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FLISR Approach for Smart Distribution Networks Using E-Terra Software—A Case Study

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Abstract: A smart grid concept has been defined in recent years, which emphasizes the importance on smart protection and measurement devices, reliable data communication and high security, optimal energy management system, and fault detection, location, isolation and service restoration (FLISR) of distribution networks (DNs). The main objectives of the FLISR approach are to achieve fast fault processing time, reduce the minimum number of interrupted customers, and improve the power supply reliability of the distribution. The conventional FLISR approach is to use signals of fault indicators (FIs) with distribution network states. The discrete installation of FIs to switches or reclosers may slow the processing time of fault detection and location, so it is necessary to develop a more efficient FLISR approach for smart distribution networks using functions of feeder terminal units (FTUs). In this paper, pick-up and tripping signals of overcurrent (OC) relays in combination with distribution grid states (e.g., switching status of devices, loss of voltage . . .) sent from feeder terminal units (FTUs) are used to detect and locate different fault types. Fault isolation and service restoration of black-out areas are then performed by solving an objective function with two main constraints, including (i) restoring the possible maximum number of out-of-service loads; and (ii) limiting the minimum number of switching operation. Thirteen performance factors (PF) are used for the post-fault service restoration process, consisting of: (i) Power Flow Violations (PFV), (ii) Bus Voltage Violations (BVV), (iii) Total Operation Cost (TOC), (iv) Lost Power (LP), (v) Outage Customer (OC), (vi) Number of Switching Steps (NSS), (vii) Power Losses (LOSS); (viii) Customer Minutes Interruption (CMI), (ix) Load Minutes Interruption (LMI), (x) MAIFI, (xi) SAIFI, (xii) SAIDI, and (xiii) Protection Validation (PRV). E-Terra platform of a distribution management system (DMS) is used to implement the proposed FLISR approach. Simulation and experiment results from a real 22 kV distribution network are also analysed to validate this FLISR approach. As a result, the novel FLISR approach has the ability to identify effectively the over-reaching of OC relays, indicate a mis-coordination risk of adjacent protection devices on the same feeder, and get the total processing time of fault detection, location and isolation as well as ranking all possible service restoration plans in distribution network at less than two minutes.

Keywords: smart distribution networks; fault detection; fault location; fault isolation; service restoration; self-healing; and fault indicator

1. Introduction

1.1. Motivation

A major challenge of distribution networks is to provide customers with high power quality and reliability. For a smart distribution network, self-healing control techniques should be taken into account to get the above requirements. Compared to a conventional distribution network, a smart distribution network should achieve self-healing control with respect to any faults, specifically, fault detection and location, fault isolation, and fast restoration of power supply of outage areas where there is no fault. How to quickly detect different types of faults, precisely locate the faulted sections and accurately isolate these faulted sections is the basis and prerequisite of self-healing control functions in smart distribution networks. Moreover, fault isolation and service restoration of black-out areas in a distribution network should meet main constraints such as: (i) to restore the possible maximum number of out-of-service loads; and (ii) to limit the minimum number of switching operation. Various performance factors for the post-fault service restoration process should be considered, mainly consisting of power flow violations, bus voltage violations, total operation cost, lost power, outage customer, the number of switching operation, power losses, customer minutes interruption, load minutes interruption, momentary average interruption frequency index (MAIFI), system average interruption frequency index (SAIFI), system average interruption duration (SAIDI), and protection validation.

1.2. Literature Review

1.2.1. Fault Detection, Location and Isolation Methods in DNs

Common fault detection and location methods mostly use signals sent from FTUs on the feeder in combination with distribution power grid states [1–3]. In [1], a simplified model of distribution network based on pre-defined minimum areas is developed for fault diagnosis in radial and ring network topologies. This method is simple to pre-determine the distribution network minimum areas. However, it is difficult to accurately locate the faults occurring inside the minimum areas of the distribution network. In [2], fault indicators are used for fault diagnosis and location, but this method may not be applicable to a distribution network with the mixed presence of both fault indicators and FTUs on feeders. In [3], fault indicators are integrated into the switches/reclosers on feeder segments of the minimum areas of distribution network in order to establish a unified network topology model. Based on fault signals sent by fault indicators and fault information on the network topology, this method can perform the fault diagnosis and location process. A faulted section can be among fault indicators in the distribution network minimum area. The minimum area only consists of feeder segments, bus segments, and loads inter-connected through the common nodes. In addition, the minimum area has no switches/circuit breakers. However, the proposed method has no mention in fast service restoration process of black-out minimum areas where there is no faults. On the other hand, the accuracy of the method is dependent on the pre-determination of minimum areas. If the network topology is complex, definition of the minimum areas may be non-effective for fault detection and location.

In general, the most common fault location method is based on apparent impedance [4,5]. However, this method has some difficulties as follows: (i) affected by fault path resistance, (ii) load capacities of lines, and iii) interconnections of multiple sources. Another fault location method is to use travelling waves [6–8]. Nevertheless, this method may be rendered non-effective by laterals and load taps. In [9–11], artificial neural networks, fuzzy logic, expert systems and hybrid methods have been applied to the fault allocation method in the DN. However, these methods may be failed under network topology changes or mis-coordinated relay settings.

In [12], fault management and decision support models have been presented. The simplest scheme of fault detection, location, isolation and restoration is that reclosers detect loss of voltage

(LoV) and give switching decisions with the pre-programmed time [13]. The second FLISR approach requires an advanced GOOSE technology and telecommunication. The last one is to use a combination of distribution network management software and a SCADA system. The computer application makes fault isolation and restoration plans based on the information on feeder devices such as FTUs, fault indicators, reclosers, etc. The SCADA/DMS can make data collection and transmission as well as give switching operations. In the network fault, feeder terminal units can communicate with each other and automatically execute FLISR steps [14]. Multi-agent systems (MAS) have been introduced to support the distribution network fault management process [15,16], which could be an emergency control agent, restoration agent, corrective control agent, and preventive control agent. In more detail, when a fault occurs, the emergency control agent gives signals to isolate the fault. Then, the latest data from database is used for restoration plans that are performed by the restoration agent.

1.2.2. Post-Fault Service Restoration Methods in DNs

In [17], conceptual aspects and recent developments in FLISR approaches have been presented. Several technical, environmental, and economic challenges of implementing the self-healing for the DN are also analysed. When a fault is detected, it must be located and isolated as fast as possible on the DN. Next, possible restoration plans are given to restore power supply to the affected customers that are not in the faulted zone by transferring them to other adjacent feeders using tie switches [18,19]. The FLISR approach is able to significantly improve the reliability of the DN and assure the service continuity for customers. There are two stages of the FLISR approaches, the first stage for fault detection, location, and isolation, and the second stage for service restoration [20]. Two distribution management systems are the centralised and decentralised systems. A centralised control system collects all the system data and processes them to obtain the FLISR scheme. However, the system size and configuration, the large amount of data to be processed, and a large number of control/decision variables to be determined could be the certain challenges for central controllers. On the other hand, a decentralised and distributed control system will divide the system into many sub-systems so that the computation time of the FLISR can be significantly reduced.

In a conventional distribution system, once a fault occurs, the entire feeder will be normally shut down [21,22]. Consequently, many customers on the feeder are interrupted, including industrial customers, commercial and residential customers. For fault detection and location, circuit breakers/reclosers and fault indicators placed along the fault current path will be activated when a fault occurs. Overcurrent protection functions are mostly used to detect various types of faults in the distribution network [23]. The distribution automation system (DAS) is built to observe and collect distribution states such as fault currents and voltages [24]. For the fault isolation process, after the DAS analyses fault information to find a faulty section, the smallest possible segment of the DN is isolated by activating upstream and downstream switches/circuit breakers of the fault to isolate the faulty point from both directions. Next, adjacent healthy feeders are estimated to support for all possible restoration plans of out-of-service loads. Finally, for the service restoration, main objectives are to restore the maximum possible out-of-service customers along with the minimum number of switching actions with the sufficiently short time. In other words, the service restoration process is to seek suitable backup feeders and power substations to transfer the loads in outage areas through a sequence of switching operations [25]. In general, it is important to develop a fast and effective FLISR algorithm within the allowable restoration time. Several approaches have been proposed to make service restoration plans in the distribution network, such as heuristics, meta-heuristics, expert systems, and mathematical programming [20,26]. Expert algorithms can be better than other algorithms because of global optimization in the number of switching operations and margins of operational constraints. On the other hand, weakness points of heuristic methods are (i) not being guaranteed the optimization; and (ii) difficulty in the large size and complex computation of the algorithm. In [27], a service restoration method is proposed for the DN with a constraint of the minimum number of switching actions. In [28–30], service restoration methods are developed using neural networks

(NN), genetic algorithm (GA), fuzzy theory, tabu searching (TS), particle swarm optimization (PSO), simulated annealing (SA), non-dominated sorting generic algorithm-II (NSGA-II), and ant colonies (ANT). However, these meta-heuristic methods need the extensively computational time when applied in practical distribution networks. In [31,32], the fault isolation and service restoration process is formulated by objective functions which will be solved by mathematical programming approaches, e.g., mixed integer non-linear/linear problem (MINLP/MILP). The mathematical programming approaches can mostly get the optimization, but the computation time usually exceeds the allowably practical time due to the problem of combinatorial expansion. A distribution automation solution based on a multi-agent system is proposed to solve the service restoration part of the FLISR problem [33–35]. With the MAS-based decentralised automation solution, each control agent is used to implement appropriate computational mechanism with the fast sufficient computation time. Coordination and communication among the agents are flexible and adaptable to the complex distribution network. Moreover, fault isolation and service restoration procedures are effective for any distribution network when considering the variable demand and operational constraints.

In general, a FLISR approach can only be successful if it relies on the operation of both hardware and software such as: the operation of smart meters, actuators, switches, communication channels, fault detection and location algorithms, switching sequences of circuit breakers and tie switches during fault isolation and system restoration. Suggestions are given to support implementation of the FLISR scheme consisting of:

- Installation of intelligent devices, e.g., remote terminal units, intelligent electronic devices (IEDs), fault indicators, or advanced metering infrastructures (AMI);
- Upgrading the currently-used devices to get smart capacities;
- Using the decentralised control system for the self-healing operation in real time;
- Using two-way data communication systems;
- Improving fault detection, location and isolation algorithms;
- Service restoration plans with the minimum number of interrupted customers and the minimum number of switching operations without violating operation constraints;
- Reducing the total processing time of fault detection, location and isolation as well as post-fault service restoration process.

1.2.3. Advanced Distribution Management System

In [36], an advanced distribution management system (ADMS) is proposed for smart distribution networks, which should include three main functionalities such as: conservation voltage reduction (CVR), demand response (DR), and fault location, isolation, and service restoration (FLISR). For FLISR application, the first step is to accurately identify the faulted location prior to the process of isolation and service restoration. Then, the service restoration is to temporarily supply critical loads until the full service is restored. A fast fault isolation and service restoration process leads to reduction in the outage time and improvement of reliability indices such as, system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI). For demand response application, DR can be categorised into two groups, namely, incentive-based DR (IBDR) and price-based DR (PBDR) [37]. The incentive-based DR contains main issues such as: direct load control [38,39], interruptible or curtailable DR services [40,41], demand bidding or buyback programs [42,43], emergency DR programs [44,45], capacity market programs, and ancillary services market programs [46]. On the other hand, the price-based DR considers the issues of time-of-use rates, real-time pricing, and critical-peak pricing [47–50]. In general, the post-fault service restoration process of the FLISR application can be considered as part of demand response management in distribution networks.

1.3. Contributions

This paper develops a novel FLISR approach for smart distribution networks. FTUs which are integrated into reclosers/circuit breakers (CBs) on feeder segments are utilised to establish a unified network topology model. Based on signals of FTUs and distribution grid states, the proposed FLISR approach can perform fault diagnosis and location. The accuracy of fault diagnosis and location is significantly dependent on pre-determination of minimum areas in the DN. However, the additional use of tripping and pickup signals of OC relays, in the novel FLISR approach, can improve the reliability of fault detection and location process with respect to complex distribution network topologies. Moreover, fault isolation and service restoration of black-out areas are performed by solving an objective function with two main constraints, including: (i) restoring the maximum number of out-of-service loads; and (ii) limiting the minimum number of switching operation. Thirteen performance factors are effectively used for the ISR process, namely consisting of: (i) Power Flow Violations (PFV), (ii) Bus Voltage Violations (BVV), (iii) Total Operation Cost (TOC), (iv) Lost Power (LP), (v) Outage Customer (OC), (vi) Number of Switching Steps (NSS), (vii) Power Losses (LOSS); (viii) Customer Minutes Interruption (CMI), (ix) Load Minutes Interruption (LMI), (x) MAIFI, (xi) SAIFI, (xii) SAIDI, and (xiii) Protection Validation (PRV). The optimization of the objective function for fault isolation and service restoration is performed by determining effectively the weights of performance factors.

In general, during faults, the proposed FLISR approach analyses the minimum area of the fault; traces the current network topology; detects and locates the fault; and automatically runs power-flow studies to determine the current loading, the available capacity and possible weakness points in the DN. Then, the FLISR approach will isolate the fault and restore the maximum number of customers, with the minimum switching steps of reclosers/CBs, and feeder reconfiguration to prevent cascading overloads to the adjacent feeders. Simulation and experiment results from a real 22 kV distribution network are used to validate the FLISR approach proposed. In addition, E-Terra software of a distribution automation system is used to implement this approach. The SCADA/DMS can make data collection and transmission as well as decisions on switching operations. A decentralised control system is used to divide the distribution system into many sub-systems so that the computation time of the FLISR can be significantly reduced.

1.4. The Organisation of the Paper

The structure of the paper is organised as follows: Section 2 presents a proposed FLISR approach for smart distribution networks. This section analyses FLISR architectures of E-terra software, the operation of DN topology processor, and an algorithm diagram of the FLISR approach. Section 3 describes a real 22 kV distribution system applying the E-terra software as a case study to evaluate the effectiveness of the developed FLISR approach. Section 4 discusses simulation and experiment results of the 22 kV distribution system. Section 5 gives conclusion and emphasises significant advantages achieved from the novel FLISR approach for smart distribution networks.

2. FLISR Approach for Smart Distribution Networks Using E-Terra Software

2.1. FLISR Architectures of E-Terra Software

E-terra software contains two main FLISR architectures, namely, Centralized FLISR (C-FLISR) and De-Centralized FLISR (DC-FLISR). For the C-FLISR architecture, all real-time data are recorded at measurement and switching devices, and remote terminal units (RTUs)/gateways (GWs) which will be transmitted to Front End Servers (FEP) through IEC 60870-5-101/104 protocol, as referred to Figure 1.

The data is then transmitted from FEPs to SCADA Servers by Inter-site Data (ISD) communication protocol [51]. A distribution management system will use the data from SCADA Server to perform the FLISR algorithm. On the other hand, the RTUs/GWs are communicated to Intelligent Electronic

Devices (IEDs) through IEC 61850 protocol. In general, the C-FLISR architecture requires high-speed data communication and the enhanced stability for fault detection, location, isolation and service restoration (FLISR).

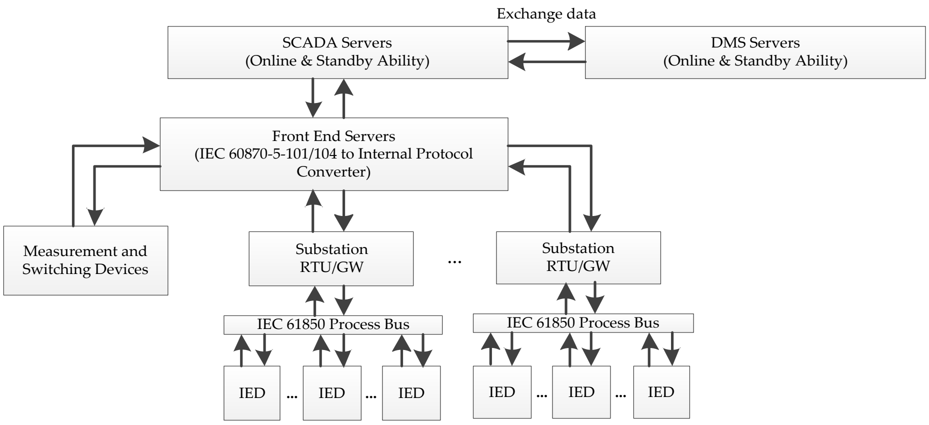

Figure 1. Centralized architecture of DMS for distribution network.

For the DC-FLISR architecture, a distribution network must be divided into different zones, referring to Figure 2. Each zone includes its individual DMS using E-terra software. Failures at one zone will not impact on other zones in the whole distribution network. As a result, the reliability of distribution network will be improved. In addition, the performance of DC-FLISR architecture requires lower bandwidth than that of the C-FLISR architecture.

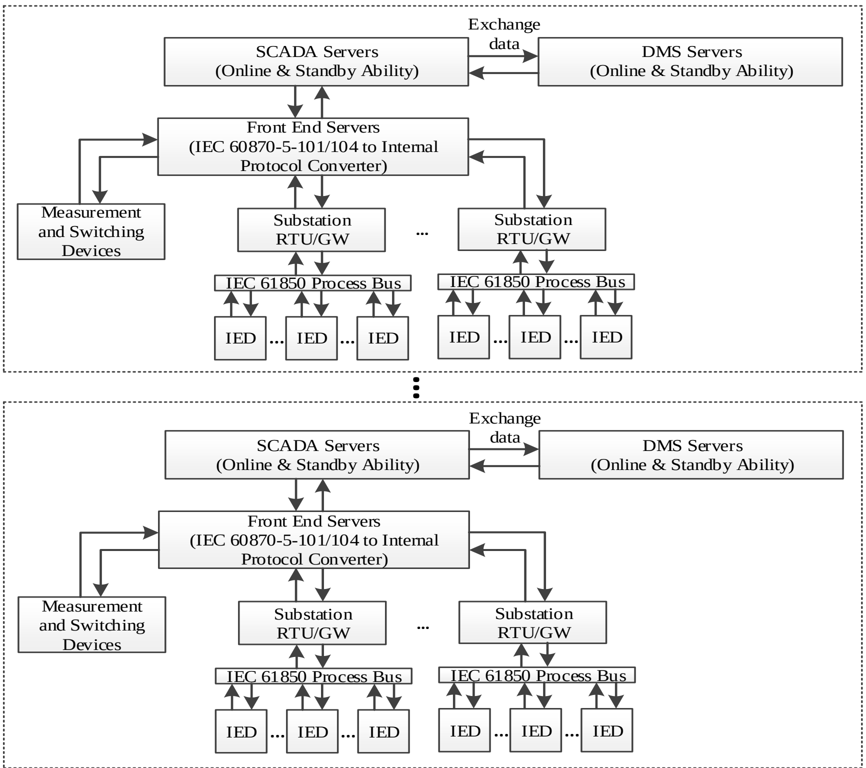

Figure 2. De-centralized architecture of DMS for distribution network.

2.2. Distribution Network Topology Processor of FLISR Architectures

A Network Topology Processor (NTP) is used to primarily determine electrical connections of a distribution system. The distribution network is generally modelled based on the database of SCADA and Geography Information System (GIS) system. Specifically, the data model shows the hierarchical views such as system–substation–feeder–equipment. These logical views are very useful for most utility distribution operators to get the necessary information in a familiar format to them. Whenever a distribution network topology is changed, the NTP will re-define which sections of the distribution network are energized. The topology changes of distribution network could be performed by controlling the operation status of switches. The NTP begins from the pre-determined and energized points (e.g., generators, sub-transmission buses) and processes through all connected electrical equipment. To clearly understand the network topology selection of the NTP, the following assumptions are made:

- System components are either electrically connected or disconnected through a point of common coupling (PCC).
- A network topology selection may contain electrically connected components that belong to different power substations in the DN.
- The NTP has two topology selection levels: Level 1—determination of network topology based on the whole substation; and Level 2—network topology selection depending on a faulted feeder and adjacent feeders.

  (i) Level 1—The whole substation is defined for network topology selection at this level. The network topology will be updated according to the database change. All components of the substation have to be included in this selection. Some components belonging to other substations that are electrically connected to the considered substation are also included in the topology selection.

  (ii) Level 2—Network topology selection starts from a faulted feeder to all its adjacent feeders, which is a specified expansion from the faulted feeder with N-tie levels. For example, the network selection searches for all neighbouring feeders that are in tie-point connections of the faulted feeder. Substations of the associated feeders, in addition, are also considered in the network selection. In general, level 2 is effectively applied for abnormal operation cases of distribution network. Table 1 summaries network selection levels using the NTP depending on different applications.

Table 1. Network topology selection levels with respect to various applications of DNs.

Topology Selection Levels	Calculations for Distribution Network
Level 1-the substation level	Periodically triggered and real-time applications, including: Distribution Power Flow (DPF) Protection Validation (PRV) Load & Voltage/VAR Management (LVM)
Level 2-N-tie Level	Fault Isolation and Service Restoration Automatic Feeder Reconfiguration (AFR) Planned Outage Request Switching Order Creation (POS)

2.3. FLISR (Fault Detection, Location, Isolation and Service Restoration) Algorithm

2.3.1. Flowchart of a Proposed FLISR Approach

A FLISR tool contains four main functions, specifically, fault detection, location, isolation and service restoration. When a fault occurs, IEDs can be able to detect the fault and send the fault information to SCADA and DMS Servers. The fault data information consists of fault currents and voltages, and the signals of FTUs. According to the received fault information, the faulted location is determined, and the FLISR tool will consider all possible scenarios for fault isolation process in the system. Then, it suggests service restoration plans based on different objective functions in priority such as the minimum amount of un-served power, the minimum number of switching operations, etc. As shown in Figure 3, the main steps of a proposed FLISR approach are as follows:

(1) Distribution power grid states are observed including loss of voltage, fault currents, fault detection signals sent from FTUs.
(2) When a bus voltage (V_{bus}) exceeds its threshold value ($V_{Threshold}$) and the measured phase and ground currents are higher than their pick-up and tripping thresholds in the OC relays, a fault is detected on the distribution network. This step identifies the existence of a fault and a faulty feeder on the DN.
(3) In order to locate faulted segments on the DN, fault alarm/pick-up signals from FTUs are used. A connection topology model of distribution network is basically formed due to fault indicators. The position of activated fault indicators in an adjacent relationship is used to locate the faulted section.
(4) After locating a faulty section, the latest 15-min data from database of the faulty feeder is analysed for the ISR process. Besides that, the FLISR tool also collects the data information on neighbouring feeders of the faulty feeder based on local measurements, and evaluates the number of customers of a power substation feeding to the faulty feeder. The usual sparse linear algebra lower-upper (LU) decomposition technique is used to calculate optimal power flows in the DN.
(5) The ISR process of black-out areas is performed by solving an objective function of

$$F = \min \sum_{i=1}^{n} w_i \times PF_i \tag{1}$$

where w_i is the weight of the ith order performance factor that is selected from 0 to infinity (∞); and n is the number of performance factors; along with two main constraints including: (i) restoring the possible maximum number of out-of-service loads and (ii) limiting the minimum number of switching operation. Thirteen performance factors which are effectively selected from E-terra platform are used for post-fault service restoration process.
(6) All possible restoration plans are ranked according to the selected performance factors.
(7) The FLISR tool proposes the switching sequence to be implemented in practice.

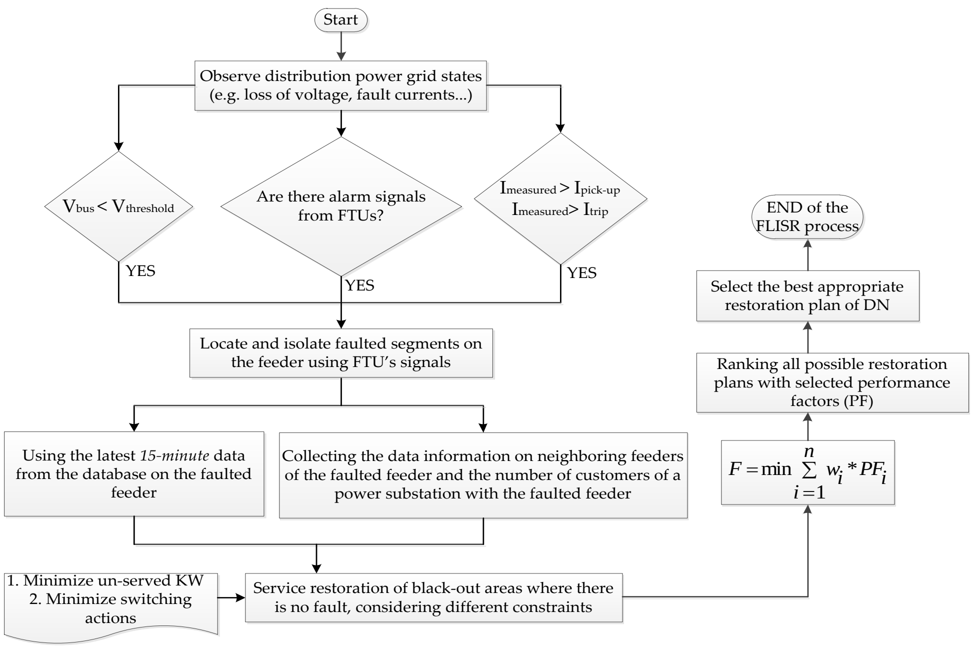

Figure 3. Flow diagram of a proposed FLISR approach for smart distribution networks.

2.3.2. Fault Detection

There are two main solutions to detect various faults by the FLISR tool, as follows: (i) combination of fault currents and loss of voltage and (ii) combination of fault indicators and loss of voltage. When protective functions of relays/reclosers are activated by the fault, fault currents and voltages are used to estimate distance from a faulted location to the feeder terminal. However, the accuracy of the distance estimation method depends on the database from the FLISR tool and complex topologies of the distribution network. Therefore, there is an alternative method that uses tripping or pick-up signals of the relays/reclosers to detect and locate the faulted section in a distribution network. These tripping or pick-up signals belong to the operating function of definite time-overcurrent (DTOC) and inverse definite minimum time-overcurrent (IDMTOC) relays.

Figure 4 shows the operating principle of overcurrent relays in a distribution network. The measured phase/neutral currents are compared to the pre-set RMS current values ($I_{threshold,\ rms}$). If the measured phase/neutral current value is larger than a threshold value, the relay/recloser continues to perform a comparison between the abnormal operation time ($t_{abnormal}$) from the fault inception time and the pre-defined fault detection time ($t_{pre\text{-}determined}$). When the time $t_{abnormal}$ exceeds the time $t_{pre\text{-}determined}$, the relays/reclosers will give a tripping signal to circuit breakers. Otherwise, they will alarm the abnormal operation of distribution network without any switching actions. It is noted that threshold current values are determined according to different load characteristics in the distribution network. When the measured phase/neutral current value exceeds the tripping threshold, different fault types can be also identified in the distribution network:

(1) Fault detection based on combination of fault currents and LoV: A faulted section is detected at a place where the measured phase current value exceeds a tripping threshold and its bus voltage value is the lowest among all bus voltage values calculated.
(2) Fault detection based on combination of FTU's signals and LoV: A flexible fault detection algorithm is proposed by using pickup signals of overcurrent relays/recloser. The use of pickup signals is to not only differentiate faults from other abnormal operation cases (e.g., switching of capacitors, power electronic switching and other excessive situations) but also figure out the miscoordination among the protective devices, as referred to Sections 2.3.3 and 2.3.4.

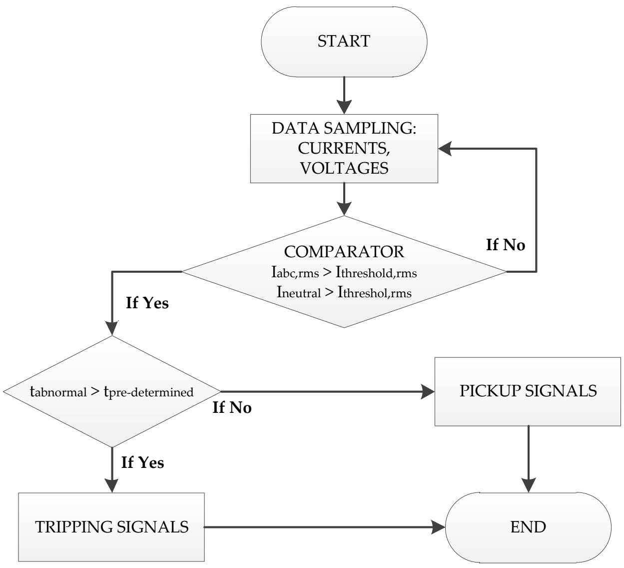

Figure 4. Operating principle of overcurrent relays/reclosers ($I_{abc,rms}$—phase currents; $I_{neutral,rms}$—neutral currents; $I_{threshold,rms}$—threshold currents; $T_{abnormal}$—the time is counted from fault inception; $T_{pre\text{-}determined}$—the defined fault detection time; Tripping signal—is given by relays/reclosers; and Pick-up signal—to give a fault alarm from a protective relay.

2.3.3. Fault Location

(1) Fault location based on fault currents and LoV: This method detects faulted sections by calculating fault impedances from a feeder terminal to places where their bus voltages are mostly lower than 80% of the rated voltage value. Positive- and zero-sequence fault impedances are calculated to determine the faulted locations according to different grounding systems of a DN.

(2) Fault location based on FTU's signals and LoV: A typical example is presented to explain the operating principle of this method. As shown in Figure 5, a circuit breaker (CB), a recloser 1 (REC1), and a recloser 2 (REC2) are placed on a feeder of a distribution network. A protection coordination algorithm among them should be taken into account through setting pickup and tripping signals of overcurrent relays.

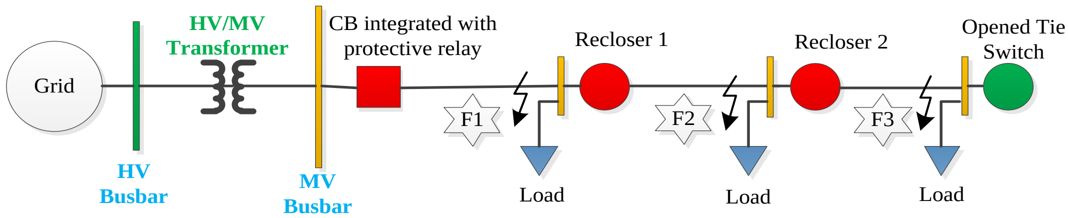

Figure 5. Single-line diagram of a typical feeder of a distribution network.

Tables 2 and 3 present the operation status of CB, REC1 and REC2 using tripping signals (TPS) and pickup signals (PUS) of overcurrent relays. The values "0" and "1" mean "Off/Opened" and "On/Closed", respectively. There are seven fault cases assumed to occur at the feeder of the distribution network. Three different fault locations are taken into account including a location F1 at between CB and REC1, a location F2 at between REC1 and REC2, and a location F3 is at the downstream side of REC2.

Table 2. The fault location method using the TPS with respect to different fault scenarios.

Fault Scenarios	Operation Status of Devices						Result of the Fault Location Method
	CB		REC1		REC2		
	TPS [1]	ST [2]	TPS	ST	TPS	ST	
Case 1–F1	1	0	0	1	0	1	Fault is at between CB and REC1
Case 2.1–F2	1	0	0	1	0	1	Fault is at between CB and REC1
Case 2.2–F2	0	1	1	0	0	1	Fault is at between REC1 and REC2
Case 2.3–F2	1	0	1	0	0	1	Fault may be occurred at: i. between CB and REC1 ii. between REC1 and REC2
Case 3.1–F3	0	1	0	1	1	0	Fault is at between REC2 and a opened tie-switch
Case 3.2–F3	0	1	1	0	0	1	Fault is at between REC1 and REC2
Case 3.3–F3	0	1	1	0	1	0	Fault may be occurred at: i. between REC1 and REC2 ii. between REC2 and a opened tie-switch

[1] The values "0" and "1" of the tripping signal (TPS) show the "Off" and "On" digital signals, respectively, sent from circuit breakers or reclosers through FTUs. [2] The values "0" and "1" of the status (ST) signal indicate the "Opened" and "Closed" statuses, respectively, for circuit breakers or reclosers.

In summary, cases 1, 2.2, and 3.1 are fault scenarios which the fault location method can correctly work, whereas faulted sections in cases 2.1, 2.3, 3.2, and 3.3 could not be effectively detected by the fault location method with the TPS, as mentioned in Table 2. In particular, cases 2.1 and 3.2 show the over-reach protection of overcurrent relays in the feeder. Besides that, the mal-operation of relays is clearly shown in cases 2.3 and 3.3. The compared results in Tables 2 and 3 demonstrate that the fault location method with the PUS is effective and flexible to recognize the over-reach problem of relays/reclosers while that with the TPS could not handle it.

Table 3. The fault location method using the PUS with respect to different fault scenarios.

Fault Scenarios	Operation Status						Result of the Fault Location Method
	CB		REC1		REC2		
	PUS [1]	ST [2]	PUS	ST	PUS	ST	
Case 1–F1	1	0	0	1	0	1	Fault is at between CB and REC1
Case 2.1–F2	1	0	1	1	0	1	Fault is at between REC1 and REC2
Case 2.2–F2	1	1	1	0	0	1	Fault is at between REC1 and REC2
Case 2.3–F2	1	0	1	0	0	1	Fault is at between REC1 and REC2
Case 3.1–F3	1	1	1	1	1	0	Fault is at between REC2 and the opened tie-switch
Case 3.2–F3	1	1	1	0	1	1	Fault is at between REC2 and the opened tie-switch
Case 3.3–F3	1	1	1	0	1	0	Fault is at between REC2 and the opened tie-switch

[1] The values "0" and "1" of the pick-up signal (PUS) show the "Off" and "On" digital signals, respectively, sent from circuit breakers or reclosers through FTUs. [2] The values "0" and "1" of the status (ST) signal indicate the "Opened" and "Closed" statuses, respectively, for circuit breakers or reclosers.

2.3.4. Fault Isolation

For a conventional distribution network (i.e., a distribution network without integration of distributed generators), the power flow is unidirectional. When a fault occurs, the nearest upstream device of the fault will be activated to eliminate high fault currents. Right after a faulted section can be detected and located in the distribution network by the FLISR tool. Finally, the nearest downstream switching device of the fault will be triggered to isolate the faulted section. Validation of this fault isolation method is indicated in Table 4 along with Figure 5.

Table 4. Fault isolation scenarios performed by the FLISR tool.

Fault Cases	Fault Isolation Schedule
Case 1–F1	CB is an upstream device of the fault while REC1 is a downstream one of the fault. CB is automatically opened, while the activation of REC1 is controlled by the FLISR tool.
Cases 2.1, 2.2, 2.3–F2	CB and REC1 are upstream devices, while the downstream one of the fault is REC2. The FLISR tool is able to identify the upstream device of the fault that is REC1 based on two fault location methods aforementioned. As a result, both REC1 and REC2 are properly operated for the fault isolation at F2
Case 3–F3	With this faulted location, all three protective devices are upstream. In order to prevent the mal-operation of CB and REC1 for isolating the location F3, the FLISR approach has used the PUS of overcurrent relays. Thus, only REC2 is opened for this fault scenario.

2.3.5. Service Restoration

Two main constraints for a service restoration process implemented by the FLISR tool are: (i) to restore the possible maximum number of out-of-service loads; and (ii) to limit the minimum number of switching operation. Thirteen performance factors (PF) are selected for Equation (1), which are given in Table 5. These performance factors are selected from the E-terra platform in order to satisfy five service restoration rules developed by the authors, which can be properly applicable to smart distribution networks.

Table 5. Performance factors used for service restoration.

No.	Performance Factors	Detailed Descriptions for Calculating PFs
1	Power Flow Violations (PFV)	$PF_{flow} = \sum_{i=1}^{m} (B_{overload,i})^2$ where m is the number of branches; if any branch is not overloaded then, $B_{overload} = 0$, otherwise $B_{overload} = P_{flow} - P_{limit}$, where P_{flow} is the calculated active power flow and P_{limit} is the maximum power capacity of the branch.
2	Bus Voltage Violations (BVV)	$PF_{voltage} = \sum_{i=1}^{n} \left(R_{voltage\_violation,i}\right)^2$ where n is the number of buses; if the calculated bus voltage is higher or lower than the rated voltage value, then $R_{voltage\_violation} = \lvert V_{calculated} - V_{limit} \rvert$, otherwise, the value $R_{voltage\_violation}$ equals zero in case of within an allowable bus-voltage threshold range.
3	Total Operation Cost (TOC)	The TOC performance factor expresses the cost of each switching operation in the service restoration plans of the FLISR tool. When the distribution network is automatically re-configured, the auto/manual switching operation cost will be included. This cost is calculated by the adjacency to the reconfigured area.
4	Lost Power (LP)	After a faulted segment is located by the fault location process, the FLISR tool will calculate a PF of the lost power by determining the outage area.
5	Outage Customer (OC)	The number of out-of-service customers can be determined according to the corresponding number of outage distribution transformers. The information of out-of-service customers is integrated with the information of distribution transformers by an Outage Management System (OMS).
6	Number of Switching Steps (NSS)	The FLISR tool counts the number of switching steps for each service restoration plan to give a fast service restoration process.
7	Power losses (LOSS)	Power losses are periodically calculated in the DN after a power flow computation algorithm gets a final iteration's result.
8	Customer Minutes Interruption (CMI)	The Customer Minutes Interruption (CMI) index is defined as the sum of interrupted minutes for all de-energized customers.
9	Load Minutes Interruption (LMI)	The Load Minutes Interruption index is calculated by: $PF_{LMI} = \sum_{i=1}^{n} (kW_i \times min_i)$ which kW is the de-energized load described in the kW unit; n is the number of customers; and min is the duration of de-energized loads considered in minutes.
10	MAIFI	The Momentary Average Interruption Frequency Index for the restoration plan is calculated for the whole distribution network.
11	SAIFI	The System Average Interruption Frequency Index for the restoration plan is calculated for the whole distribution network.
12	SAIDI	The System Average Interruption Duration Index for the restoration plan is calculated for the whole distribution network.
13	Protection Validation (PRV)	Corresponding to the topology change of distribution network, the FLISR tool will compare the existing setting parameters of overcurrent protection relays/reclosers to the re-calculated short-circuit current values. If the minimum value of re-calculated currents is higher than the existing setting parameters, the FLISR tool will send an "invalid" message. Otherwise, the existing overcurrent protection settings are still available for a new topology of the distribution network. However, it is noted that the reliability of overcurrent protection system may be reduced due to certain reasons, such as: malfunction of overcurrent relays, over/under tripping, protection mis-coordination among OC relays, etc. [52–56].

These rules are in detail as follows:

- Rule 1: An out-of-service area could be restored by closing tie-switches between a faulted feeder and its adjacent feeders. It is worth noting that the adjacent feeders belonging to the same power transformer must be non-overloaded after restoring the out-of-service loads.
- Rule 2: If a main power transformer (MPT) which serves the adjacency feeders does not have enough capacity for the restoration plan of all non-faulted segments, the amount of reserve power will be taken from back-up power transformers (BPT).
- Rule 3: If any adjacent feeder regarding the faulted feeder that is feed by the BPT exceeds its capacity limit, the reserve power of the unaffected out-of-service loads will be automatically re-distributed/re-dispatched to other feeders that are also adjacent to the faulted feeder.
- Rule 4: The FLISR tool will solve the above objective function in order to give many possible re-configuration solutions of the distribution network for supplying power to unaffected out-of-service loads based on the adjacent feeders.
- Rule 5: The FLISR tool must check an effective performance factor of PRV for each topology change in a distribution network. Calculation of the PRV performance factor is one of the important priorities in the rating of the isolation and service restoration plans.

On the other hand, the optimization of the above objective function is performed by determining effectively the weights of performance factors. Depending on practical experiences of distribution network operators, the weighting interval between the most significant PF and the least significant PF should be largely sufficient to prevent service restoration plans which contain low weights are ranked higher.

3. A Real 22 kV Distribution System Applying E-Terra Software: A Case Study

Figure 6 shows a single-line diagram of real 22 kV distribution network. The BAU DUNG power substation contains three main feeders, namely, 471 Ba Thien (blue lines), 473 Go Noi (green lines), and 475 Phu Thuan (red lines) as seen in Figure 7. A 16 MVA 110/22 kV power transformer is used in the power substation. Three main circuit breakers are installed at three terminals of all the feeders. Circle and square symbols are represented for normally opened/closed load-break-switches/reclosers and circuit breakers, respectively. A tie-switch between the 471-Ba-Thien feeder and the 475 Phu-Thuan feeder is an An-Phu-1 recloser (signed by REC An-Phu-1). The load-break-switch (LBS Bau Dung) and a recloser (REC Sa Nho) are used to configure a ring topology between the 475 Phu-Thuan feeder and the 473 Go Noi feeder. In addition, a recloser Lo 6 (REC Lo 6) and a recloser (REC Trung Binh) are normally opened reclosers. These reclosers will be closed when the BAU DUNG power substation is overloaded or has other abnormal operation situations. A CU-CHI-2 back-up power substation contains a 63 MVA 110/22 kV transformer with two main feeders, a 482 Kinh Ly feeder and the 478 Ap Tay feeder. The former feeder uses the REC Lo 6 to connect to the BAU DUNG power substation, while the latter feeder is connected to the BAU DUNG substation due to the REC Trung Binh. It is noted that all reclosers are supported by SCADA functions for remotely monitoring and controlling of switching operations. For example, when a fault occurs, the reclosers will be activated to isolate the faulted section, and right after the FLISR tool will propose all possible solutions for the best service restoration of DN based on the abovementioned objective function and constraints.

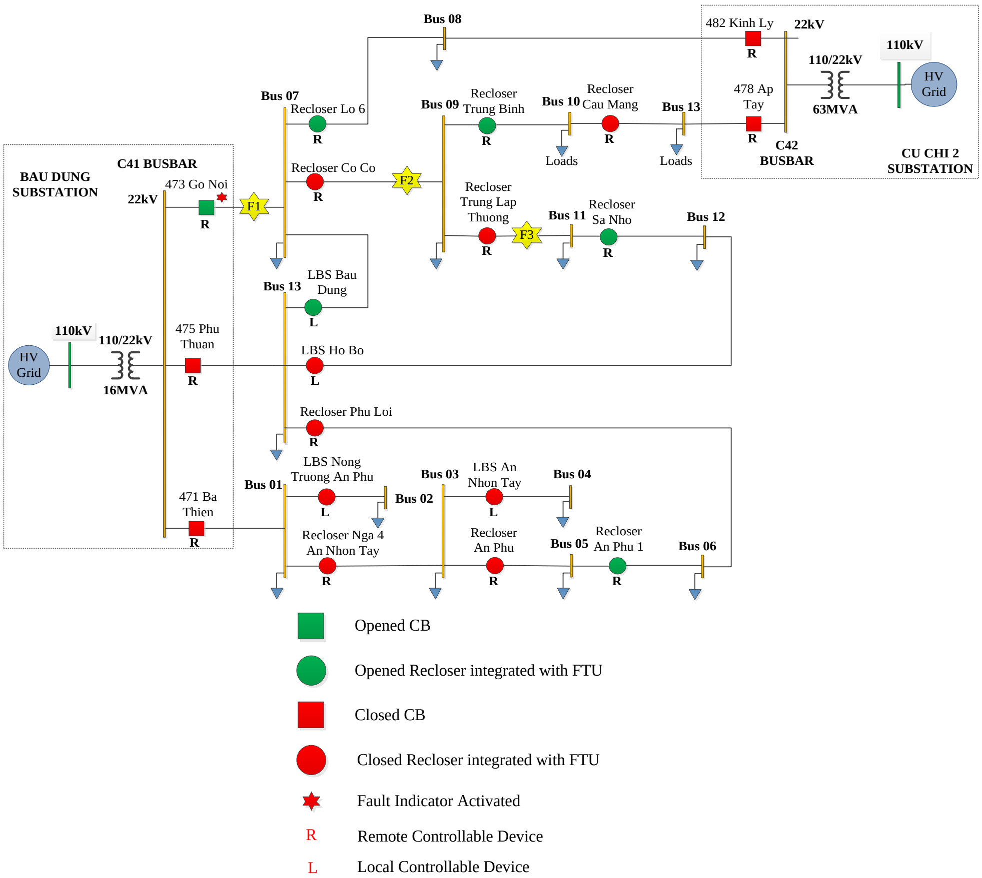

Figure 6. A single-line diagram of 22 kV distribution network with protective devices such as Reclosers, Load Break Switches, and Circuit Breakers and three different fault locations, F1, F2 and F3.

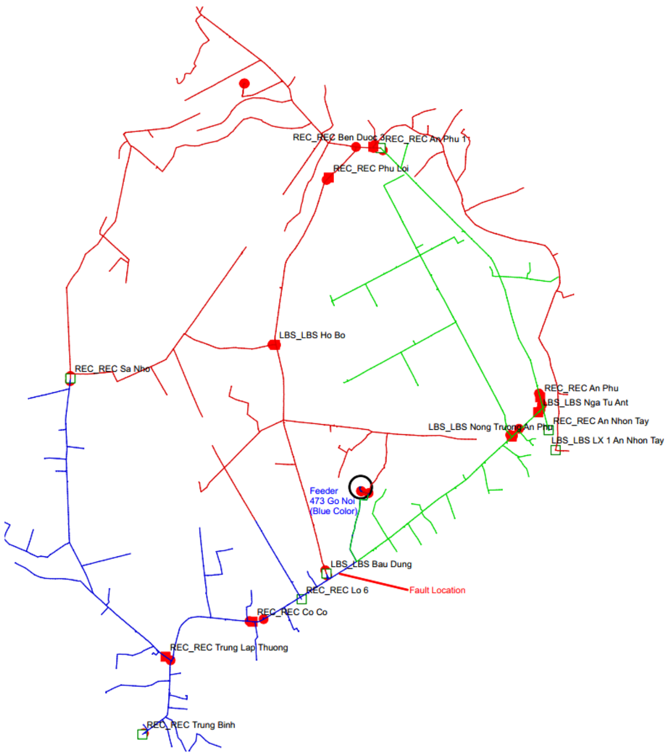

Figure 7. A geographical mapping of the BAU DUNG power substation.

Table 6 shows line parameters of the real 22 kV distribution system. Table 7 indicates transformer parameters of a real 22 kV distribution system. Tables 8 and 9 present all protection settings of overcurrent relays and reclosers in the distribution system.

Table 6. Line parameters of a real 22 kV distribution system.

From Node	To Node	Length (km)	Line Impedance	
			Positive Impedance (R_1 + jX_1) (Ω)	Zero Impedance (R_0 + jX_0) (Ω)
471 Ba Thien	Bus 01	2.292	0.0231 + 0.1547j	0.119 + 0.6564j
Bus 01	Rec Nga 4 An Nhon Tay	3.32	0.009 + 0.2516j	0.1859 + 1.0757j
Bus 01	LBS NT An Phu	3.316	0.009 + 0.2513j	0.1857 +1.0744j
LBS NT An Phu	Bus 02	5.248	0.2309 + 0.4193j	0.2939 + 1.7004j
Rec Nga 4 An Nhon Tay	Bus 03	0.701	0.0019 + 0.0531j	0.0393 + 0.2271j
Bus 03	Rec An Phu	0.0001	0.275×10^{-6} + 0.758×10^{-5}j	5.6×10^{-6} + 3.24×10^{-5}j
Bus 03	LBS An Nhon Tay	0.0001	0.275×10^{-6} + 0.758×10^{-5}j	5.6×10^{-6} + 3.24×10^{-5}j
LBS An Nhơn Tay	Bus 04	0.392	0.001078 + 0.0297j	0.0219 + 0.127j
Rec An Phu	Bus 05	5.546	0.244 + 0.4431j	0.4032 + 1.8856j
Bus 05	Rec An Phu 1	0.0001	0.44×10^{-5} + 0.799×10^{-5}j	0.727×10^{-5} + 3.4×10^{-5}j
473 Go Noi	Bus 07	0.053	0.00196 + 0.00196j	0.00196 + 0.0078j
Bus 07	Rec Co Co	3.616	0.0099 + 0.2741j	0.1857 + 1.0744j
Bus 07	Rec Lo 6	2.682	0.0074 + 0.2033j	0.1502 + 0.869j
Bus 07	LBS Bau Dung	2.065	0.0057 + 0.1565j	0.1156 + 0.6691j
Rec Co Co	Bus 09	1.92	0.0053 + 0.1455j	0.1075 + 0.6621j
Bus 09	Rec Trung Binh	1.486	0.0041 + 0.1126j	0.0832 + 0.4815j
Bus 09	Rec Trung Lap Thuong	0.0001	0.275×10^{-6} + 0.758×10^{-5}j	5.6×10^{-6} + 3.24×10^{-5}j
Rec Trung Lap Thuong	Bus 11	5.58	0.2455 + 0.4458j	0.4057 + 1.8972j
Bus 11	Rec Sa Nho	0.0001	0.44×10^{-5} + 0.799×10^{-5}j	0.727×10^{-5} + 3.4×10^{-5}j
Rec Lo 6	Bus 08	3.352	0.0092 + 0.2541j	0.1877 + 1.086j
475 Phu Thuan	Bus 13	0.123	0.0046 + 0.0046j	0.0046 + 0.0182j
Bus 13	LBS Bau Dung	5.69	0.0156 + 0.4313j	0.3186 + 1.8436j
Bus 13	LBS Ho Bo	4.246	0.0117 + 0.3218j	0.2378 + 1.3757j
Bus 13	Rec Phu Loi	7.333	0.1475 + 0.5684j	0.4631 + 2.4252j
LBS Ho Bo	Bus 12	1.636	0.1145 + 0.1358j	0.161 + 0.5819j

Table 7. Transformer parameters of a real 22 kV distribution system.

Transformers	Rated Capacity (MVA)	Connection Wiring	No-Load Losses (kW)	Losses Having Load (kW)	No-Load Current (%)	Short-Circuit Impedance (%)
BAU DUNG	16 (115/23/11 kV)	Yn/Yn0/D-11	11.34	86.4	0.17%	11.15%
CU CHI 2	63 (115/23/11 kV)	Yn/Yn0/D-11	34.25	228.7	0.14%	14.03%

Table 8. Setting of overcurrent relays in the BAU DUNG power substation (a ratio of current transformer (CT) is 800/1 and a ratio of voltage transformer (VT) is 22 kV/110 V).

Feeders	Protective Relay Settings			
	Phase Settings		Ground Settings	
	DTOC (Tripping Currents at Two Levels)	IDMTOC (Pick-Up Current—Ipickup and Time Dial—TD)	DTOC (Tripping Currents at Two Levels)	IDMTOC (Pick-Up Current—Ipickup and Time Dial—TD)
471 Ba Thien	Ilevel 2 = 6400 A – trip at 0.2 s Ilevel 1 = 4800 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 960 A time dial = 0.2	Ilevel 2 = 5600 A − trip at 0.2 s Ilevel 1 = 4000 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 160 A time dial = 0.6
473 Go Noi	Ilevel 2 = 6400 A − trip at 0.2 s Ilevel 1 = 4800 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 960 A time dial = 0.2	Ilevel 2 = 5600 A − trip at 0.2 s Ilevel 1 = 4000 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 160 A time dial = 0.6
475 Phu Thuan	Ilevel 2 = 6400 A − trip at 0.2 s Ilevel 1 = 4800 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 960 A time dial = 0.2	Ilevel 2 = 5600 A − trip at 0.2 s Ilevel 1 = 4000 A − trip at 0.25 s	IEC Very Inverse Curve Ipickup = 160 A time dial = 0.6
478 Ap Tay	Ilevel 2 = 7600 A − trip at 0.2 s Ilevel 1 = 4800 A − trip at 0.45 s	IEC Very Inverse Curve Ipickup = 960 A time dial = 0.25	Ilevel 2 = 5600 A − trip at 0.2 s Ilevel 1 = 4000 A − trip at 0.45 s	IEC Very Inverse Curve Ipickup = 160 A time dial = 0.65
482 Kinh Ly	Ilevel 2 = 7600 A − trip at 0.2 s Ilevel 1 = 4800 A − trip at 0.45 s	IEC Very Inverse Curve Ipickup = 960 A time dial = 0.25	Ilevel 2 = 5600 A − trip at 0.2 s Ilevel 1 = 4000 A − trip at 0.45 s	IEC Very Inverse Curve Ipickup = 160 A time dial = 0.65

Table 9. Recloser settings in the BAU DUNG Distribution Network (the current transformer ratio of 1000/1 and the voltage transformer ratio of 22 kV/100 V).

Reclosers	Recloser Settings			
	Phase Settings		Ground Settings	
	DTOC (Tripping Current—Itrip and Operating Time)	IDMTOC (Pick-Up Current—Ipickup and Time Dial—TD)	DTOC (Tripping Current—Itrip and Operating Time)	IDMTOC (Pick-Up Current—Ipickup and Time Dial—TD)
Co Co	Itrip = 1600 A − trip at 0.2 s	IEC Very Inverse Curve Ipickup = 500 A time dial = 0.12	Itrip = 1500 A − trip at 0.2 s	IEC Very Inverse Curve Ipickup = 70 A time dial = 0.45
Trung Lap Thuong	Itrip = 1200 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 400 A time dial = 0.05	Itrip = 800 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 60 A time dial = 0.08
Sa Nho	Itrip = 1200 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 400 A time dial = 0.05	Itrip = 800 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 60 A time dial = 0.08
Trung Binh	Itrip = 1200 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 400 A time dial = 0.05	Itrip = 800 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 60 A time dial = 0.08
Lo 6	Itrip = 1200 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 500 A time dial = 0.05	Itrip = 800 A − trip at 0.0 s	IEC Very Inverse Curve Ipickup = 70 A time dial = 0.08
Cau Mang	Itrip = 3000 A − trip at 0.21 s	IEC Very Inverse Curve Ipickup = 600 A time dial = 0.14	Itrip = 2400 A − trip at 0.21 s	IEC Very Inverse Curve Ipickup = 80 A time dial = 0.45

4. Results, Analysis and Discussion

4.1. Fault Simulation Cases and Staged Fault Tests

In this section, three different faulted locations, F1, F2 and F3 are assumed to occur in a real 22 kV distribution network, as referred to Figure 6. The location F1 is at between the C41 bus-bar and bus 7 at the 473 Go Noi feeder. The location F2 is at between bus 7 and bus 9 while the location F3 is at between bus 9 and bus 11. For each fault location, simulation and experiment results are analysed to validate the FLISR approach proposed for a smart distribution network. In more details, all fault types (e.g., single-phase to ground fault-SPGF, double-phase fault-DPF, double-phase to ground fault-DPGF, and three-phase to ground fault-TPGF) are simulated at the three locations F1, F2 and F3 to evaluate the total processing time of fault detection, location, isolation and post-fault service restoration of the distribution network. Besides that, staged fault tests are done at F1, F2 and F3, specifically, a SPGF at F1, DPGF at F2 and TPGF at F3. Table 10 shows main protection devices and the back-up power supply in case of fault scenarios at F1, F2 and F3.

Table 10. Main protection devices and the back-up power supply in case of various fault scenarios.

Faulted Feeder	Fault Locations	Main Protection Devices	Backup Power Supply
473 Go Noi	F1	Overcurrent relays 473 Go Noi	From the 478 Ap Tay feeder of a Cu Chi 2 power substation through a REC Trung Binh recloser to restore two downstream segments; or from the 475 Phu Thuan feeder through a REC Sa Nho recloser;
	F2.1, F2.2, F2.3	Co Co recloser	From the 482 Kinh Ly feeder of a Cu Chi 2 power substation through a REC Lo 6 recloser to restore the upstream segments; or from the 475 Phu Thuan feeder through a REC Sa Nho recloser to restore the downstream sections;
	F3.1, F3.2, F3.3	Trung Lap Thuong recloser	From the 478 Ap Tay feeder of a Cu Chi 2 power substation through a Trung Binh recloser to restore two upstream sections; or from the 482 Kinh Ly feeder through a REC Lo 6 recloser;

4.2. Results of Staged Fault Tests

4.2.1. Single Phase to Ground Fault (SPGF) at F1

A single phase-to-ground fault occurred on the 473 Go Noi feeder at 11:53:04 a.m. on 10 January 2018 with fault information shown in Table 11. Figure 8 shows fault current and voltage waveforms and tripping signals from ground OC relays of a 473 Go Noi circuit breaker. It is noted that setting parameters of the ground OC relays are presented in Table 8.

Table 11. Fault information with respect to a SPGF at F1 (a location on the 473 Go Noi feeder).

Parameters	Fault Information			
	Phase A	Phase B	Phase C	Ground
Fault currents	4084.6 Amp	2.3 Amp	4.0 Amp	4078.4 Amp
Fault voltages	≈1 kV	≈2 kV	≈2 kV	≈6 kV

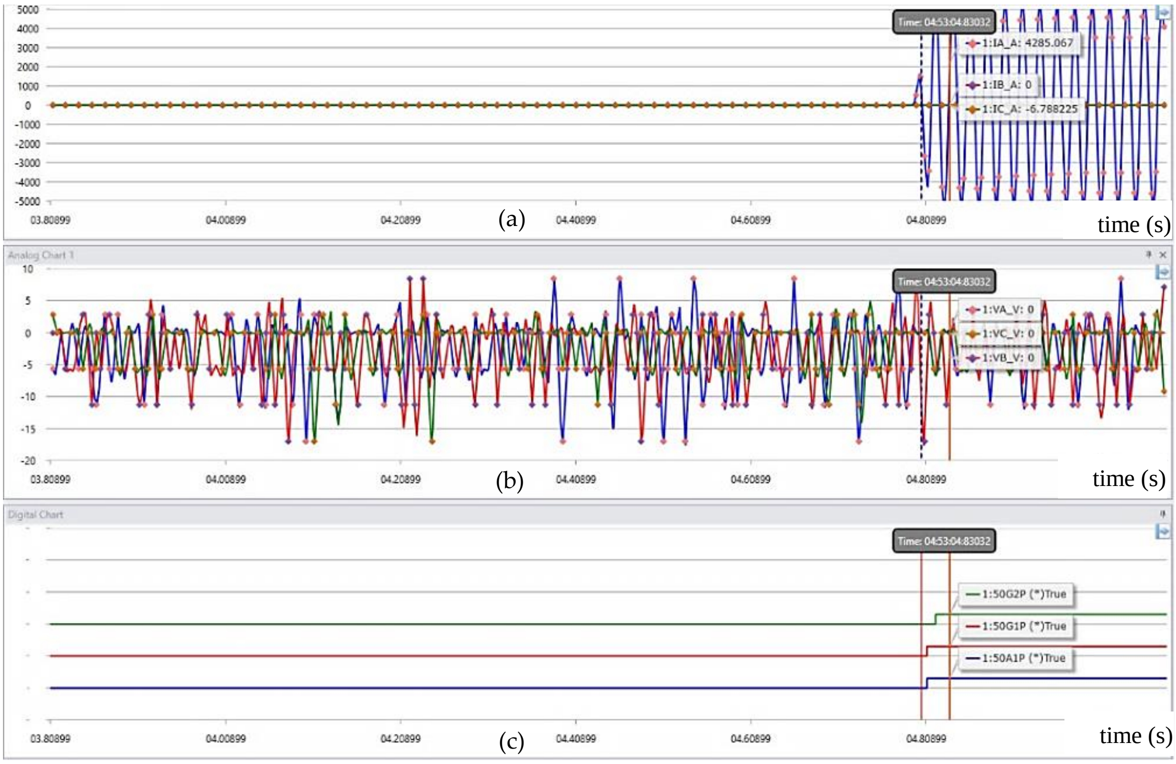

Figure 8. Fault waveforms and tripping signals corresponding to the SPGF at F1: (**a**) three phase currents (Ia (A), Ib (A), and Ic (A)); (**b**) three phase voltages (Va (V), Vb (C), and Vc (V)); (**c**) tripping signals of the ground OC relay (50G1P and 50G2P are two tripping signals of the ground OC relay at levels 1 and 2, respectively, while the 50A1P shows a faulted phase-A).

The fault F1 causes the power interruption of all customers on the 473 Go Noi feeder with the approximate power amount of 1.9 MW. This fault is detected by a ground OC relay and is then isolated by a 473 Go Noi circuit breaker. This CB is placed at the terminal of the 473 Go Noi feeder. As seen in Figure 8b, three phase voltages (VA_V, VB_C, and VC_V) are fluctuating significantly in the time domain between the 4.0th second and 4.8th second. In Figure 8a, the phase-A current increases from a load current value of 50A to an approximate fault current value of 4085 A and maintains around this value during 12.5 cycles (about 250 ms). This fault current value definitely exceeds tripping and pick-up thresholds of the phase and ground DTOC relays. Thus, the 473-Go-Noi circuit breaker receives a tripping signal that is sent by the DTOC relay in order to eliminate the high fault current within 10 cycles (about 200 ms).

For the fault location process, it is effective to use fault alarm signals from FTUs installed at both circuit breakers and reclosers. The pick-up signals of relays only exist in a few milliseconds, which could not be observed by a SCADA/DMS system. In order to solve this problem, the signals from FTUs should be hold in the pre-defined time duration. As a result, the combination of the switching operation of the 473 Go Noi CB, loss of bus voltages, and the fault alarm signal is the basic for a proposed FLISR approach to determine a faulted segment at F1. To be more clearly, it is necessary to identify the faulted area and the black-out area where there is no fault. Regarding the fault F1, a black-out area is figured out by checking the abnormally opened action of the 473 Go Noi CB and the normally closed statuses of two Co Co and Trung Lap Thuong reclosers. Due to the installation of FTUs, the faulted area at F1 is easily realised at between the upstream 473 Go Noi circuit breaker and the downstream Co Co recloser, by referring to Table 12.

Table 12. The operation status of the OC relay and reclosers with respect to the fault F1.

Operation Status of the OC Relay and Reclosers								
473 Go Noi CB			**REC Co Co**			**REC Trung Lap Thuong**		
PUS	ST	LoV	PUS	ST	LoV	PUS	ST	LoV
On	Open	Yes	Off	Close	Yes	Off	Close	Yes

Right after a faulted location F1 is detected, the FLISR tool will run two isolation and service restoration algorithms at the same time. The detailed results are shown in Tables 13 and 14 to validate the proposed FLISR approach for the DN. The total processing time to give all possible isolation and service restoration schemes is about 2 min. The time of data collection and validation occupies approximately 98% of the total time. This implies that the reliability of proposed FLISR approach significantly depends on data accuracy and communication channels of SCADA/DMS system. On the other hand, placement of remote controlled devices on the DN also plays an important role to support the FLISR approach for making more exactly isolation and service restoration plans. As seen in Table 14, performance factors of NSS, TOC, LP, OC and PRV remarkably impact to the ranking of all isolation and restoration plans. The lowest performance factor is, the highest ranked the isolation and restoration plan will be. In Table 13, the maximum and minimum device voltages (%) and the maximum segment loading (%) are within the allowable limit values, so two PFV and BVV PFs are zero as indicated in Table 14. Moreover, the third ranked ISR plan in Table 13 has more the switching steps than the two others (e.g., 4 switching steps compared to two switching steps). Thus, the first ranked ISR plan is the most adaptable one to two main constraints as mentioned in Section 2.3.4. In detail, the restored power amount is about 1.38 MW, i.e., approximately 81% out-of-service customers.

4.2.2. Double-Phase to Ground Fault (DPGF) at F2

A double-phase-to-ground fault occurred on the 473 Go Noi feeder at 10:21:05 p.m. on 14 April 2018 with fault information shown in Table 15. Figure 9 shows fault current and voltage waveforms and tripping signals from phase and ground OC relays of a Co-Co recloser. It is noted that setting parameters of the phase and ground OC relays are presented in Table 9. The fault F2 causes power interruption of 81% customers on the 473 Go Noi feeder, with an approximate power amount of 0.923 MW. This fault is detected by phase and ground OC protection functions and is then isolated by a Co-Co recloser. The Co-Co recloser is placed behind a circuit breaker of the 473 Go-Noi feeder from bus 7 to bus 9. As seen in Figure 9b, three phase voltages (VA_V, VB_C, and VC_V) are significantly fluctuated at between the 3.125th cycle and the 5.75th cycle. In Figure 9a, two phase-A and phase-B currents increase from a load-current value to a fault-current value of approximately 6.3 kA. The current value maintains during 1.5 cycles (about 30 ms). Moreover, this fault current value definitely exceeds tripping and pick-up thresholds of phase and ground OC protective relays. Consequently, the Co-Co recloser is fast activated to eliminate high fault current within 3.75 cycles (about 75 ms) on the 473 Go Noi feeder.

By referring to Table 16, due to the installation of FTUs, a faulted area at F2 is accurately located at between an upstream Co-Co recloser and a downstream Trung-Lap-Thuong recloser of the fault. When the fault F2 is detected and located, the FLISR tool will run two fault isolation and service restoration algorithms at the same time. The detailed results are shown in Tables 17 and 18 to validate the proposed FLISR approach for the distribution network.

Table 13. Possible fault isolation and service restoration plans based on two proposed constraints (with the SPGF at F1).

Rank	Switching Operation	Distribution Power Grid States						Total Performance Factor	
		No. of Restored Customers	No. of Non-Restored Customers	Un-Served Power (kW)	Maximum Segment Loading (%)	Maximum Device Voltage (%)	Minimum Device Voltage (%)	Minimum Amount of Un-Served Power	Minimum Number of Switching Operations
1	• Step 1: Open a Co Co REC to isolate the fault • Step 2: Close a Sa Nho REC to restore downstream out-of-service loads through an adjacent 475 Phu Thuan feeder of the BAU DUNG power substation	4720	1049	525.33	82.7	100.22	97.15	1841.47	3821.46
2	• Step 1: Open a Co Co REC to isolate the fault • Step 2: Close a Trung Binh REC to restore downstream out-of-service loads through the adjacent 478 Ap Tay feeder of the CU CHI 2 back-up power substation	4720	1049	525.33	80.7	100.46	98.9	4066.39	6038.84
3	• Step 1: Open a Trung Lap Thuong REC • Step 2: Close a Sa Nho REC to restore some downstream loads through the adjacent 475 Phu Thuan feeder • Step 3: Open a Co Co REC • Step 4: Close a Trung Binh REC to restore other downstream out-of-service loads through the adjacent 478 Ap Tay feeder of the CU CHI 2 back-up power substation	4720	1049	525.33	77.4	100.31	97.36	4333.53	8286.07

Table 14. Performance factors (PF) of the FLISR approach with respect to SPGF at F1.

Isolation and Service Restoration Plans	NSS PF	TOC PF	PFV PF	BVV PF	LP PF	LOS PF	OC PF	PRV PF	CMI PF	LMI PF	MAIFI PF	SAIFI PF	SAIDI PF	Total PF
The firstly ranked plan is based on the minimum amount of un-served power.	20	2	0	0	525.33	0	1049	245.14	0	0	0	0	0	1841.47
The secondly ranked plan is based on the minimum amount of un-served power.	20	2	0	0	525.33	0	1049	2470.06	0	0	0	0	0	4066.39
The thirdly ranked plan is based on the minimum amount of un-served power.	40	4	0	0	525.33	0	1049	2715.2	0	0	0	0	0	4333.53

Table 15. Fault information at F2 on the 473 Go-Noi feeder.

Parameters	Fault Information			
	Phase A	**Phase B**	**Phase C**	**Ground Current**
Fault currents	≈6.3 kA	≈6.2 kA	≈20.0 Amp	≈2.5 kA
Fault voltages	≈11 kV	≈6 kV	≈17 kV	Non-measured

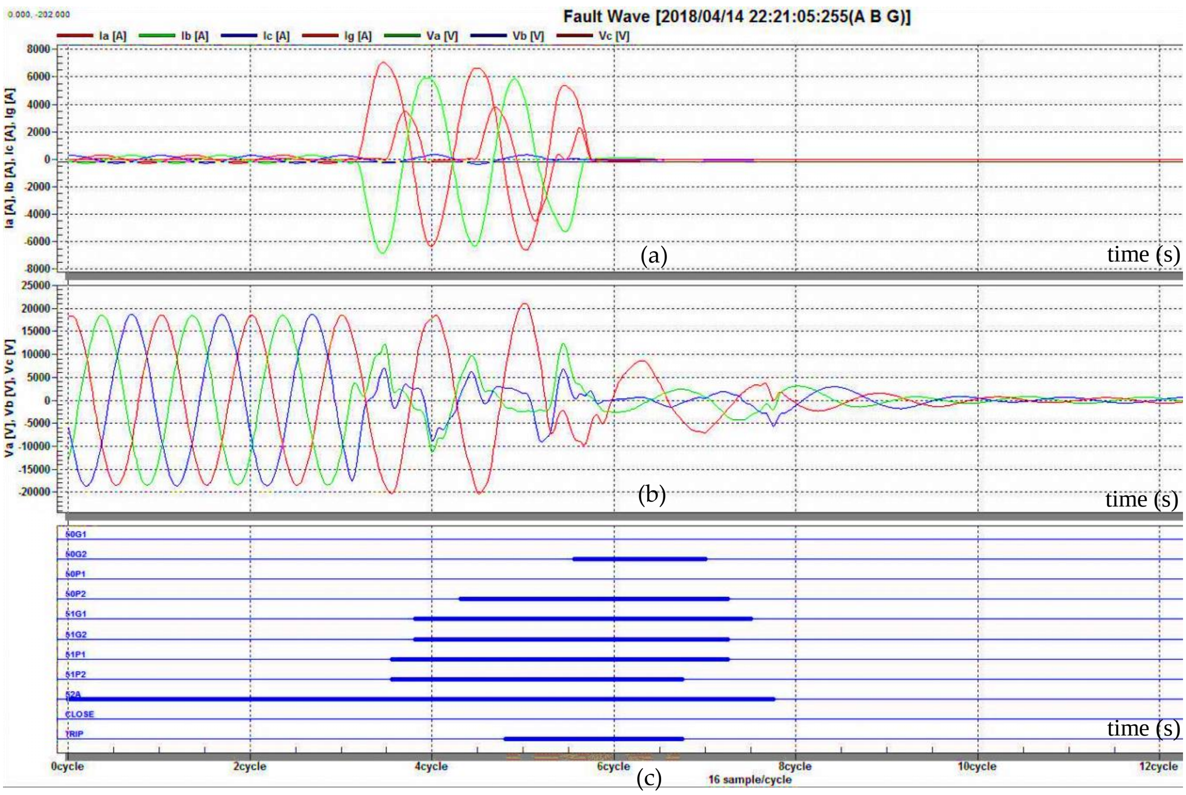

Figure 9. DPGF waveforms at the 473 Go-Noi feeder: (**a**) three phase currents Ia (A), Ib (A), Ic (A) and ground current Ig (A); (**b**) three phase voltages (Va (V),Vb (V), and Vc (V)); (**c**) tripping signals of the Co-Co recloser (51P1, 51P2, 50P2 are phase tripping signals; 50G2, 51G1, 51G2 are ground tripping signals; 52A shows a closed status of the recloser; and a TRIP signal shows the tripping action performed by the recloser).

Table 16. The operation status of the OC relays and reclosers with respect to the fault F2.

Operation Status of the OC Relays and Reclosers								
473 Go Noi CB			**Co Co REC**			**Trung-Lap-Thuong REC**		
PUS	ST	LoV	PUS	ST	LoV	PUS	ST	LoV
On	Close	No	On	Open	Yes	Off	Close	Yes

Table 17. Possible isolation and service restoration (ISR) plans based on two proposed constraints (with the DPGF at F2).

Rank	Switching Operation	Distribution Power Grid States						Total Performance Factor	
		No. of Restored Customers	No. of Non-Restored Customers	Un-Served Power (kW)	Maximum Segment Loading (%)	Maximum Device Voltage (%)	Minimum Device Voltage (%)	Minimum Amount of Un-Served power	Minimum Number of Switching Operations
1	• Step 1: Open a Trung-Lap-Thuong REC to isolate the fault • Step 2: Close a Sa-Nho REC to restore downstream out-of-service loads through an 475 Phu-Thuan adjacent feeder of the BAU DUNG power substation	2467	2253	647.57	57.4	100.24	97.42	3626.96	5606.86

Table 18. Performance factors (PF) of the FLISR approach with respect to a DPGF at F2.

Isolation and Service Restoration Plans	NSS PF	TOC PF	PFV PF	BVV PF	LP PF	LOS PF	OC PF	PRV PF	CMI PF	LMI PF	MAIFI PF	SAIFI PF	SAIDI PF	Total PF
The ranked plan is based on the minimum amount of un-served power.	20	2	0	0	647.47	0	2467	490.39	0	0	0	0	0	3626.96

4.2.3. Three-Phase to Ground Fault (TPGF) at F3

A three phase-to-ground fault occurred on the 473 Go Noi feeder at 10:01:58 a.m. on 6 July 2017 with fault information shown in Table 19. Figure 10 shows fault current and voltage waveforms and tripping signals from phase and ground OC protective functions of a Trung-Lap-Thuong recloser. It is noted that setting parameters of the phase and ground OC relays are presented in Table 9. The fault F3 causes power interruption of 48% customers on the 473 Go-Noi feeder, with the approximate power amount of 0.286 MW. This fault is detected by phase and ground OC protective functions and is then isolated by a Trung Lap Thuong recloser. This recloser is placed after the Co Co recloser between bus 9 and bus 11. As seen in Figure 10b, three phase voltages (VA_V, VB_V, and VC_V) are slightly fluctuated at the time domain from 4th cycle from 15th cycle. In Figure 10a, the phase-A, phase-B and phase-C currents increase from their load-current values to a fault current value of about 1.7 kA. This fault current value maintains during 11 cycles (about 220 ms), which exceeds tripping and pick-up thresholds of the phase and ground OC relays. Consequently, the Trung-Lap-Thuong recloser is quickly activated to eliminate high fault current on the 473 Go Noi feeder. Due to the installation of FTUs, a faulted area at F3 is detected and located at between an upstream Trung-Lap-Thuong recloser and a downstream Sa-Nho recloser, by referring to Table 20. There are no any proposed service restoration plans because a faulted segment is at the end of 473 Go Noi feeder.

Table 19. Information of fault corresponding to the three phase to ground fault F3 at 473 Go Noi feeder.

Parameters	Fault Information			
	Phase A	**Phase B**	**Phase C**	**Ground Current**
Fault currents	≈1.5 kA	≈1.7 kA	≈2.0 kA	≈0.5 kA
Fault voltages	≈17 kV	≈16 kV	≈16 kV	Non-measured

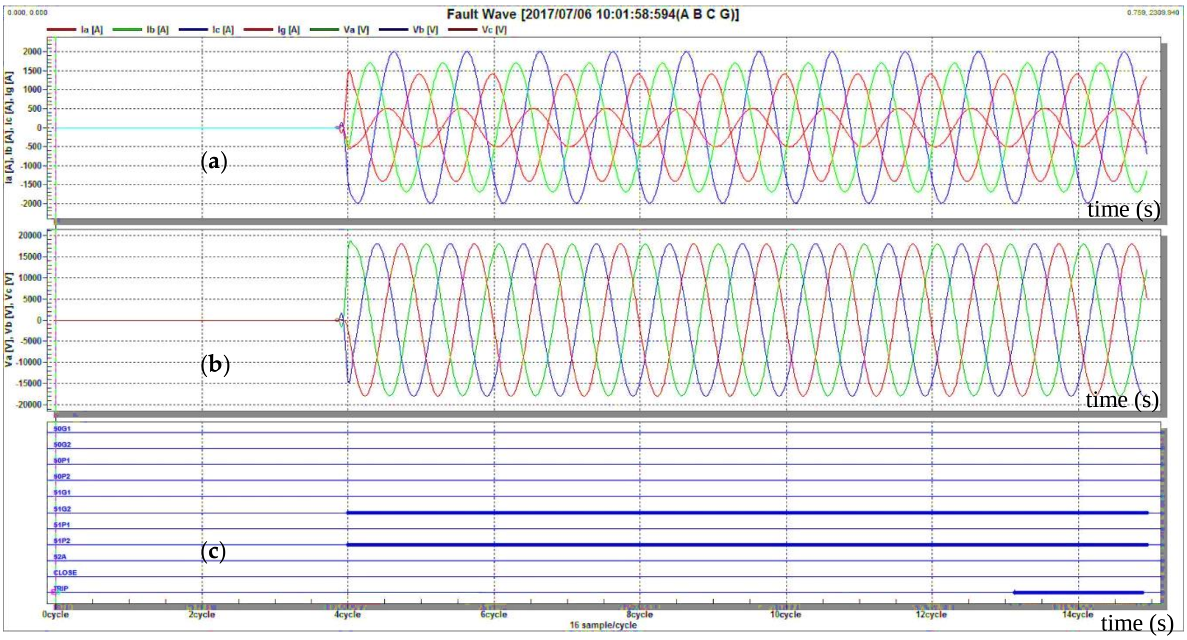

Figure 10. Fault waveforms corresponding to a TPGF at F3: (**a**) three phase currents, Ia (A), Ib (A), Ic (A), and a ground current Ig (A)); (**b**) three phase voltages, Va (V), Vb (V), and Vc (V); (**c**) tripping signals of the Co-Co recloser (51P2 and 51G2 are respectively phase and ground tripping signals; a TRIP signal shows the tripping action implemented by the recloser).

Table 20. The operation status of overcurrent relays and reclosers with a TPGF at F3.

Operation Status of the OC Relays and Reclosers								
473 Go Noi CB			REC Co Co			REC Trung Lap Thuong		
PUS	ST	LoV	PUS	ST	LoV	PUS	ST	LoV
On	Close	No	On	Close	No	On	Open	Yes

4.3. Fault Simulation Results

Simulation results of the proposed FLISR approach for a 22 kV distribution system are shown in Tables 21 and 22. Table 21 shows the operation status of OC relays and reclosers with respect to seven different simulation scenarios (F1, F2.1, F2.2, F2.3, F3.1, F3.2, and F3.3). Table 22 depicts the number of switching steps as well as the useful information of every proposed ISR plan (e.g., the number of restored customers, the number of non-restored customers, un-served kW, maximum segment loading (%), maximum device voltage (%), and minimum device voltage (%)) in order to satisfy two constraints (including the possible maximum number of restored out-of-service loads and the minimum number of switching operation) for all fault simulation scenarios.

As seen in Table 22b,c, with respect to two fault cases F2.1 and F3.2, the proposed FLISR approach can be able to identify the over-reaching of OC relays. With two fault cases F2.3 and F3.3, the FLISR approach has no isolation and service restoration plans. A main reason is that the fault cases F2.3 and F3.3 cause the mal-operation of OC relays and reclosers which are adjacently placed on the 22 kV distribution system. The other reason is that faults may occur at two adjacent segments at the same time. The FLISR approach can consider non-SCADA switching devices (e.g., load break switches, dis-connectors) to minimise an out-of-service area, however, the opened/closed operation of non-SCADA devices may be time-consuming.

For different fault scenarios (e.g., F1, F2.1, F2.2), all possible isolation and service restoration plans are ranked in priority of restoring downstream out-of-service loads. For example, a normally opened Sa-Nho recloser is selected to firstly close for restoring downstream segments of the faults F1, F2.1, or F2.2. Moreover, the FLISR approach firstly finds the adjacently healthy feeders in a main power substation (e.g., the BAU-DUNG power substation) before considering the backup power substation (e.g., the CU-CHI-2 power substation). In other words, selection of the adjacent feeders from the same power substation is the next priority factor for ranking the possible isolation and service restoration plans proposed by the FLISR approach.

Last but not least, Tables 23–25 show performance factors for each ISR plan at F1, F2 and F3, respectively. In Table 23, three possible isolation and service restoration plans are proposed when considering constraints of the minimum number of switching operation or the minimum un-served power. Among these three ISR plans, the smallest PRV PF belongs to the 1st ranked ISR plan, which indicates the lowest risk of protection mis-coordination in comparison with the other plans. In Table 24, two possible isolation and service restoration plans are proposed for each fault scenario F2.1 or F2.2, while there is no any isolation and service restoration plan for a fault scenario F2.3. In Table 25, the FLISR approach does not give any plan for F3.1 and F3.3, while there are two ISR plans for a fault scenario F3.2.

Table 21. The operation status of OC relays and reclosers for all seven different simulation scenarios.

Operation Status									Fault Location Detected by the FLISR Approach	Fault Scenarios
473 Go Noi CB			Co Co REC			Trung Lap Thuong REC				
PUS	ST	LoV	PUS	ST	LoV	PUS	ST	LoV		
On	Open	Yes	Off	Close	Yes	Off	Close	Yes	At a feeder segment between the 473 Go Noi CB and the Co Co REC	F1
On	Open	Yes	On	Close	Yes	Off	Close	Yes	At a feeder segment between the Co Co REC and the Trung Lap Thuong REC	F2.1
On	Close	No	On	Open	Yes	Off	Close	Yes	At a feeder segment between the Co Co REC and the Trung Lap Thuong REC	F2.2
On	Open	Yes	On	Open	Yes	Off	Close	Yes	A fault location may be at one of two segments, as follows: (i) between a 473 Go Noi CB and a Co Co REC (ii) between a Co Co REC and a Trung Lap Thuong REC	F2.3
On	Close	No	On	Close	No	On	Open	Yes	At a feeder segment between a Trung Lap Thuong REC and a Sa Nho REC	F3.1
On	Close	No	On	Open	Yes	On	Close	Yes	At a feeder segment between a Trung Lap Thuong REC and a Sa Nho REC	F3.2
On	Close	No	On	Open	Yes	On	Open	Yes	A fault location may be at one of two segments, as follows: (i) a Co Co REC and a Trung Lap Thuong REC (ii) a Trung Lap Thuong REC and a Sa Nho REC	F3.3

Table 22. (**a**) The number of switching steps and all possibly ranked ISR plans with respect to faults at F1. (**b**). The number of switching steps and all possibly ranked ISR plans with respect to fault cases at F2. (**c**) The number of switching steps and all possibly ranked ISR plans with respect to fault cases at F3.

(a)

Rank	Switching Operation of Each ISR Plan	No. of Restored Customers	No. of Non-Restored Customers	Un-Served Power (kW)	Maximum Segment Loading (%)	Maximum Device Voltage (%)	Minimum Device Voltage (%)	Total Performance Factor (PF): Minimum Unserved Power Constraint	Total Performance Factor (PF): Minimum Number of Switching Operations Constraint
1	• Step 1: Open a Co-Co REC to isolate a faulted section • Step 2: Close the Sa-Nho REC to restore out-of-service downstream loads that will be supplied by the 475 Phu Thuan adjacent feeder of the BAU-DUNG substation	4720	1049	525.33	82.7	100.22	97.15	1841.47	3821.46
2	• Step 1: Open a Co-Co REC to isolate a faulted segment • Step 2: Close a Trung-Binh REC to restore out-of-service downstream loads by using the 478 Ap Tay adjacent feeder of the CU-CHI-2 back-up substation	4720	1049	525.33	80.7	100.46	98.9	4066.39	6038.84
3	• Step 1: Open a Trung-Lap-Thuong REC to isolate the fault • Step 2: Close the Sa-Nho REC to restore some of out-of-service loads due to the 475 Phu-Thuan adjacent feeder • Step 3: Open the Co-Co REC to isolate the fault • Step 4: Close the Trung-Binh REC to restore other out-of-service downstream loads using the 478 Ap-Tay adjacent feeder of the CU-CHI-2 back-up substation	4720	1049	525.33	77.4	100.31	97.36	4333.53	8286.07

(b)

Fault Cases	Switching Operation of Each ISR Plan	No. of Restored Customers	No. of Non-Restored Customers	Un-Served Power (kW)	Maximum Segment Loading (%)	Maximum Device Voltage (%)	Minimum Device Voltage (%)	Total Performance Factor (PF): Minimum Un-Served Power Constraint	Total Performance Factor (PF): Minimum Number of Switching Operations Constraint
F2.1	• Step 1: Open the Trung-Lap-Thuong REC • Step 2: Close the Sa-Nho REC to restore a part of out-of-service loads based on the 475 Phu Thuan adjacent feeder. A fault location is determined at between the Trung Lap Thuong REC and the Sa Nho REC • Step 3: Open the Co Co REC • Step 4: Close the 473 Go Noi CB to restore power from the feeder terminal to the Co Co REC	3302	2467	647.57	57.5	100.24	97.42	3402.96	7362.96
F2.2	• Step 1: Open the Trung-Lap-Thuong REC • Step 2: Close the Sa-Nho REC to restore downstream out-of-service loads by taking power from the 475 Phu-Thuan adjacent feeder of the BAU DUNG power substation	2467	2253	647.57	57.4	100.24	97.42	3626.96	5606.86
F2.3	No Plan								

Table 22. *Cont.*

(c)									
								Total Performance Factor (PF)	
Fault Cases	Switching Operation of Each ISR Plan	No. of Restored Customers	No. of Non-Restored Customers	Un-Served Power (kW)	Maximum Segment Loading (%)	Maximum Device Voltage (%)	Minimum Device Voltage (%)	Minimun Minimum Un-Served Power Cosntraint	Minimum Un-Served Power Constraint
F3.1	No Plan								
F3.2	• Step 1: Open a Trung-Lap-Thuong REC to isolate the fault • Step 2: Close the Co-Co REC to restore power for the segment from the Co-Co REC to the Trung-Lap-Thuong REC	2467	2253	879.22	56.2	100.45	99.46	3398.86	5398.86
F3.3	No Plan								

Table 23. Performance factors for each ISR plan at F1.

Isolation and Service Restoration Plans (ISR Plans)	Total PF	NSS PF	TOC PF	PFV PF	BVV PF	LP PF	LOS PF	OC PF	PRV PF	CMI PF	LMI PF	MAIFI PF	SAIFI PF	SAIDI PF
Considering the minimum number of switching operation														
The 1st ISR plan	3821.46	2000	2	0	0	525.33	0	1049	245.03	0	0	0	0	0
The 2nd ISR plan	6038.84	2000	2	0	0	525.33	0	1049	2462.40	0	0	0	0	0
The 3rd ISR plan	8286.07	4000	4	0	0	525.33	0	1049	2707.43	0	0	0	0	0
Considering the minimum un-served power														
The 1st ISR plan	1841.47	20	2	0	0	525.33	0	1049	245.14	0	0	0	0	0
The 2nd ISR plan	4066.39	20	2	0	0	525.33	0	1049	2470.06	0	0	0	0	0
The 3rd ISR plan	4333.53	40	4	0	0	525.33	0	1049	2715.2	0	0	0	0	0

Table 24. Performance factors for each ISR plan at F2.

Faults	Isolation and Service Restoration Plans	Total PF	NSS PF	TOC PF	PFV PF	BVV PF	LP PF	LOS PF	OC PF	PRV PF	CMI PF	LMI PF	MAIFI PF	SAIFI PF	SAIDI PF
F2.1	An ISR plan is proposed, based on the "minimum number of switching operation"	7362.96	4000	3.25	0	0	647.57	0	2467	245.14	0	0	0	0	0
	An ISR plan is proposed, based on the "minimum unserved power"	3402.96	40	3.25	0	0	647.57	0	2467	245.14	0	0	0	0	0
F2.2	An ISR plan is proposed, based on the "minimum number of switching operation"	5606.86	2000	2	0	0	647.47	0	2467	490.39	0	0	0	0	0
	An ISR plan is proposed, based on the "minimum unserved power"	3626.96	20	2	0	0	647.47	0	2467	490.39	0	0	0	0	0
F2.3	No Plan														

Table 25. Performance factors for each ISR plan at F3.

Faults	Isolation and Service Restoration Plans	Total PF	NSS PF	TOC PF	PFV PF	BVV PF	LP PF	LOS PF	OC PF	PRV PF	CMI PF	LMI PF	MAIFI PF	SAIFI PF	SAIDI PF
F3.1	No Plan														
F3.2	An ISR plan is proposed, based on the "minimum number of switching operation"	5398.86	2000	1.5	0	0	879.22	0	2253	245.14	0	0	0	0	0
	An ISR plan is proposed, based on the "minimum unserved power"	3398.86	20	1.5	0	0	879.22	0	2253	245.14	0	0	0	0	0
F3.3	No Plan														

5. Conclusions

This paper has developed a novel FLISR approach for smart distribution networks, which uses signals from FTUs in combination with distribution grid states to quickly detect and accurately locate faulted segments in the distribution network. Specifically, the authors have used a combination of FTU's pick-up and tripping signals and the loss of voltage (LoV) for both fault detection and location. Right after a faulted section is determined, the nearest upstream and downstream switching devices will be triggered to isolate the faulted section. In various fault scenarios, all possible isolation and service restoration plans are ranked in priority of restoring out-of-service loads. Moreover, the FLISR approach finds the adjacently healthy feeders in a main power substation before considering the backup power substation. The paper also analyses three staged fault tests and seven different fault simulation cases from a real 22 kV distribution network to highlight advantages of the proposed FLISR approach, such as: (i) identifying the over-reaching of OC relays; (ii) warning mis-coordination of adjacent protection devices through a PRV performance factor; (iii) implementing fault isolation and service restoration process by solving an objective function with two main constraints (the maximum number of out-of-service loads and the minimum number of switching operation) and thirteen performance factors; and (iv) having the total processing time of fault detection, location and isolation as well as ranking all possible service restoration plans at less than two minutes.

This paper only considers the proposed FLISR approach for distribution networks without penetration of distributed generators (DGs). New distribution network topologies with integration of DGs may lead to certain difficulties on the proposed FLISR approach, such as bi-directional power flows, contribution of DG short-circuit currents, mis-coordination of protective relays and reclosers, over/under tripping of OC relays, etc. In currently operational policies, DG units are automatically disconnected when any fault occurs in a distribution network [17,57]. Disconnection of the DG units is to eliminate their effects on fault currents to a traditional protection system of distribution networks. However, the automatic disconnection of DG units during faults reduces reliability of the distribution power supply and increases difficulty of fault isolation and service restoration plans. Therefore, the proposed FLISR approach should be expanded to be adaptable to high penetration of various DG types (e.g., rotating-based DGs and inverter-based DGs) into the distribution network in future.

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