considered for each section, and the adaptability analysis on the recommended fault diagnosis and protection scheme considers both distribution grids with and without DER.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60870-2-1, Telecontrol equipment and systems—Part 2: Operating conditions—Section 1: Power supply and electromagnetic compatibility.¹⁰

IEC 60870-5-101, Telecontrol equipment and systems—Part 5–101: Transmission protocols—Companion standard for basic telecontrol tasks.

IEC 60870-5-104, Telecontrol equipment and systems—Part 5–104: Transmission protocols—Network access for IEC 60870-5-101 using standard transport profiles.

¹⁰IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

automatic circuit recloser: A self-controlled device for automatically interrupting and reclosing an alternating-current circuit, with a predetermined sequence of opening and reclosing followed by resetting, hold-closed, or lock-out operation. (Refer to IEEE Std 1909.1TM-2014)

distribution system: That portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer. (Refer to IEEE Std 1366TM-2022)

fault detection: The ability to detect the presence of a fault by observing one of its physical manifestations. However, detection may not yield enough information to identify the precise location of a fault. (See IEEE Std 1581TM-2011)

fault diagnosis: The ability to both detect and locate a fault. This process may require correlating several different manifestations of the fault. (Adapted from IEEE Std 1581-2011)

feeder: A cable or set of conductors that originates at a main distribution center (main switchboard) and supply secondary distribution centers, transformers, or motor control centers. (Bus tie circuits between generator and distribution switchboards, including those between main and emergency switchboards, are not considered as feeders.) (Refer to IEEE Std 45.8TM-2016)

intelligent electronic device (IED): Any device incorporating one or more processors with the capability to receive or send data/control from or to an external source (e.g., electronic multifunction meters, digital relays, controllers). (Refer to IEEE Std C37.92TM-2023)

line protection: Scheme to detect line faults and trip all breakers attached to the faulted line. (Refer to IEEE Std C37.230TM-2020 and IEEE Std 1646TM-2004)

line switch: A device used as a breaker or load-break switch in an ac power circuit. (This device function number is normally not necessary unless the switch is electrically operated or has electrical accessories, such as an auxiliary switch, a magnetic lock, etc.) (Adapted from IEEE Std C37.2TM-2008)

sectionalizer: A circuit-opening device that automatically opens the main electrical circuit through it after sensing and responding to a predetermined number of successive main current impulses equal to or greater than a predetermined magnitude. It opens while the main electrical circuit is de-energized. It may also have provision to be manually operated to interrupt loads. (Adapted from IEEE Std C37.63TM-2013)

smart distribution: The integration of power measurements, two-way communications, analytical decision making, and supervision to execute decisions to improve the delivery of electric energy. (Refer to IEEE Std C37.92-2023)

¹¹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

3.2 Acronyms and abbreviations

ACSI	Abstract Communication Service Interface
CP	capacitor
DA	distribution automation
DER	distributed energy resource
EPS	electric power system
FA	feeder automation
FI	fault indicator
FLISR	fault location, isolation, and service restoration
HV	high voltage
ICT	information and communication technology
IED	intelligent electronic device
LD	load
LN	line
LV	low voltage
MV	medium voltage
PCC	point of common coupling
RMU	ring main unit
RTU	remote terminal unit
SCL	Substation Configuration Description Language
SCSM	Specific Communication Service Mapping
SEC	section
SO	source
ZBR	zero impedance branch circuit

4. Typical grid structure

4.1 Radial topology

A radial distribution network has only one-side power SO and, therefore, the power current flows unidirectionally from the power SO side to end users through lines. Radial topology is simple and more economical in aspects of both construction and operation. However, the drawback is the difficulty of maintaining supply in the event of a fault occurring or routine maintenance.

Two typical radial topology are shown in [Figure 2](#) and [Figure 3](#). [Figure 2](#) shows the network composed of overhead lines, and [Figure 3](#) shows the network composed of cables. In practice, there exists the combination of overhead lines and cables.

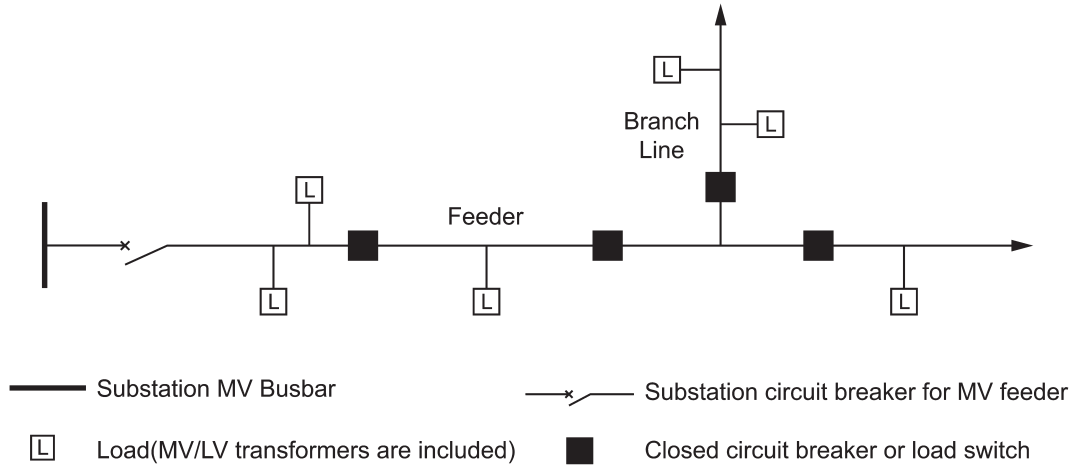


Figure 2—A typical radial distribution network built with overhead lines

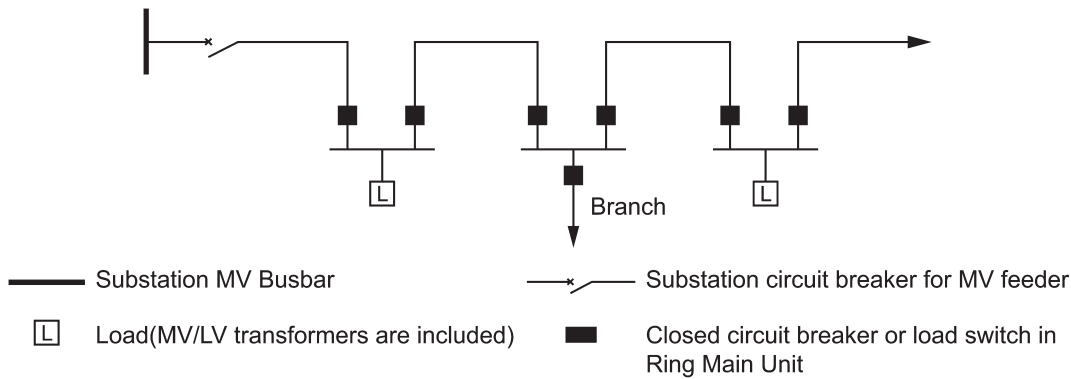


Figure 3—A typical radial distribution network built with cables

In a radial network composed of overhead lines, the feeder can have one or more sectionalizers, which can be circuit breakers (CBs) or load switches. The switch equipped at the outlet of the branch can be a CB, a load switch, a load switch-fuse combination, or other electric protection component that possesses the capacity of close-open.

NOTE—The terms *feeder*, *line*, and *circuit* are used interchangeably to describe the same part of a distribution system in many countries around the world for a long period of time, for historical reasons. The term *lateral* is primarily used in North America to identify a branch of a main feeder/line/circuit. A consistent naming convention for different parts of a distribution system, which uses either an overhead line or a cable or a combination, is used in this document as shown in Figure 2 and Figure 3. The terms *feeder*, *branch* (same as ‘lateral’ in North America), and *line* (all other parts of a distribution system other than *branch* and *feeder*) are used in this document. *Line* is also used as a general term in Clause 5, as the feeder/branch/line is irrelevant when discussing the fault characteristics and diagnosis principles.¹²

In a radial network composed of cables, the incoming or outgoing feeder of the ring main unit (RMU) can equip a CB or load break switch (LBS); the outgoing line of RMU can equip a CB or a load-switch-fuse combination, depending on the requirement of close-open capacity.

¹² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Generally, DER can be connected to the distribution network by three ways: T-type connection (see Figure 4), bus connection at switching substation (see Figure 5), and dedicated line connection, which is not covered in this recommend practice.

The connection location and the level of DER output may change the original distribution of the power flow and fault current, which can impact the selectiveness and sensitivity of relay protection, probably leading to maloperation of switches.

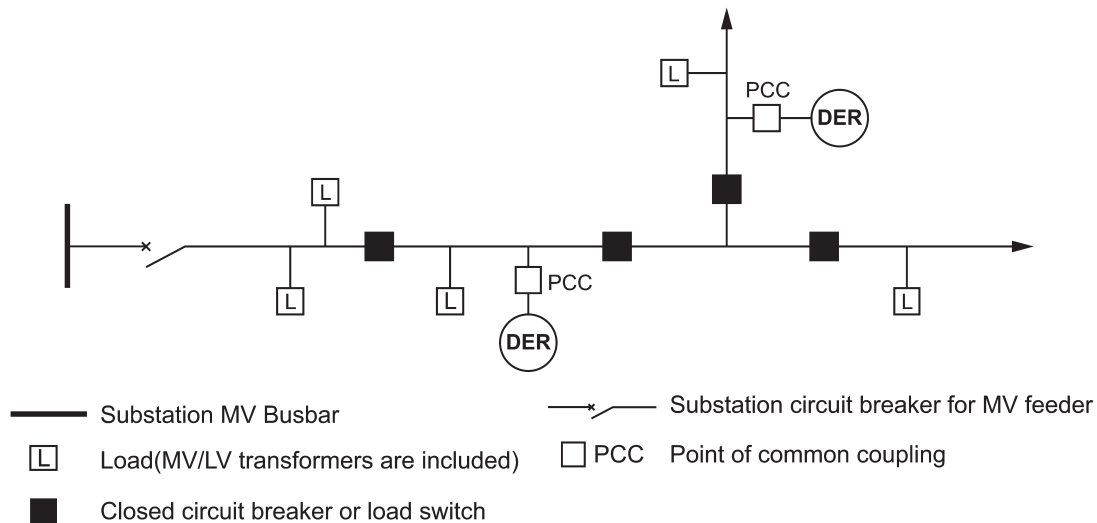


Figure 4—DER connected through T-type connection

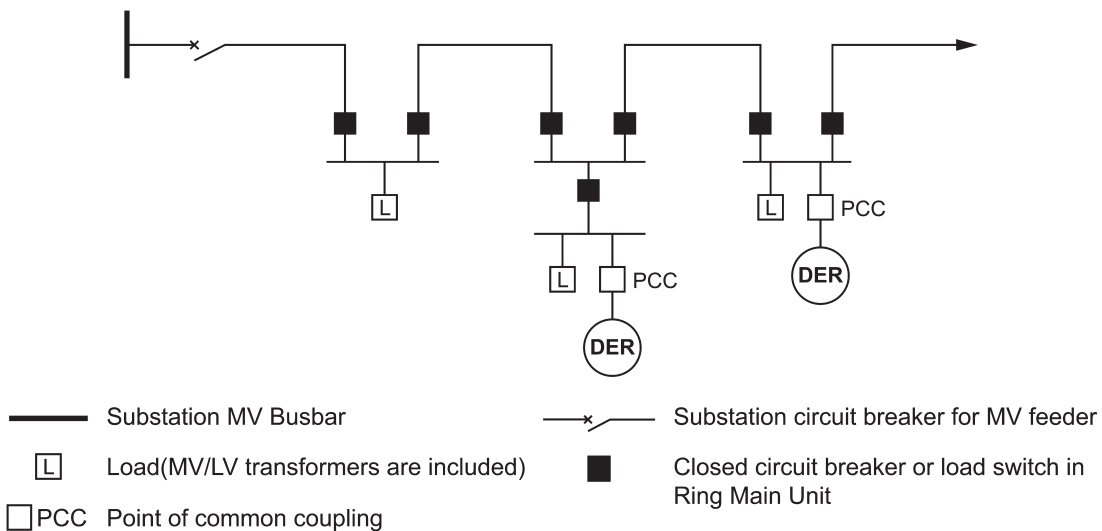


Figure 5—DER connected through a switching substation

4.2 Ring topology and its operation modes

4.2.1 Ring topology

A ring topology is a network configuration where switch connections create a circular power path. Each networked switch is connected to two others, like points on a circle. In a ring network, the power flows from one switch to the next until it reaches its terminal load. Profiting from this topology, each feeder from the bus-tie switch on the circle is supplied with at least one bus-tie power SOs, making it suitable to be used in areas with higher reliability requirements. The ring network operates usually in two modes, open-loop and closed-loop mode.

4.2.2 Ring network in open-loop operation mode

Typically, the ring main network adopts open-loop operation in order to limit fault current and simplify the protection relay coordination. Two typical open-loop networks are shown below. Figure 6 shows the network composed of overhead lines, and Figure 7 shows the network composed of cables. In practice, there exists a combination of overhead lines and cables. Bus-tie switches are installed between feeders. Loss of supply will be restored by closing the bus-tie switch manually or automatically.

The feeder of an open-loop network are equipped with several switches, which can be all CBs, all load break switches, or a combination of both. The switches configuration at the outlet of the branches is the same as that of the radial topology.

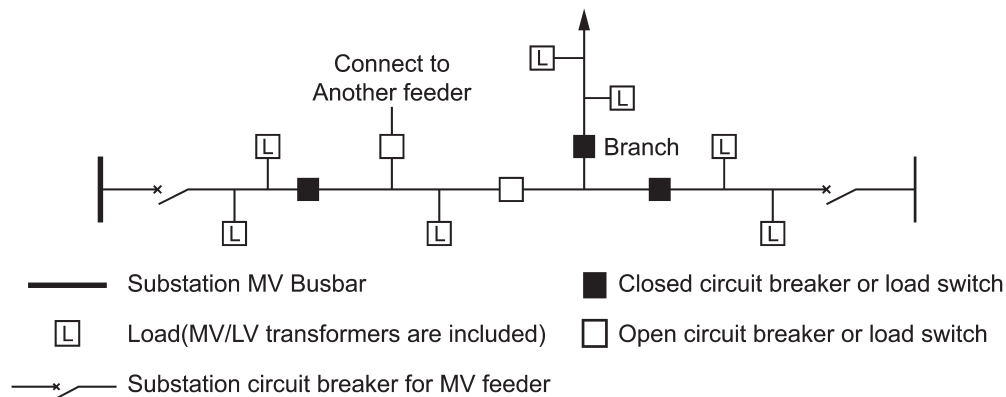


Figure 6—A typical open-loop network built with overhead lines

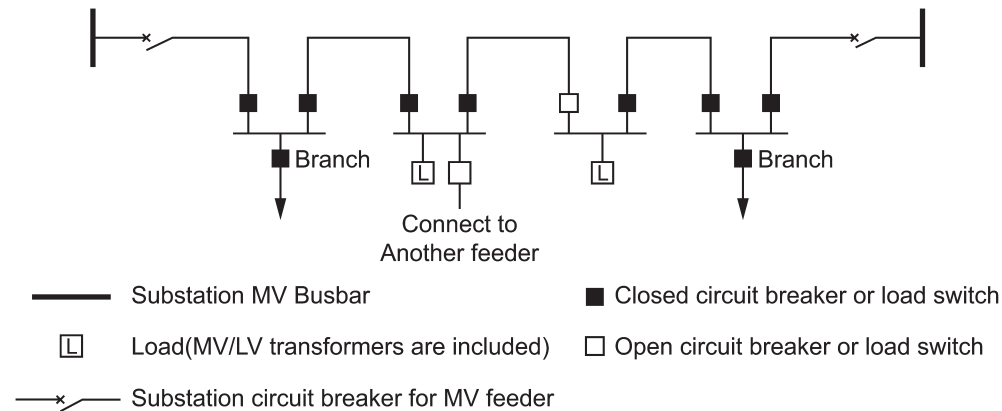


Figure 7—A typical open-loop network built with cables

In open-loop operation mode, the network is separated by the opening bus-tie switch into two parts. In the case that one part of network loses its power supply caused by a fault, the bus-tie switch closes to restore power supply after the fault is isolated completely. The fault isolation can only be executed after the CB on the feeder outlet trip to de-energize the entire feeder if load break switches, instead of CBs, are equipped along the feeder. The feeder automation (FA) system can isolate the fault and restore the power supply to the healthy (unfaulted) section.

The influence from the DER connection is equivalent to that of the radial topology. Regardless of the connection ways, it is difficult to avoid the bidirectional power flow brought by the DER and that may impact the performance of the existing protection scheme, except that the DER are connected at the power supply side.

4.2.3 Ring network in closed-loop operation mode

A closed-loop ring network operates with all bus-tie switches in normal closed position. As shown in Figure 8, the power supplies of the ring network may come from the same or different buses in an upstream substation or even two different substations.

The switches in closed-loop ring network can equip CBs, which possesses the capability of breaking fault current to directly isolate the fault, meanwhile helping avoid power outages on healthy sections. The closed-loop operation is suitable for networks with higher reliability requirements, where it can effectively help avoid long-time outage and significantly reduce the total outage period.

The ring network in the closed-loop operation mode is usually built with cables and equips low-resistance grounding.

The power flow and fault current can be bidirectional in a closed-loop network, and the power capacity of DER is commonly much smaller than that of the power SO in the main network. Therefore, the DER connection neither impact the original power flow direction nor the performance of the existing protection scheme, giving closed-loop systems advantages in accommodating DER.

The short-circuit current in a closed-loop system can be larger than that of a radial or open-loop network, and this phenomenon results in a higher reliability requirement of protection scheme to ensure the speed and selectivity of protection operation.

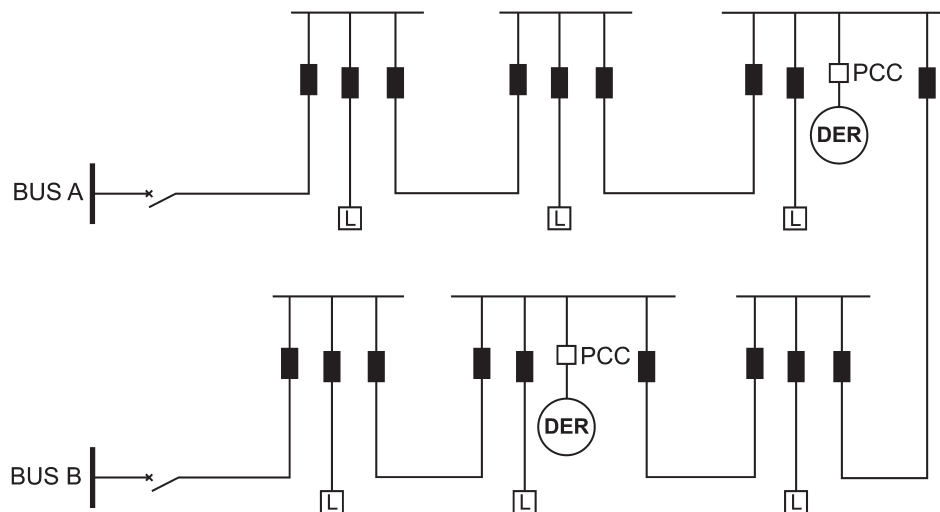


Figure 8—A typical closed-loop network with DER