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Advanced FLISR With Intentional Islanding Operations in an ADMS Environment Using GridAPPS-D

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ABSTRACT An advanced distribution management system (ADMS) is a software platform that supports grid management and decision support applications to address the growing operational challenges faced by power distribution systems to ensure reliable, resilient, and economic operations. In this paper, a fault location, isolation, and restoration (FLISR) application is developed and integrated with an open-source standards-based platform for ADMS application development viz. GridAPPS-D, developed by Pacific Northwest National Laboratory (PNNL). Also, a new distribution system restoration (DSR) algorithm, an integral part of the FLISR application, is proposed that utilizes backup feeders and distributed generators (along with intentional islanding features) to restore critical loads. The proposed application is developed in python and is tested on a modified IEEE 8500-node test system using the GridAPPS-D platform. The successful deployment of the FLISR application on the GridAPPS-D platform provides a proof-of-concept for the adoption of new and advanced ADMS applications to support future power distribution systems.

INDEX TERMS Distributed power generation, fault location, power distribution, power distribution faults, power system restoration.

NOMENCLATURE

Acronyms

ADMS	Advanced Distribution Management System
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
CIS	Customer Information System
CI	Customer Interrupted
DER	Distributed Energy Resource
DSR	Distribution System Restoration
FLB	Feeder Load Balancing
FLISR	Fault Location, Isolation and Service Restoration
GIS	Geographical Information System
IVR	Interactive Voice Response
MEMS	Micro-grid Energy Management System
OMS	Outage Management System
VVC	Volt/VAR Control

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Sets, Variables, and Parameters

τ	Directed edge in a tree $\mathcal{T}$
$\mathcal{G}$	Distribution network represented as a graph
$\mathcal{W}_v$	List of all possible paths from $\mathcal{S}$ to a node v
Ω_S	List of protective devices operated after faults
$\mathcal{T}_t$	Operating tree at given time step t
τ^p, τ^c	Parent and child node of edge τ corresponding to $\mathcal{T}_t$
$\mathcal{V}_S$	Set of buses with controllable loads
$\mathcal{E}_v$	Set of DER switches
$\mathcal{E}$	Set of distribution lines
$\mathcal{F}$	Set of nodes to pinpoint fault location corresponding to Ω_S
$\mathcal{E}_S^s$	Set of normally-closed sectionalizing switches
$\mathcal{E}_S^t$	Set of normally-open tie switches
$\mathcal{V}$	Set of physical buses
$\mathcal{I}_S$	Set of switches to operate for fault isolation as a response to Ω_S
$\mathcal{E}_S$	Set of switchable lines. i.e. $\mathcal{E}_S^s \cup \mathcal{E}_S^t$
$\mathcal{S}$	Substation bus or root node of $\mathcal{G}$
e	Undirected edge in a graph $\mathcal{G}$

I. INTRODUCTION

The electric power distribution system is mired with unprecedented challenges due to an increase in severe weather events leading to prolonged outages, stricter regulatory requirements for increased reliability and resilience levels, and growing penetrations of distributed energy resources (DERs) [1]. This motivates the need for a sophisticated operational platform that can support advanced applications to manage distribution systems operations, especially during stressed conditions. Addressing this need led to the recent advances in advanced distribution management systems (ADMS), and the development of new applications to ensure reliable, resilient, and economic distribution grid operations. One such critical application is Fault Location, Isolation, and Service Restoration (FLISR), that is currently being adopted by the majority of utility companies and made available by most ADMS vendors [2], [3]. With the integration of DERs, microgrids, and smart switches that can be used to reconfigure and intentionally island parts of the distribution systems, the traditional FLISR application requires upgrading. Further research is needed to enable model-based FLISR applicable for large-scale unbalanced power distribution systems with numerous reconfiguration possibilities. Additionally, the acceptance of advanced applications by the utility companies requires a rigorous proof-of-concept regarding the ease of integration within the ADMS environment and their benefits to the industry. *This work aims at developing an advanced FLISR application and integrating it within an ADMS environment.*

Traditionally, a Distribution Management System (DMS) is employed by the utility companies that, in conjugation with multiple other subsystems, executes the functions of FLISR. Unfortunately, a traditional DMS is not able to fully leverage the interactions among the subsystems towards optimally operating the grid. An ADMS addresses the shortcomings of a traditional DMS by integrating operations across numerous subsystems to support the development of advanced grid management applications [3]. Essentially, an ADMS allows for the integration of new applications that can readily access information from various systems including but not limited to Distributed Energy Resource Management System (DERMS), Supervisory Control and Data Acquisition (SCADA), Outage Management Systems (OMS), and Advanced Metering Infrastructure (AMI) [4] (See Fig. 1). Recently Pacific Northwest National Laboratory (PNNL) has developed a standards-based open-source platform – GridAPPS-D for ADMS application development. Specifically, the GridAPPS-D platform provides a control and communication-rich environment to develop and demonstrate advanced applications, with consideration to the integration of DERs, microgrids, alternate control strategies, and diverse model-based and data-driven algorithms. These new developments call for research not only on advanced applications for the distribution systems that leverage the interoperability of the ADMS platform but also on providing a proof-of-concept for integrating such advanced applications into an ADMS environment. Towards this goal, the objectives of this paper are *(1) to develop an advanced FLISR application for unbalanced power distribution systems* that efficiently utilizes the emerging technologies to reduce outage duration and quickly restore the systems' critical loads; and *(2) to provide a proof-of-concept for developing advanced applications in an ADMS environment using the GridAPPS-D platform.* A FLISR application performs three related actions to restore the power supply after an outage: locate the fault using triggered protection devices and smart meter pings or customer calls, isolate the fault by opening the appropriate switching devices, and restore the power supply to the healthy feeders using feeder reconfiguration and intentional islanding using DERs [5]. A distribution service restoration (DSR) algorithm is employed to perform the final and most computationally expensive task. The related literature details several methods for DSR, see [6]–[12]. While there has been significant research in the area, there remain some critical gaps including (1) the existing algorithms are inapplicable to real-world distribution systems because of their computational complexity or the modeling assumptions [6], [8]–[11]; (2) they are not able to handle all possible scenarios (single or multiple faults) [6], [7]; (3) they fail to prioritize service restoration using backup feeder and DER islanding [7], [12], [13]. Moreover, industry adoption and deployment to the ADMS platform requires additional features that are usually overlooked in the existing research articles. Some of these concerns include a scalable approach for solving large-scale distribution systems, a mechanism to update the network model based on available information, and the ability to handle different possible distribution network configurations [9], [11], [12].

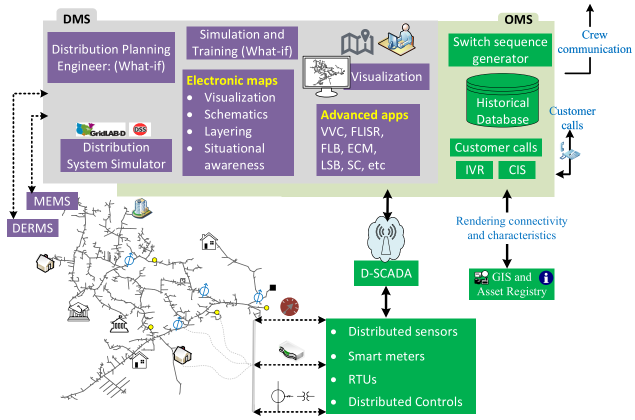


FIGURE 1. ADMS architecture.

With these considerations, we propose a FLISR application that integrates a novel distribution system restoration (DSR) algorithm suitable for large-scale unbalanced power distribution systems with a wide range of fault scenarios. Further, we demonstrate the applicability of the proposed module for a modern distribution system by successfully hosting it onto GridAPPS-D. The specific contributions of this paper are two fold:

- An advanced FLISR with a scalable model-based DSR module. The proposed DSR algorithm identifies switching actions to enable feeder reconfiguration and active islanding using grid-forming DERs for optimal system restoration for a wide range of fault/damage scenarios.
- Proof-of-concept for ADMS integration by hosting the proposed FLISR application into the GridAPPS-D platform using a large-scale three-phase unbalanced distribution test system with multiple DERs.

II. GridAPPS-D ARCHITECTURE AND APPLICATION DEVELOPMENT

GridAPPS-D is an open-source, standards-based platform designed to support the development of advanced, data-driven distribution system applications that take advantage of the data-rich environment expected in modernized electric power distribution systems [14]. Fig. 2 depicts the logical functionality and conceptual architecture of the GridAPPS-D platform in relation to the application developer and commercial tools. The platform utilizes two different classes of data flow; 1) "Control" and configuration data enabling the application developer to manage the platform (dashed line) and 2) network and real-time measurement data specific to an application (solid line). Here, "Data Ingest" module provides the ability to exchange data with the existing sub-systems such as energy management systems (EMS), OMS, GIS, data historians, and so forth. A provision is included for access to tools such as distribution power flow and optimizers. The key feature of this framework is standards-based data representation using a common information model (CIM) thus providing application developers with a standardized approach to data. With these functionalities, GridAPPS-D supports the full suite of distribution management applications, such as voltage and reactive power optimization; fault location, isolation and service restoration; economic dispatches; and optimization routines. Reader should refer to [14], [15] for further details regarding the GridAPPS-D platform including the design, objectives, functionality, and data exchange mechanisms.

The realization of an autonomous FLISR application requires measurement and control-rich environment that provides post-fault situational awareness and the ability to remotely deploy the decisions for restoration. A successful deployment relies on the ADMS that enables real-time communication and data exchange between the several sub-systems employed by the distribution companies to 1) provide distribution system condition monitoring during normal and outaged conditions, 2) obtain the statuses of available network components and grid resources, and 3) estimate the load demand and their priorities. Fig. 3 depicts a schematic for the interactions among the distribution system's operational sub-system to enable the proposed FLISR application.

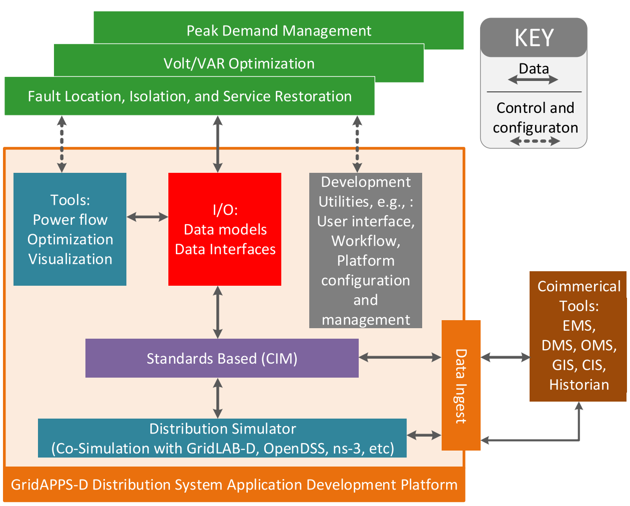


FIGURE 2. GridAPPS-D: Logical functionality and conceptual architecture [14].

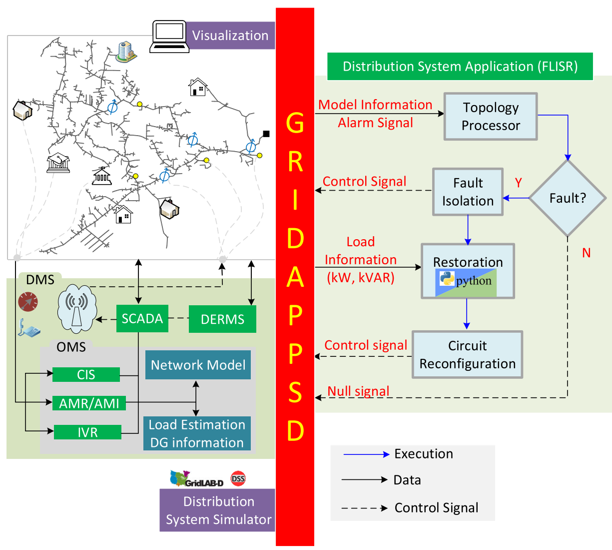


FIGURE 3. FLISR architecture on the GridAPPS-D platform and integration of proposed application to the GridAPPS-D platform. GOSS/FNCS is the PNNL's platform for data exchange among subsystems. GOSS: GridOPTICS Software System; FNCS: Framework for network simulation.

III. FAULT LOCATION, ISOLATION, AND SERVICE RESTORATION (FLISR)

The goal of FLISR is to optimally restore the electric power supply to the affected customers using all available grid resources. As such, FLISR requires information about the as-built and as-operated models for the distribution system, situational awareness during disruptions, available grid resources for restoration, and a decision-making framework to reconfigure/island the affected parts of the distribution system to restore the power supply. It is important to note that FLISR does not avoid outages but minimizes their impacts on customers when they do occur [16]. The overall architecture of the proposed FLISR application is shown in Fig. 3 and is comprised of three modules: (1) interface for data exchange, (2) topology processor (for fault location and isolation), and (3) service restoration.

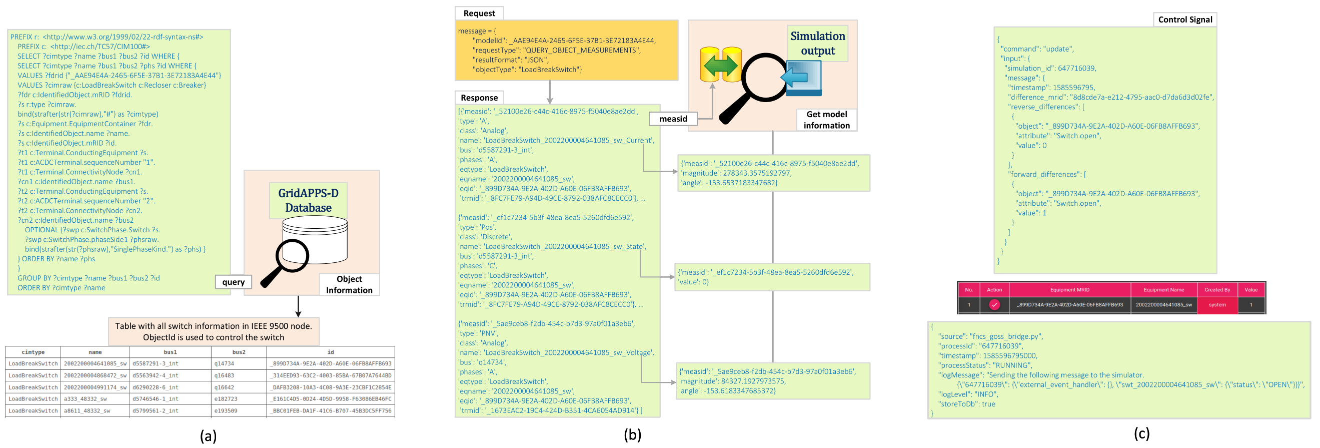


FIGURE 4. **Information collection and communication with platform. (a) A sample query for switch information, (b) Extracting the real-time measurements using simulation output from platform. The available measurements are VA, PNV, POS, and A. However, VA are not available for switches, and (c) Control signal to open a switch.**

A. INTERFACE FOR DATA EXCHANGE

An ADMS platform typically integrates other related data and decision-support systems/subsystems such as DERMS, SCADA, OMS, GIS, AMI, CIS. In the GridAPPS-D platform, a ''Data Ingest'' provides the ability to exchange data with the existing systems/sub-systems. The information required to initialize an application is obtained by sending relevant network queries to the GridAPPS-D platform using the pub-sub based standardized application programming interface (API). Here, the Grid Optics Software System (GOSS) is used to manage the platform data and the message bus, while the Framework for Network Co-simulation (FNCS) handles the time clock and the message traffic between platform and simulator [17]–[19]. In the GridAPPS-D platform, the base network resides in a graph-based data store and the application queries it using GridAPPS-D platform's API. The network measurement data originates from a three-phase unbalanced distributor simulator driven by GridLAB-D [20]. Applications interact with the GridAPPS-D platform to query the power grid model data store using Python API that includes SPARQL [21]. The information collection and processing are done by i) publishing relevant queries and subscribing to responses, ii) subscribing to simulation outputs, and iii) subscribing to specific service output like alarms, voltage violations. A few sample queries and responses are shown in Fig. 4. The static parameters such as peak load, line parameters, switch locations and DER parameters are retrieved using the GridAPPS-D database (Fig. 4a). Real-time information such as load consumption, switch status, capacitor, and regulator tap positions are obtained by screening through the simulation output from the platform (Fig. 4b). For sending control signals, JSON messages are created based on the attributes and device types (Fig. 4c). For example, to toggle the switch, ''Switch.open'' is used, and to dispatch the DERs, ''RotatingMachine.p'' or ''PowerElectronicsConnection.p'' is used.

B. TOPOLOGY PROCESSOR

At each pre-defined time step, the application communicates with the platform and the application-specific information is retrieved. For FLISR, the following data is queried from the platform: switch statuses, statuses of protective relays, fault indicators, alarm signals, available DERs, and load data.

1) FAULT LOCATION AND ISOLATION

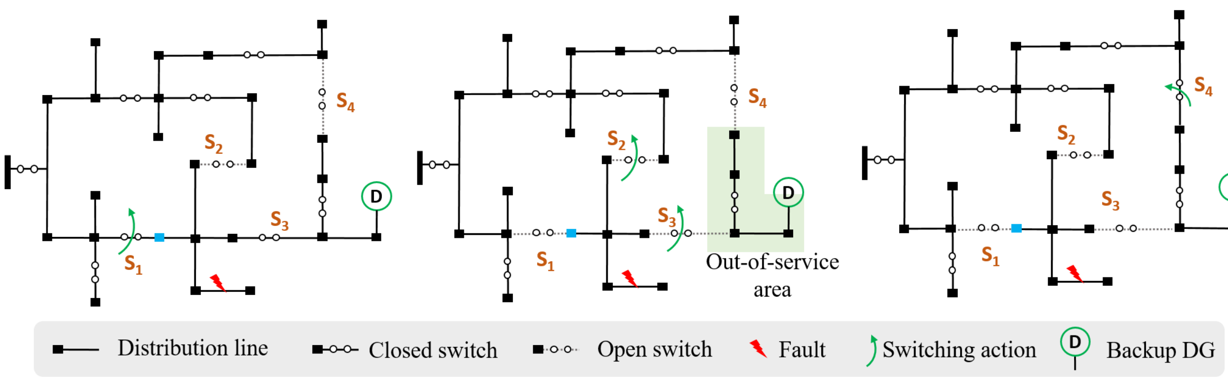
Based on the query results on the statuses of the protective relays, fault indicators, and switch statuses, the FLISR application runs a network processor to estimate the fault location. Next, the faulted zones are isolated from all possible power flow directions by opening appropriate tie/sectionalizing switches, see Fig. 5. To do so, we use a simple algorithm that identifies the candidate switches to open based on the direction for downstream power flow on the current operating topology. Once the switches are identified, the switch open command is generated and sent to the GRIDAPPS-D platform using the GOSS message bus.

2) SYSTEM MODEL IDENTIFICATION

After the faulted section(s) are isolated, a new query is initiated to obtain the updated statuses of the network devices including the switching devices to account for any misoperation in the execution of the fault isolation command. Additional information is extracted from the platform to initiate the service restoration routine. This includes the available resources for restoration including additional substation or grid-forming DERs, load data including load priority information, and the controllable switches. This information is used to generate an optimal service restoration plan for the affected distribution system.

C. RESTORATION

Once the fault is isolated and the new system model is identified, the service restoration algorithm is executed to



(a) Fault Location (b) Fault Isolation (c) Service Restoration

FIGURE 5. **Pictorial representation of proposed fault location, fault isolation, and service restoration.**

generate an optimal and feasible restoration plan. We describe a mathematical programming approach for service restoration using all available resources including DERs in Section V. Essentially, with the confirmation that the faulted portion of the feeder is isolated, the FLISR application toggles the set of the normally-open tie switches and normally-closed sectionalizing switches to connect to the outaged customers to the neighboring backup feeder(s) and/or DERs. This action restores service to the outaged customers using other feeders/DERs thus reducing the number and duration of the customer interruption (see Fig. 5).

To evaluate the performance of the proposed application and quantify its benefits towards improving the reliability, the reduced number of customers interrupted (CI) is used as a metric [16], [22]. Here, CI is a measure of the number of customers interrupted by an outage.

IV. FAULT LOCATION AND ISOLATION ALGORITHM

This section details the algorithm for (1) fault location based on the operation of protective devices and (2) fault isolation to disconnect the affected/faulted sections from all possible directions. We propose a graph-theory based fault location and isolation algorithm, which can effectively identify the faulted zones and isolate the faulted sections from all possible directions. Note that the identification of the faulted zones provides with enough information to isolate the fault; however, it is not sufficient to accurately locate the faulted lines/equipment. The main motivation of this work is to automate the FLISR application to reduce the number of customer interruptions by enabling restoration before the faulted sections are repaired. The identification and isolation of the faulted zones serve this motivation. The detailed algorithm is given in Algorithm 1 and described in the following subsections.

A. FAULT LOCATION

The fault location module subscribes to two different data streams from the platform: Switch/protective device status and alarm signals. The alarm signal distinguishes operator actions from fault actions. When the operator deliberately executes certain switching commands that result in a network topology change, the alarm signal is OFF. However, if the topology change results without operator action, the alarm gets triggered indicating a fault condition. Thus, when a protection device is operated and an alarm for the same received, the FLISR application is called upon. Given Ω_S and $\mathcal{T}_{t-1}$, a node corresponding to each element of Ω_S is obtained and the final set is stored as $\mathcal{F}$. To locate the fault,

Algorithm 1 Fault Location and Isolation

Given: $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, Alarm, Ω_S, and $\mathcal{T}_{t-1}$
A: Fault Location
$\mathcal{F} \leftarrow \{\}$
for e *in* $\mathcal{E}$ **do**
  if $e \in \Omega_S$ **then**
    for τ *in* $\mathcal{T}_{t-1}$ **do**
      if $e = \tau$ **then**
        $\mathcal{F} \leftarrow \tau^c$
B: Fault Isolation
$\mathcal{I}_S \leftarrow \{\}$
for v *in* $\mathcal{F}$ **do**
  /* List all possible paths from $\mathcal{S}$ to v */
  $\mathcal{W} \leftarrow$ all_simple_paths $[\mathcal{G}, \mathcal{S}, v]$
  for w *in* $\mathcal{W}$ **do**
    $k \leftarrow 0$
    for u *in* w **do**
      /* Screen the path backward from v */
      $edge = \big[\mathrm{u}\big[|w|\text{-}k\big]\ \mathrm{u}\big[|w|\text{-}k\text{-}1\big]\big]$
      if $edge \in \mathcal{E}_S$ **then**
        $\mathcal{I}_S \leftarrow edge$
        Go to step 16
      $k \leftarrow k + 1$
Output: $\mathcal{I}_S$

the application requires a radial operating tree just before the fault has occurred. Since the time of fault is unknown, we save the few most recent trees information ($\mathcal{T}_{t-3}$, $\mathcal{T}_{t-2}$, and $\mathcal{T}_{t-1}$). The memory requirement to save every operating topology in real time is demanding and it is mostly unnecessary to store an operational topology that is not recent. Therefore, the information that is not recent i.e., those before time instant $t-3$, are flushed. We identify the orientation of the protective device on the operating tree just before the fault that is always available in the memory. The child node of the switch provides information about the faulted zone. The pseudocode for this module is given in Section A of Algorithm 1. Note that partial knowledge of the infrastructure or uncertainity of the status of available assets make the restoration problem a real-time and asynchronous decision-making problem [23]. In such a case, fault location, isolation, and service restoration might take longer than usual and can also result in a sub-optimal solution. For example, due to significant delay in communication or lack of sufficient information, it might be necessary to dispatch crew members to identify the faulted zone which is a time-consuming process and significantly increases the duration of outage. For the accurate fault location, analytical methods using smart meter data and remote fault indicators [24], [25] can be used in addition to this graph-based method.

B. FAULT ISOLATION

Once a faulted zone is located and stored as ($\mathcal{F}$), the fault isolation module is called (See Section B in Algorithm 1). First, all the possible paths from Ω_S to each node in $\mathcal{F}$ is identified using the ''ways'' function of networkx package. Once all the paths are identified, a search is initiated to obtain the nearest switch from the fault location (v) by traversing each path, individually, from fault point towards Ω_S. Once a switch is identified in the path, the search process is terminated. The process is repeated for each identified path in $\mathcal{W}$. The list of the nearest switches from all possible directions is stored and tagged as the set of isolating switches ($\mathcal{I}_S$) for the given fault scenario.

The fault location and isolation modules are depicted in Fig. 5. Once a fault occurs on a line at time t as shown in the figure, the protection devices, S_1, operate (opens) in response to the fault current, and simultaneously an alarm is received. As discussed before, the fault location module identifies a node τ^c based on the operating tree prior to the fault ($\mathcal{T}_{t-1}$), and the protection devices operated to clear the fault i.e., S_1. The node is highlighted in blue. It is worth mentioning that the AMI reading and Interactive voice response systems (IVR) can be used in conjunction with the proposed approach to improve the performance of the fault location algorithm. Once the faulted section is identified, the isolation module isolates the fault based on the aforementioned algorithm. Here, switches S_2 and S_3 are opened to isolate the fault from all possible directions. Note that S_2 is already opened and needs no action. However, it should be ensured that S_2 is not involved in the restoration process to avoid feeding the fault during the restoration process. Once a fault is isolated from all directions, service restoration closes the switch S_4 to restore the out-of-service area. The detailed problem formulation for the service restoration module is described in the following section.

V. DISTRIBUTION SERVICE RESTORATION ALGORITHM

This section presents the problem formulation and important aspects related to the operational practices of the restoration problem. If a fault occurs in a distribution circuit, the downstream load will not be supplied. This is referred to as the out-of-service area (see Fig. 5). In this case, an efficient restoration plan needs to be executed to restore as much load as possible using switching operations. The topology of distribution system changes during service restoration operation; however, a radial topology shall be maintained for the restored network. Due to the varying topology and the connected loads, the bus voltages and line currents also change during the service restoration process. To maintain the safety and security of different power system components (such as transformers and lines), the bus voltages and line currents mustn't exceed their respective operating limits.

Mathematically, the service restoration problem is formulated as a multi-objective constrained optimization problem with constraints on the satisfaction of the system's operational and connectivity constraints. Typically, the problem objective is to maximize the total load restored while minimizing the number of switching operations. The constraints pertain to (1) network connectivity (2) power flow model, (2) operating limits (voltage and thermal limit).

- Objectives:
  1) Maximize the amount of load restored
  2) Minimize the number of switching operations
- Constraints:
  1) Graphical/Network constraints
  2) Power flow constraints
  3) Operational constraints

The primary objective is to maximize the amount of load restored while considering different weight factors for each load (w_i) that indicate load priority. Let s_i be the load pick-up variable and $S^{\phi}_{Li} = P^{\phi}_{Li} + jQ^{\phi}_{Li}$ represents the load connected at the i^{th} bus. The objective is defined as the following.

$$\text{Maximize} \sum_{i\in\mathcal{V}_S} \sum_{\phi\in\{a,b,c\}} w_i\, s_i\, P^{\phi}_{Li} \tag{1}$$

The secondary objective is to minimize the number of switching operations (or more generally the cost of operation), thus keeping the final network configuration close to the nominal one. Note that, the number of switching operations determines the performance of the restoration plan as it closely relates to the time it takes to execute the restoration plan. Therefore, it is desirable to minimize the number of switching operations so that the restoration plan can be executed in an efficient and timely manner.

The objective of minimizing the total number of switching operations is defined in (2).

$$\text{Minimize} \left(\sum_{e\in\mathcal{E}_S^s} (1-\delta_e) + \sum_{e\in\mathcal{E}_S^t} \delta_e + \sum_{e\in\mathcal{E}_v} \delta_e \right). \tag{2}$$

where, δ_e is the switch decision variable, $\mathcal{E}_s^s$ is the set of normally closed sectionalizing switch, $\mathcal{E}_s^t$ is the set of normally open tie switch, and $\mathcal{E}_v$ is the set of DER switch. We define a multi-objective restoration problem using a weighted combination of the two previously defined objective functions in (3).

$$\text{Maximize} \Bigg(\alpha \sum_{i\in\mathcal{V}_S} \sum_{\phi\in\{a,b,c\}} w_i\, s_i\, P_{Li}^{\phi} - \beta \Big(\sum_{e\in\mathcal{E}_S^s} (1-\delta_e) - \sum_{e\in\mathcal{E}_S^t} \delta_e \Big) - \gamma \sum_{e\in\mathcal{E}_v} \delta_e \Bigg). \tag{3}$$

As the customer's satisfaction depends upon the availability of power, the maximization of the restored load is defined as the primary objective and is always given the highest preference. The weights α, β, and γ are defined such that the primary objective is always prioritized. Since the secondary objective is a sum of binary variables only, making $\beta < 1, \gamma < 1$, and assigning α a large number ensures that the problem first restores the maximum weighted loads and then minimizes the switching operations. Also, DERs must not operate in an islanded mode unless it is required. Thus, the priority for restoration is to use feeder backup by switching a pair of sectionalizing and tie switches. When a normally open tie switch operates, a normally closed sectionalizing switch has to be opened to maintain a radial topology. Thus, gamma is made at least $2|\mathcal{E}_s^t|$ times higher than β (i.e, $\gamma \geq 2|\mathcal{E}_s^t|\beta$).

A valid restoration plan must satisfy different constraints. First, no fault must be fed. Second, the restored network configuration must comply with a range of operating constraints including maintaining voltage and power flow within certain limits. Most importantly for present purposes, circuit-breakers, lines, and transformers have capacities, which the power flow must not exceed. A third relevant constraint is the set of topological constraints required to ensure a connected network for the restored loads and a radial restored network/s topology. Please refer to [12], [26] for a detailed formulation of the constraints for the DSR problem. With the proposed objective and the relevant constraints, the resting formulation for the DSR problem is a mixed-integer linear program (MILP) that can be solved by any off-the-shelf MILP solver.

VI. SIMULATION RESULTS

The proposed FLISR application is tested on the modified IEEE 8500-node test system [27] (See Fig. 6). The D-Net library [28] allows modeling power distribution networks and constructing an optimization problem as described in Section III. The simulation is carried out on a PC of Intel Core i7-6700 @ 3.4 GHz processor with 16 GB RAM. The FLISR application is developed in a python programming language where optimization for service restoration is modeled and solved using PuLP's modeling functions, which will then call a solver [29], [30].

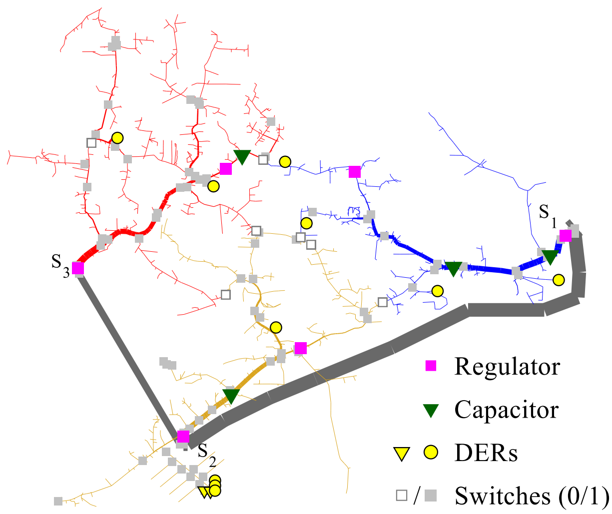


FIGURE 6. Modified IEEE 8500-node test case. Different color lines indicate part of three different substations (S_1, S_2, andS_3).

A. TEST CASE DESCRIPTION

The validation of an advanced ADMS application requires a suitable test case that represents the features of an active distribution system [31]. Unfortunately, the existing distribution test systems do not include the crucial features required for integrating the advanced applications that leverage emerging smart grid technologies in an ADMS environment. To validate the proposed FLISR application, we had the following three requirements from the test system; (1) it should be supplied by multiple substations/feeders that can serve as backup feeders during the restoration process, (2) the system should be sufficiently large with numerous tie- and sectionalizing switches with a large number of possible reconfiguration options; and (3) it should include DERs to provide intentional islanding capabilities via grid-forming technologies in order to support the critical loads. To meet the above requirements, we modified the original IEEE 8500-node test system [32], [33] to include the required additional features. In what follows, we describe the specific changes made to the IEEE 8500-node test system.

1) FEEDER SPLIT INTO THREE SUBSTATIONS

The original IEEE 8500-node test case is modified to supply the entire load from three different substations (S_1, S_2, and S_3). The regulator and capacitor are the same as the original test feeder except that an additional regulator is added for each substation. The total number of customers in the new test case is 1275 and the total load sums up to 12302.34 kW and 3437.80 kVAR. A new set of loads is added near S_2 and the region is referred to as a new neighborhood. The details

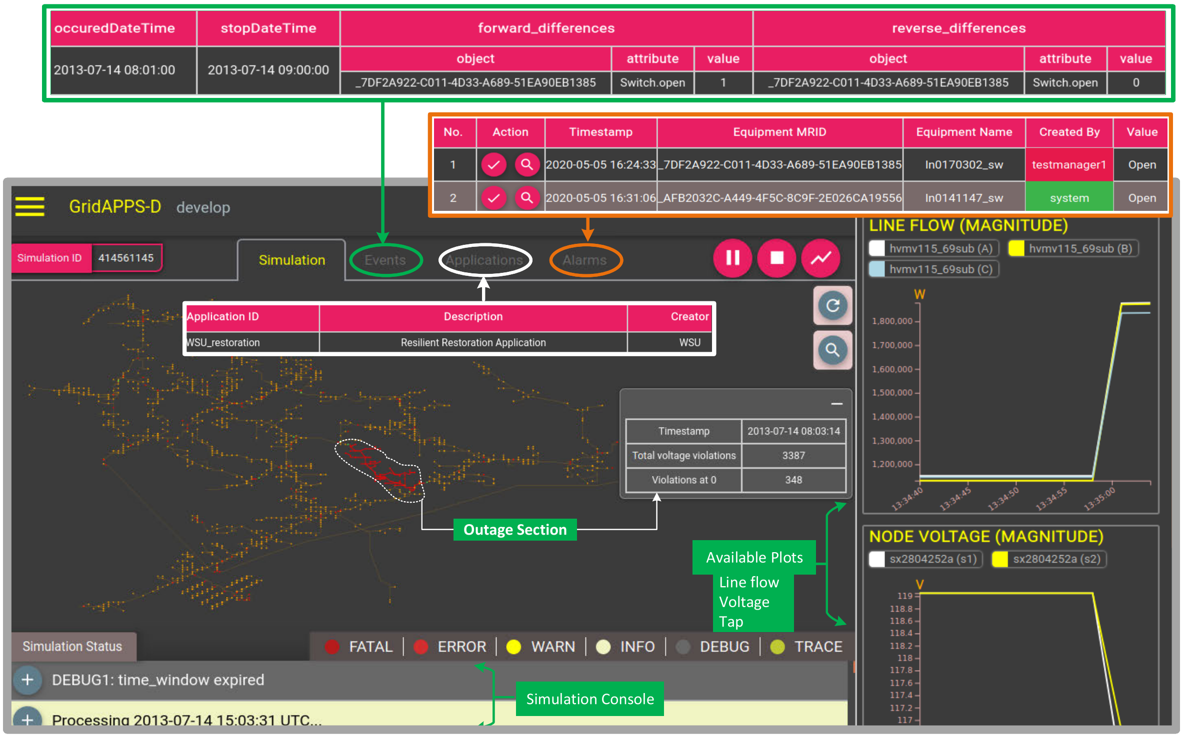


FIGURE 7. Modified IEEE 8500-node running in the platform.

of load and distribution system components are summarized in Table 1.

TABLE 1. Load in three different substations.

Sub.	No. of Loads	Load kW	Load kVAR	No. of Reg	No. of Cap	No. of DERs
s_1	268	3237.9	811.5	2	2	4
s_2	475	4476.1	1476.3	2	1	6
s_3	532	4588.3	1149.9	2	1	2
Tot.	1275	12302.34	3437.8	6	4	12

2) UPGRADING SWITCHES

Enhancement of restoration capability through distribution automation requires installing remote-controlled switches to provide alternate restoration paths. Thus, we modify the IEEE 8500-node system by adding several sectionalizing and tie-switches. Note that while these switches can be optimally placed along the feeder [34], such optimization is not within the scope of this work. In total, we place 101 sectionalizing switches and 7 tie switches in the modified test case. This leads to 2386 possible cycles in the network resulting in several possible radial operational topologies. Thus, the test case simulates a large number of restoration possibilities making it suitable to validate the performance of the proposed model-based FLISR application.

3) DISTRIBUTED ENERGY RESOURCES

Several utility-scale distributed energy resources (DERs) are installed in the modified test case. These DERs are equipped with grid-forming ability and can form islands to support critical loads, if necessary. The parameters of the DERs are summarized in Table 2. During normal operating conditions, only a few of them are ON. Note that DERs can be dispatched as desired by the application for a reliable, resilient, and economical operation of the grid. Besides, different sections of the feeders are interfaced with residential PVs on secondary distribution circuits in conjugation with the residential loads. Here, out of 1275 loads, 177 have rooftop PVs installed. Further, the simulated new neighborhood includes 100% PV penetration.

TABLE 2. DER parameters in the modified IEEE 8500-Node model.

DER Type	Name	S_{rated} (kVA)	Status (ON/OFF)
Steam plant	SteamGen1	4000	1
PV	PVFarm1	750	1
Diesel Genset	Diesel620	775	0
LNG Engine Genset	LNGengine100	125	0
Microturbine	MicroTurb-1,2,3	250×3	1/0/0
LNG Engine Generator	LNGengine1800	2250	0
Diesel Genset	Diesel590	737	0
Microturbine	MicroTurb-4	250	1
Storage	Storage.Battery1,2	250×2	0/0

B. PLATFORM VISUALIZATION

The platform currently runs in a Linux virtual machine through docker containers [35]. The application is started and run through the browser interface. Fig. 7 shows the visualization of the test feeder currently running on the platform.

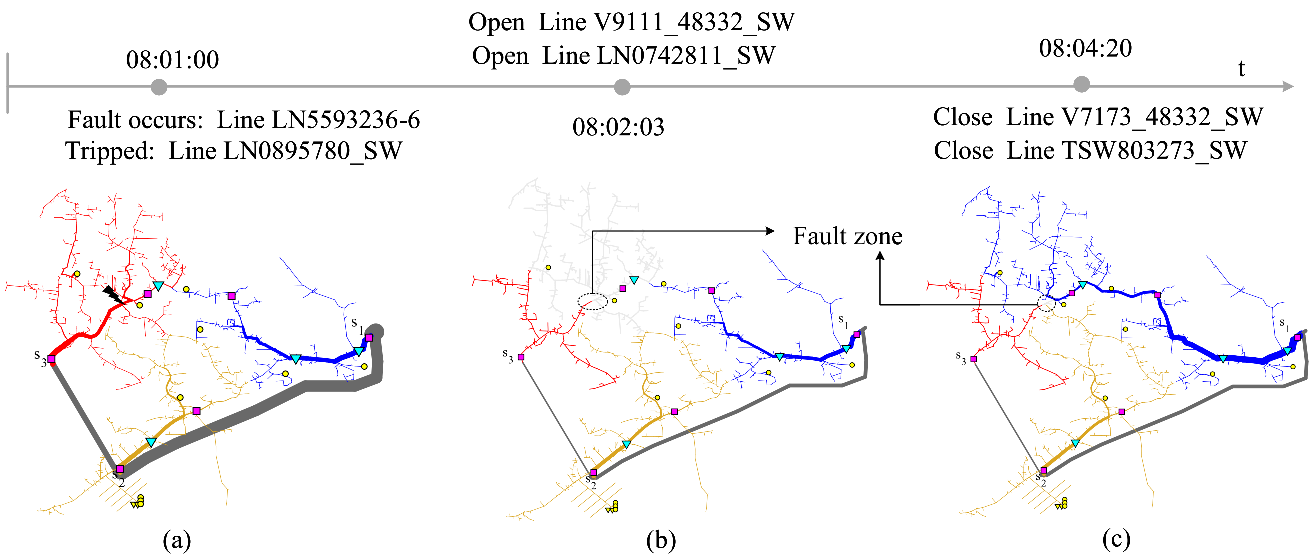


FIGURE 8. Simulation of Event-I. The colored segments represent the substation they belong to. (a) Fault at line LN5593236-6, (b) Isolated area because of fault, and (c) Isolated area supplied by closing two tie switches from S_2 and S_3.

TABLE 3. Switching scheme for different events.

Fault at line/s	Switches tripped	Isolation	Outage Size kW	Outage Size CI	Restoration	Reduced CI	Restoration Time (s)
LN5593236-6	LN0895780_SW LN5001CHP_SW LN1047PVFRM_SW	Open V9111_48332_SW Open LN0742811_SW	3284.8	379	Close V7173_48332_SW Close TSW803273_SW	4	200
LN5895818-1	HVMV69S2B2_SW LN2000001_SW	Open L5523_48332_SW	4476.2	475	Close TSW803273_SW Adjust DER output (Fig. 12)	75	202
LN6291253-1 LN5714974-1 LN5745257-1	A8869_48332_SW LN0170302_SW HVMV69S1B2_SW	Open V7041_48332_SW Open L5437_48332_SW Open LN0141147_SW Open XJ171_48332_SW	3583.9	316	Close TSW320328_SW Close A333_48332_SW Close V7173_48332_SW Open LN0504876_SW Open LN0504876_SW	150	242

Additionally, to visualize the topology of the feeder, the platform also allows the user to plot complex power flow in all AC line segments (VA), phase to neutral voltage (PNV) at each node, and regulator tap or switch status (Pos). The tabs show different functionalities of the platform such as simulation, events, and application. The "Events" tab shows if any event is currently active in the test system and the "Applications" tab shows the name of the application currently running on the platform. The alarm tab shows if any action has taken place to toggle the devices such as a switch, capacitor, and regulator taps. Simulation status allows the operator to see whether the actions are well carried out and verify if the application is running smoothly.

C. CASE STUDY

The performance of the application is tested under three different scenarios: (1) typical fault, (2) fault scenario requiring islanding of the new neighborhood, and (3) multiple faults including a substation outage requiring intentional islanding using grid-forming DERs.

1) EVENT-I

In this event, a fault is simulated at line LN5593236-6. In response to this fault, the nearest upstream switch is opened (LN0895780_SW). Also, the additional two DERs in the outage area are tripped and cease to energize the area in response to the abnormal condition [36]. Once the fault is identified and the switches have operated to clear the fault, it is observed that 379 customers in S_3 are out of power supply (See Fig. 8b). The FLISR application receives the topology change information from the platform along with the alarm signal and gets triggered. It first locates the faulted zones and then opens respective switches to isolate it from all directions. Next, the restoration module identifies a set of candidate switches to restore the power supply to the out-of-service area. In this case, the optimum decision is to close the two tie-switches to restore the customers from S_1 and S_2 as shown in Fig. 8c. The switching actions are given in Table 3. To further analyze the given restoration plan, the substation power is also plotted in Fig. 11a. Note that when the fault occurs, the flow in S_3 is reduced as the switch is tripped disconnecting all downstream loads in s_3. Once the system is restored, the flow in S_1 and S_2 is increased as those are used to pick up the disconnected loads in S_3 due to the fault. It takes around 200 seconds to restore the service to 375 customers after the fault has occurred. Note that the remaining 4 customers are in the fault zone and can be restored only after the fault is repaired.

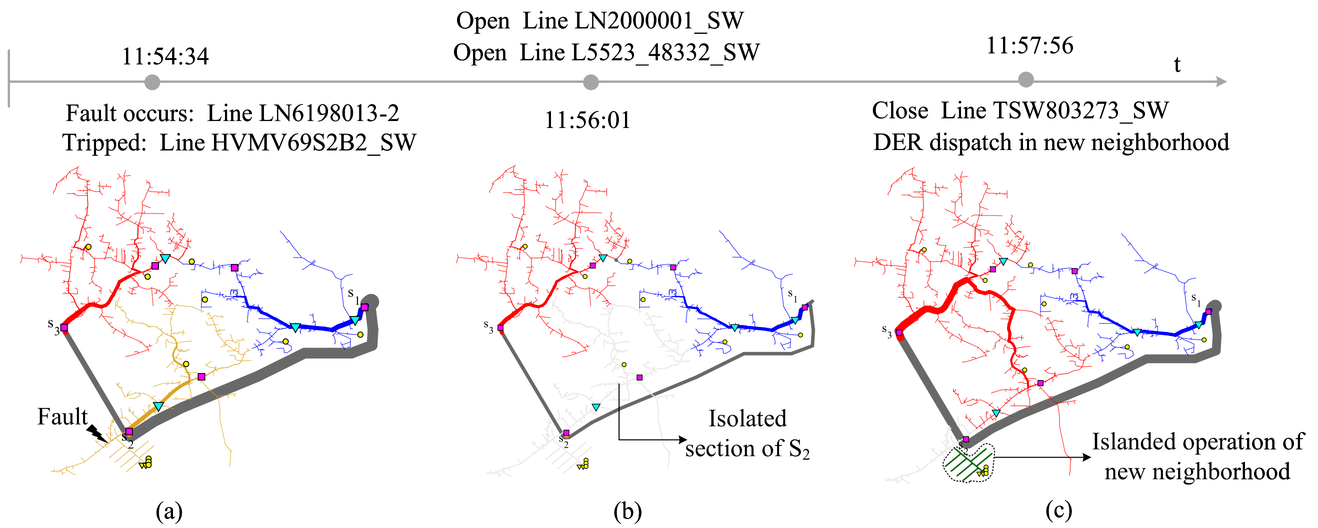


FIGURE 9. Simulation of Event-II. The colored segments represent the substation they belong to. (a) Fault at line LN5895818-1, (b) Isolated area because of fault, and (c) Isolated area supplied by closing tie switches from s_3 and DERs in the new neighborhood.

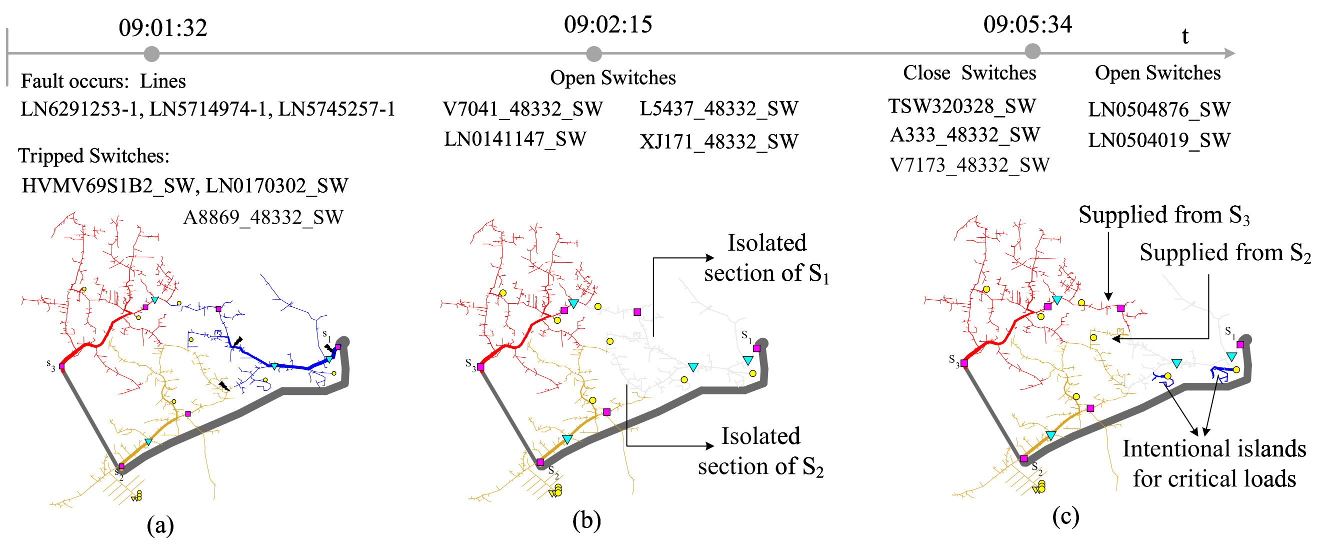


FIGURE 10. Simulation of Event-III. The colored segments represent the substation they belong to. (a) Fault at several lines, (b) Isolated area because of fault, and (c) Isolated area supplied by closing two tie switches from s_2 and s_3 and islanding of two DERs.

2) EVENT-II

In this scenario, a fault at a line LN5895818-1 near S_2 is simulated. In response to the event, S_2 breaker is tripped off. The outage area is shown in Fig. 9b where 475 customers are interrupted. To isolate the fault from all possible directions, an additional switch L5523_48332_SW is opened. After the optimization, proper control actions are identified to supply the outaged sections of S_2. Specifically, Tie switch TSW803273_SW is closed to pick-up the outaged loads using S_3 thus increasing the power flow in S_3 as observed in Fig. 9c. To observe the given restoration plans, the substation power is also plotted in Fig. 11b. When the fault occurs, the flow in S_2 goes to zero as the substation switch is tripped off because of the fault. Once the system is restored, the flow in S_3 is indicating the supply to the outaged sections.

Note that the new neighborhood includes DERs to support its local loads. Thus, in response to this fault, the new neighborhood is isolated. Next, the DERs in the new neighborhood are dispatched accordingly to balance the demand within the neighborhood thus forming a microgrid. At the time of the event, the demand in the new neighborhood is 1029.87 kW. For load sharing, we simply divide the total demand among the DERs based on their capacity (See Fig. 12). The DER dispatch signals are provided for serving the customers in the new neighborhood. There are micro-turbines (MTs) with the grid-forming capability to incorporate losses in the network during power-sharing and for maintaining voltage and

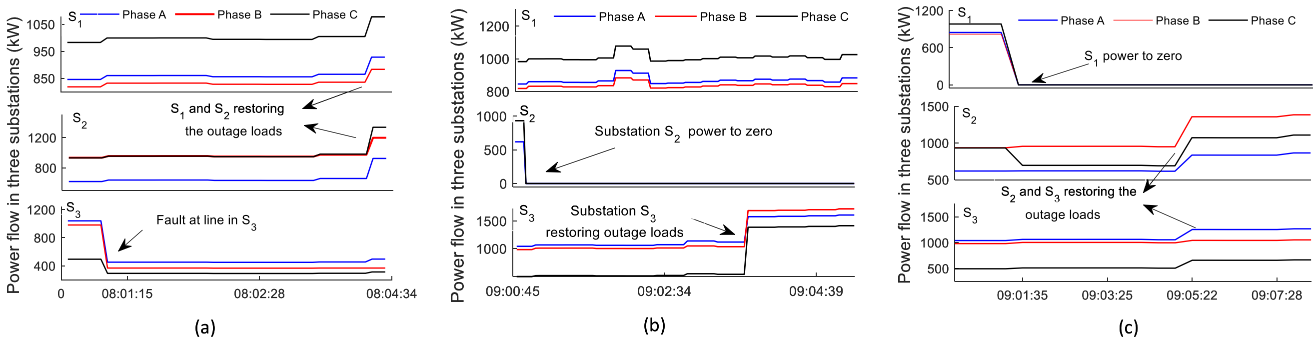


FIGURE 11. Substation flow for several switching instants during fault event, isolation, and restoration for (a) Event-I, (b) Event-II, and (c) Event-III.

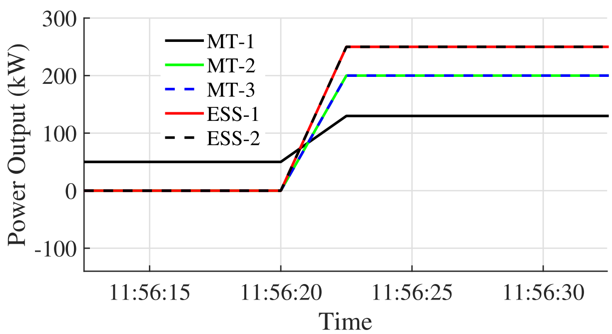


FIGURE 12. DER dispatch in new neighborhood during islanding.

frequency within the island. With these switching actions and control signals, 400 out of 475 customers are restored after around three and a half minutes. The remaining 75 customers can be supplied after the fault is repaired.

3) EVENT-III

In this case, we tested the performance of the FLISR application for multiple fault scenario. Three different faults are simulated including one near S_1 (See Fig. 10a). In response, three nearest upstream switches are tripped. Additionally, the DERs in the isolated area are switched off. All the customers supplied by S_1 and a few by S_2 are out of service as shown in Fig. 10b. With these actions, there is an outage area that consists of 316 customers. Upon triggering the FLISR application, the three faults are isolated by opening 4 different switches (See Table 3). Once isolation is done, restoration algorithm finds the candidate switches to operate in order to restore service in the outage area. Three tie switches are closed such that a portion of S_1 is supplied from S_3 and S_2 whereas the outage section of S_2 is restored by itself. In addition to the feeder reconfiguration, two intentional islands are formed supplied by two DERs with the grid-forming capability to restore the critical loads in their neighborhood (See Fig. 10c). The power output from these DERs is shown in Fig. 13. Diesel generator restores 10 customers including one big critical load at node "L3234149". Similarly, the LNG engine restores 9 customers by forming an island. With these switching actions and DER control signals, 166 out of 316 customers are restored. 166 customers observe an outage for around 4 minutes only while the remaining 150 customers are not supplied until the faults are repaired.

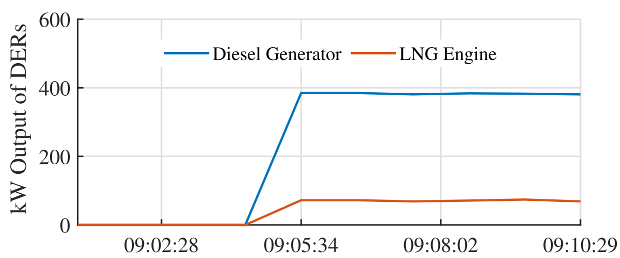


FIGURE 13. DER dispatched for restoring critical loads.

D. DISCUSSIONS

The case studies in this paper successfully demonstrate that upon integrating the automated FLISR application in an ADMS, there is a reduction in the number of customer interruptions (CI). Note that the associated customer minutes of interruptions depends on the restoration time. For quickly restoring the service, the DSR module should be scalable to solve the restoration problem for a large distribution system within a reasonable time. It can be observed from the results that the proposed model-based DSR approach is scalable and solves the restoration problem for any event for a sizeable distribution system (here with $\sim$ 9500 nodes) in less than 5 minutes. Note that any outage of fewer than a 5-min interval counts toward the Momentary Average Interruption Frequency Index instead of the System Average Interruption Frequency Index (SAIFI); therefore, if the restoration can be automated, unlike other existing approaches, a model-based DSR presented in this paper can help significantly improve the system reliability. The existing approaches for DSR, such as those based on heuristics, and nonlinear optimization models are not able to solve sizeable distribution systems to an optimum solution in a reasonable time. This is because of the following two reasons: (1) mixed-integer nonlinear optimization problems are known not to scale well and pose convergence issues for large systems; (2) heuristics-based methods need to evaluate a large number of possible configurations to reach to the optimum. Thus, they get progressively slower as the system size increases. Other approaches, such as spanning tree-based methods, are not applicable for multiple faults and the cases with a large number of options for restoration. Besides, none of the existing literature has solved the DSR problem in an ADMS environment, and they do not report the actual time for restoration after an event has occurred. In what follows, we further summarize the major benefits of the proposed DSR approach and key findings from the simulated scenarios.

- We tested the approach in a sizeable distribution system model with multiple substations and DERs that allows for reconfiguration using normally open tie switches and normally closed sectionalizing switches representing the real-world scenario of distribution system restoration.
- The proposed approach can intentionally island parts of the distribution network to support the critical loads using DERs during emergency conditions. These islands are dynamically sized using the algorithms based on the fault scenario and available resources.
- We simulated different events (including both single and multiple faults) in an ADMS environment and reported the actual time of restoration. Our restoration plans comply with the IEEE 1547 standard related to abnormal conditions and DERs intentional islanding.

VII. CONCLUSIONS

In this paper, we proposed a FLISR application with a scalable DSR module and demonstrated its successful deployment on the ADMS environment using the GridAPPS-D platform. GridAPPS-D is an open-source, standards-based platform developed by PNNL to facilitate the development of advanced DMS applications. The proposed FLISR application is validated using the IEEE 8500-node test feeder that is modified to include (1) multiple feeds/substation, (2) numerous sectionalizing and tie switches, and (3) DERs with grid forming capability. It is demonstrated that the proposed FLISR application is successfully able to isolate the faulted zones and restore the service to the remaining customers by transferring them to adjacent feeders. When required, intentional islanding was triggered to restore critical loads using DERs with grid-forming capabilities. The proposed application is successfully hosted within an ADMS environment using the GridAPPS-D platform. The working of the application within GridAPPS-D is demonstrated using three different fault scenarios requiring different restoration actions depending upon the severity of the fault scenario. The validation and deployment of the FLISR application using the GridAPPS-D platform provide a proof-of-concept for the integration of advanced applications within an ADMS environment and its benefits to the emerging distribution systems. The source code and documentation are available at [19], [28]–[30], [37].

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