Evaluation of Centralized Model-Based FLISR in a Lab Setup

Preprint

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***Abstract*—Utilities are installing advanced distribution management systems (ADMS) around the globe to improve the sensing and control of distribution systems. ADMS is becoming a critical component to improve the resiliency and reliability of distribution systems. These management systems host a multitude of applications that can be used to sense, control, and operate distribution systems. Fault location, isolation, and service restoration (FLISR) is one of the ADMS applications that is critical to improving resilience during fault conditions. FLISR applications use smart, controllable devices that are installed in the distribution system for FLISR operation. These controllable devices include distributed energy resources (DER) and reclosers. Evaluating such ADMS applications before installation in the field can help de-risk the field implementation and avoid costly failures in the field. This paper presents a background on experimental setup that are typically used to evaluate ADMS applications. This is followed by briefly presenting the setup used to evaluate the FLISR application in an off-the-shelf ADMS tool. Finally, results from the evaluation experiments are presented.**

***Index Terms*—Advanced distribution management systems, fault location, isolation, and service restoration, FLISR, software-in-the-loop, power hardware-in-the-loop, controller-in-the-loop, smart grid.**

I. Introduction

In the past, utilities had minimal visibility into the distribution grid. Because of this, utility operators relied on field crews to identify issues in the field and manually restore power. This restoration can take anywhere from minutes to several hours. Human operators cannot swiftly react to the transient events in the system and dispatch the necessary resources to restore power. Utilities have since opted for additional automation in the form of distribution management systems (DMS) and outage management systems (OMS). Distribution systems are undergoing a paradigm shift with a massive amount of smart, controllable devices, such as reclosers and distributed energy resources (DERs). The increasing complexity of distribution networks with DERs creates challenges for distribution system operators (DSOs) with solar variability, loss of generation, voltage regulation, changing fault current levels, and other factors. DSOs need to keep the grid balanced and optimized in real time while maintaining reliability and power quality. Legacy DMS and OMS have limited functionality which limits them from using reclosers and DERs to their maximum capability. But the newer DMSs contain advanced functionalities that can leverage smart, controllable devices to improve resiliency and reliability and to reduce restoration time.

As a key component of grid modernization strategies toward smarter distribution grid solutions, utilities are replacing legacy management systems with ADMS. ADMS combines the different functional domains that are part of DMS, OMS, and supervisory control and data acquisition systems (SCADA) with advanced functions, such as network analysis and optimization as a single seamless management system (see Fig. 1) [1]. ADMS provides grid operators the visibility and control necessary to monitor, and operate the grid in real time. This functionality enables the utilities to respond to outages safely, efficiently, and in addition optimizes the performance of the network assets.

Among the applications available in an ADMS, fault location, isolation, and service restoration (FLISR) application enables the utility to improve resilience and reliability of the distribution grid. The FLISR application achieves this by detecting, locating, and isolating the faulted section of the network and resumes service to customers that are downstream of a fault through switching actions. Early FLISR applications were developed under the assumption of a single-source contribution to a fault. High penetration of inverter based DERs has changed this assumption as these DERs act as multiple sources that can contribute to faults. These inverter based DERs also provides reduced current contribution to the faults. Multiple generation sources combined with low fault current characteristics affect the capability of traditional FLISR system to detect a faulted feeder and provide an effective restoration plan [2].

To accommodate multiple generation sources, researchers are proposing improvements in FLISR algorithms/methods [3]. One such improvement is to make the ADMS applications

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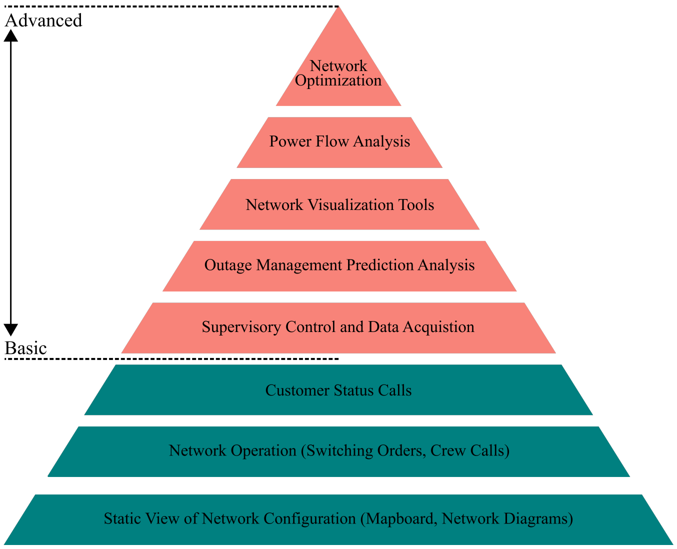


Fig. 1: ADMS Overview

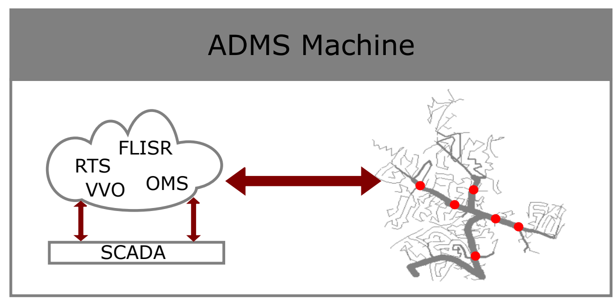
DER-aware. FLISR application uses sensor data from various locations to generate optimal decisions. Utilities in the United States are deploying FLISR applications; however, it is difficult to test the functionality of the application in the field because of the multiple systems involved. To ensure the reliable operation of FLISR application, they must be evaluated for different intended functionalities before being deployed to the grid. Development of ADMS evaluation test cases and ADMS evaluation test bed capabilities are discussed in [4]–[9]. Moreover, the present-day distribution network and proposed FLISR applications are more complex. Various architecture choices of FLISR require different evaluation use cases and procedures. This paper leverages one of the commonly used framework–software-in-the-loop (SIL)–framework to evaluate FLISR applications. The SIL steps identified in this paper follow traditional software evaluation processes. The framework presented here uses the distribution system simulation tool available in most commercial ADMS for the evaluation process. Typical next stages for evaluation will be through the controller-hardware-in-the-loop (CHIL) or power-hardware-in-the-loop (PHIL) setup. These CHIL and PHIL evaluation approaches can be used based on the requirements of the utility. As indicated earlier, this paper focuses on the use of simulation tools in a commercial ADMS platform and SIL approach for the evaluation.

The rest of this paper is organized as follows. Section II presents the different evaluation approaches available to evaluate ADMS application. Section III presents a background on the ADMS FLISR application and the importance of using accurate distribution system models. Section IV presents the two test cases and results of the SIL evaluation. Section V concludes the paper and presents possible future work.

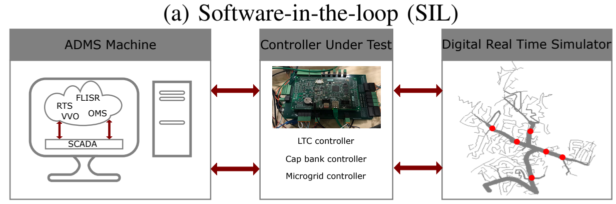
II. Approaches to Evaluate ADMS Applications

The distribution grid is growing in sophistication, and utilities face many challenges that increase the complexity of management and operation. Different management systems under ADMS are emerging as a single integrated platform that supports grid optimization and management. Evaluation of these ADMS platforms before deployment is a critical step for utilities to investigate the applications for the intended operational objectives. These evaluation steps will de-risk the installation investment and other associated costs.

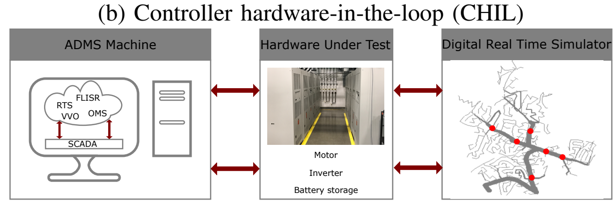
Typically ADMS evaluation needs models that reflect field setting effectively. ADMS test beds usually consist of software simulation and hardware elements that can create a distribution system and interface with ADMS SCADA using standard communication protocols. Energy management systems (EMS) and microgrid controllers also need to be integrated in the test beds if the evaluation requires the understanding of interaction between ADMS and EMS or the interaction between ADMS and microgrid controller. The test bed can integrate distribution system hardware and can make use of advanced 3D visualization capabilities. A block diagram of the ADMS testbed is shown in Fig. 2. The following are different components in a typical ADMS test bed:



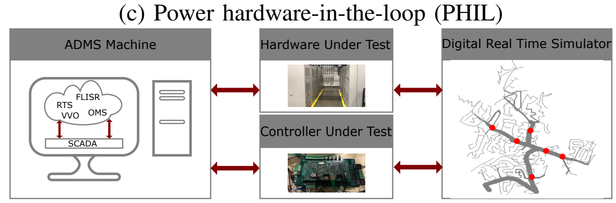
(a) Software-in-the-loop (SIL)



(b) Controller hardware-in-the-loop (CHIL)



(c) Power hardware-in-the-loop (PHIL)



(d) Power and control hardware-in-the-loop (PHIL+CHIL)

Fig. 2: ADMS Evaluation Procedures

Digital Real Time Simulation: Simulation of the distribution system under study in a digital real time simulator is a critical component in the test bed. Power system phenomena can be simulated across different timescales, from a fraction of a cycle to hours. Different simulation tools can be used to model and simulate the distribution system phenomena. Quasi-steady-state, phasor-domain, and electromagnetic transient (EMT) simulation are normally used for digital simulation of the distribution system [10].

Controller Hardware: Controller hardware are the next most commonly used equipment in the test bed. Equipment such as protection relays, capacitor bank controllers, voltage regulators and load tap changers are used in the setup. Interaction between these controllers and the ADMS application are crucial for successful operation of an ADMS. Controller hardware-in-the-loop (CHIL) setup in Fig. 2b can be used to validate the controller performance under various conditions of the utility grid.

Power Hardware: Power hardware like inverters are also integrated into the test beds to understand the interaction between the ADMS applications and the power hardware. Power hardware-in-the-loop (PHIL) setup in Fig. 2c links the power hardware equipment such as inverters to a digital real-time simulators. The PHIL environment tests the equipment interaction with the ADMS at scale and validates software models.

Remote Hardware: Real-time simulators and hardware used in PHIL and CHIL are often resource intensive and costly [11]. To address this issue, remote hardware-in-the-loop (RHIL) was introduced, wherein the hardware located in different geographic locations can be connected over a secure communication. All tests that can be performed in a PHIL and CHIL setup can also be performed using an RHIL setup. Remote CHIL is more commonly used compare to remote PHIL. This is due to the delays in the communication between facilities and these delays can make the PHIL experiments unstable, unreliable, and expensive. Even-though, solutions have been proposed in the literature to run remote PHIL, they are complicated and can be expensive to implement.

ADMS is a multi-application suite offering many functions to utilities. There are wide range of use cases that different stakeholders would like to test and address any issues before field deployment. A collaborative process using multi stakeholders is shown in Fig. 3 [8]. Once a use case and test plan are defined and prepared, the test bed can be configured for specific use cases.

III. Fault Location, Isolation, and Service Restoration

The goal of FLISR application is to quickly restore power to the affected customers by using automatic switching devices. Faster power restoration to customers improves the utility reliability metrics, such as the system average interruption duration index (SAIDI) and the system average frequency interruption index (SAIFI). The effect of FLISR on outage time is discussed using time charts in [12]. FLISR depends on information from different sources—such as fault indicators, breaker status, reclosers, and remote terminal unit (RTU) to

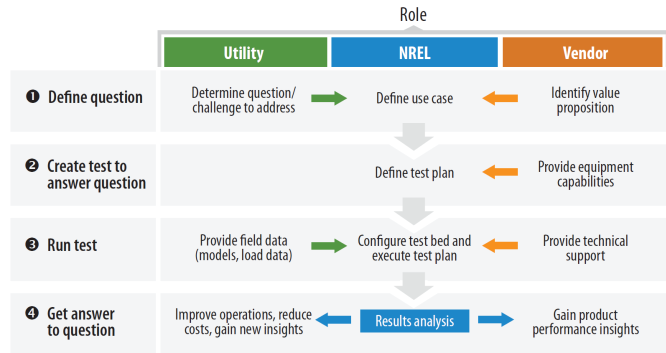


Fig. 3: Use Case Selection [8]

identify the fault location and optimally restore service to the customers.

The FLISR application is responsible only for dealing with permanent faults on the feeder and substation faults that cause the sustained loss of one or more feeders. Temporary faults must be cleared by reclosers, and there should be sufficient delay for all the backup devices before FLISR steps in. FLISR does not respond to power loss caused by blown fuses, manual tripping, and maintenance work [2].

Various architectures of FLISR deployment are [12]:

1) **Centralized FLISR:** The centralized approach is a model-driven solution, and it is implemented as an ADMS application at the main control center. Because FLISR uses a real-time power flow model, an optimized restoration solution can be achieved at the highest level with more complex switching and effective load distribution. The optimization algorithm used in the FLISR application considers the network constraints and protection relay settings to make decisions. After identifying the fault location, FLISR restoration plan is implemented through automation or with manual intervention. The accuracy of the solution provided by the application depends on the network model used in the DMS. To be more accurate, utilities need to continuously update the network model to reflect reality. In a centralized system, each device needs two-way communications to transmit the data and to receive instructions from the control center. This centralized approach requires a large bandwidth to operate and is susceptible to a single point of failure along the communications path.
2) **Distributed FLISR:** The distributed approach is a rule- or script-based solution and uses controllable devices at the switch/breaker location. These devices communicate among themselves using peer-to-peer communications infrastructure to determine the fault location and to determine the appropriate switching actions necessary for the restoration. The devices are distributed throughout the network, which makes it a highly reliable scheme; however, each switch location requires a controller.
3) **Substation FLISR:** The substation-based FLISR is a model-driven solution in which the controller is hosted

at the substation level instead of at the control center. Through implementing a substation-based FLISR, communications needed for monitoring and reconfiguring the network only need to extend from the field devices to the substation.

FLISR may be implemented in a variety of architectures; most utilities currently implement a centralized FLISR application for system-wide deployment [2]. Moreover, centralized solutions offer additional advantages, such as the ability to coordinate with other ADMS applications. A decentralized (distributed or substation) implementation is comparatively easier to deploy if the targeted number of feeders is fewer. The goal of this work is not to identify which architecture would be more suitable for different utilities. Requirements of utilities can change, and appropriate steps should be taken to finalize an architecture to meet the FLISR goals. Regardless of the architecture chosen, there are still steps in the typical FLISR application that are common to different architectures. They are:

Fault Location: The fault location algorithm is triggered by the action of any protective devices and real-time data received through field devices.

Fault Isolation: After identifying the fault location and feeder section, the goal of the fault isolation is to minimize the impact of an outage through a reconfiguration of the network using breakers, switches, and reclosers.

Service Restoration: Restoration takes into account the network constraints of a feeder that take up the faulted feeder load. The process closes tie-switches and the associated feeder switches to restore the healthy sections of the faulted feeder.

IV. Evaluation of FLISR Use Case

FLISR is an important and critical application offered by the commercial ADMS platforms which are deployed in distribution systems. FLISR enables automated power restoration through fault detecting, locating, and switching of smart devices. This automated function of ADMS reduces the number of interrupted customers and the minutes of interruptions by converting permanent outages into momentary outages. These outages affect the reliability and the resiliency of the system and are tracked through SAIDI and SAIFI metrics. Typically the SAIDI and SAIFI are calculated over long period of time (over a year). So, the metric data is not calculated for test cases discussed in the following.

A. Test Cases

The objective of the test cases is to evaluate the ADMS FLISR application through the software simulation setup. The FLISR application makes the switching decisions based on predefined rules set by the operating utility. The utilities design the switching schemes to reduce the number of customers interrupted by outages. In addition to SIL evaluation, FLISR actions can be tested in the PHIL and RHIL setup before being deployed in the field.

The one-line diagram shown in Fig. 4 is part of a utility's larger medium-voltage (12.47 kV) distribution system. ADMS

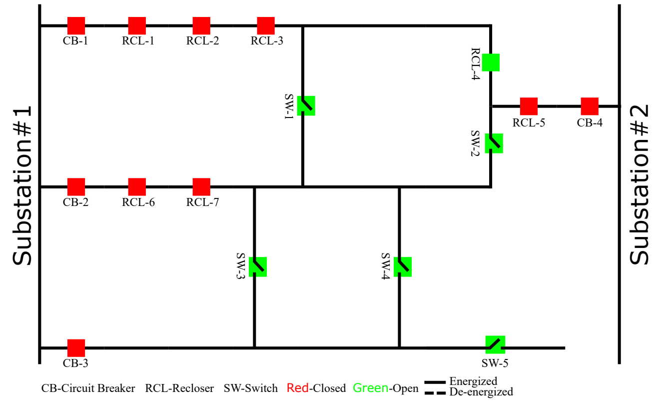


Fig. 4: One-line diagram of a utility test system in ADMS

is programmed to sense and control this distribution system. The test system in Fig. 4 has two substations with four feeders connected through reconfigurable switches (breakers, reclosers) and normally open switches. The low-voltage network containing loads are not shown in Fig. 4. Circuit breakers (CB-1, CB-2, CB-3, and CB-4) are feeder breakers located inside the substation. Reclosers (RCL-1, RCL-7) are used to detect the fault location, isolate the faulted section, and then reconfigure the network. Switches (SW-1 to SW-5) are used to manually reconfigure the network. In Fig. 4, the status of the switches are indicated by the colors red and green. Red indicates normally closed, and green indicates normally open. The test systems normal configuration is shown in Fig. 4. All the architectures discussed in section III can be evaluated the same way. The ADMS FLISR application used for this test network uses a centralized model-based architecture and is evaluated using the SIL.

1) Test Case 1: Fault Between Recloser 2 and 3: A three-phase permanent fault is placed between reclosers RCL-2 and RCL-3 in the simulated model of the test system as shown in Fig. 4. A fault in the system leads to a sudden increase in current, which is normally detected by the reclosers and breakers. RCL-2 and RCL-3 detects the fault current and opens the recloser to protect the line. Because of the high rate of temporary faults, utilities employ the three- or two-shot reclosing on to the disconnected network and restore power. It is important to remember that the FLISR application does not act until the recloser locks out after the final failed reclosing attempt.

In Fig. 5, RCL- 2 and RCL-3 are open, and part of the network is de-energized, which is shown as a dashed line. The real-time graphical user interface in ADMS shows the de-energized network as a white line in Fig. 6. After the failed reclosing attempts, FLISR acts to close the normally opened recloser RCL-4 and energizes the network up to RCL-3 and SW-1. The planned reconfigured network through FLISR switching is shown in Fig. 7. The planned actions are validated through the ADMS SIL setup. Fig. 8 shows that the network from RCL-4 is energized up to RCL- 3 and SW-1.

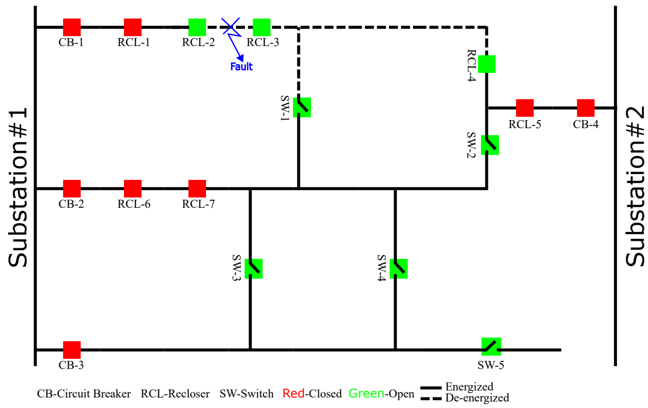


Fig. 5: Predefined operation of protection scheme for fault between RCL-2 and 3

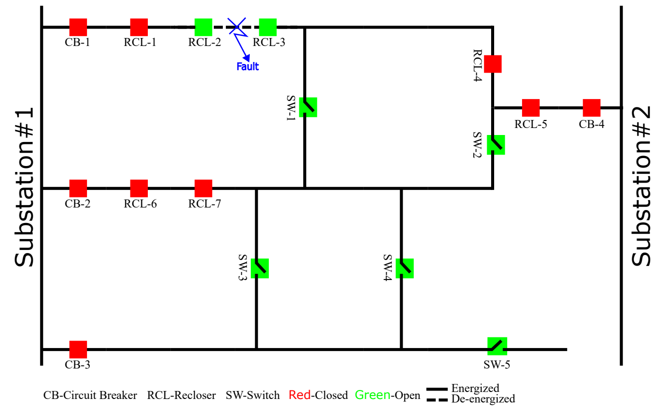


Fig. 7: Predefined operation of FLISR scheme for fault between RCL-2 and 3

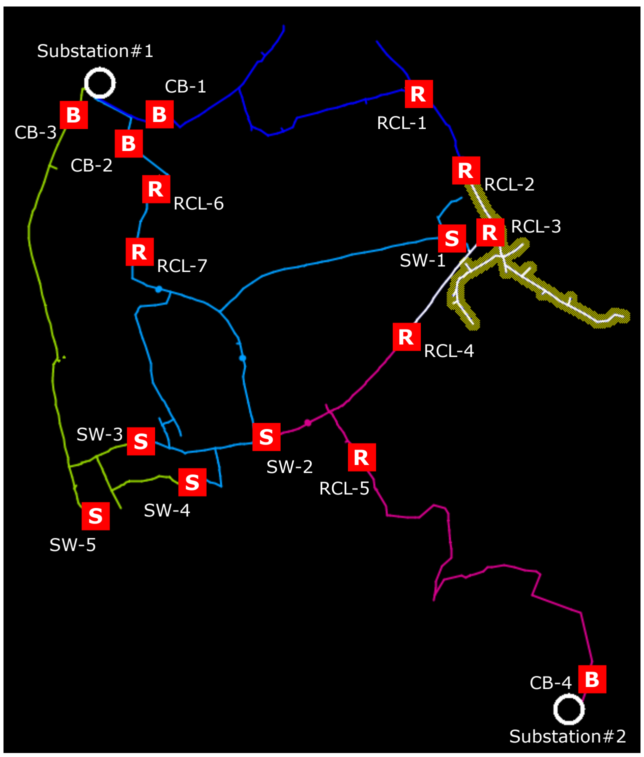


Fig. 6: Protection scheme evaluation for fault between RCL-2 and 3

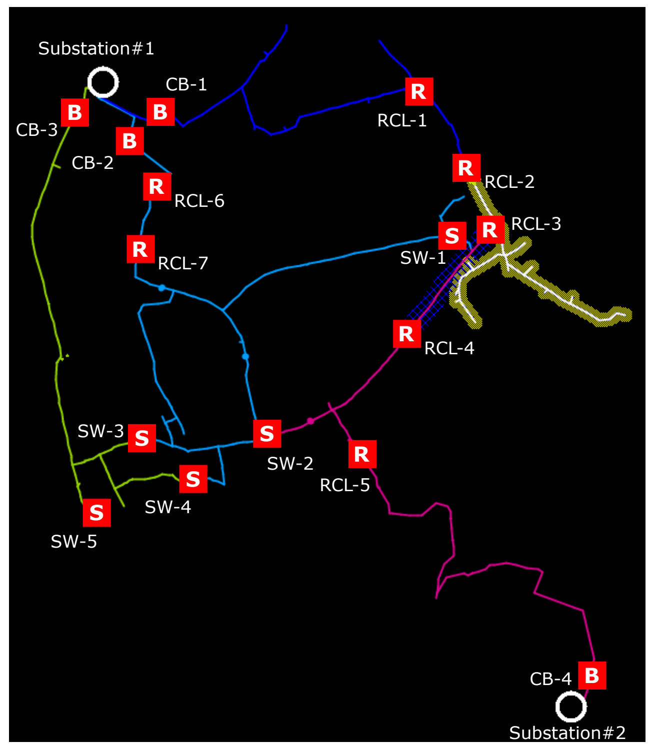


Fig. 8: FLISR operation for fault between RCL- 2 and 3

2) Test Case 2: Fault Between Recloser 6 and 7: A three-phase permanent fault is placed between reclosers RCL-6 and RCL-7 in the simulated model of the test system as shown in Fig. 4. A fault in the system leads to a sudden increase in current, which is normally detected by the reclosers and breakers. A high current detected by RCL-6 and RCL-7 triggers the reclosers to open and isolate the fault. The planned and evaluated de-energized part of the network with open RCL-6 and RCL-7 is shown in figs. 9, 10. Because the de-energized network is surrounded by the manually operated switches, automatic reconfiguration of the network through FLISR action is not possible. This test case is chosen to highlight the importance of smart switches, which can reduce customer interruptions.

V. Conclusions

ADMS is becoming a key infrastructure for utilities operating distribution systems. Understanding the evaluation requirements of the ADMS applications is critical for the success of these expensive investments. Different ADMS applications require different types of approaches that need to be employed for ADMS application evaluation. In this paper, we focused on the evaluation of FLISR application and presented the different FLISR architectures available to utilities. The in-the-loop setup that is commonly used in power systems and power electronics

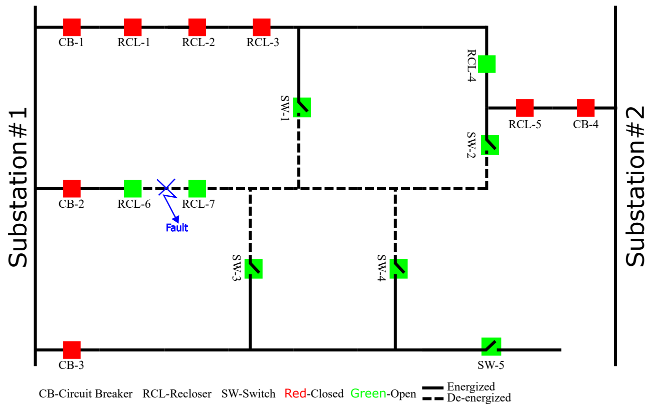


Fig. 9: Predefined operation of the protection scheme for a fault between RCL-6 and 7

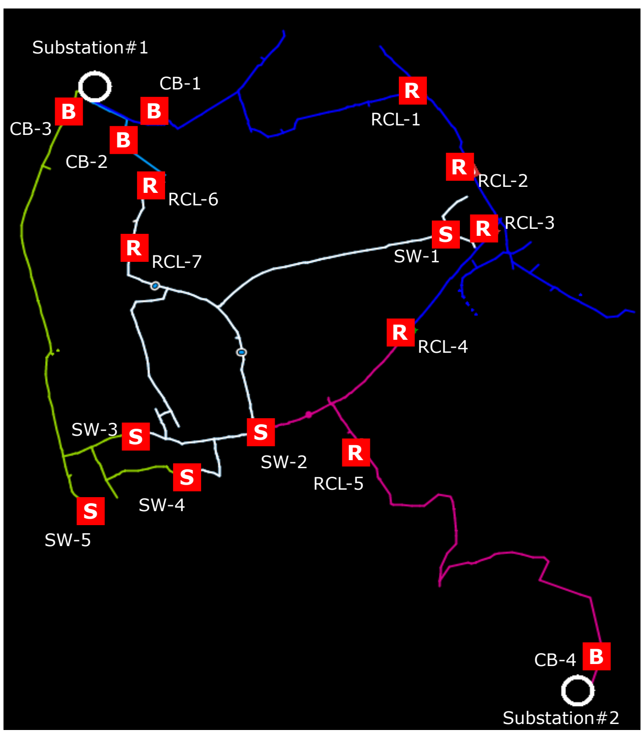


Fig. 10: Real-time operation of the protection scheme for a fault between RCL-6 and 7

evaluation purposes was leveraged in this work. In this paper, a simple SIL approach was used to evaluate the performance of a FLISR application in ADMS. Results showing the operation of the FLISR application under fault conditions were presented. In future work, this application will be evaluated in a CHIL setup with the key controllable devices modeled in controller hardware and the distribution system modeled in a digital real-time simulator.

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References

[1] E. Boardman, "Advanced Applications in an Advanced Distribution Management System: Essentials for Implementation and Integration," en, *IEEE Power and Energy Magazine*, vol. 18, no. 1, pp. 43–54, Jan. 2020.

[2] X. Lu, R. Singh, J. Wang, and J. T. Reilly, "Foundational Report Series: Advanced Distribution Management Systems for Grid Modernization, Business Case Calculations for DMS34871.pdf," Mar. 2017.

[3] S. Poudel, A. Dubey, and K. P. Schneider, "Advanced FLISR With Intentional Islanding Operations in an ADMS Environment Using GridAPPS-D," en, vol. 8, p. 13, 2020.

[4] S. Veda, H. Wu, M. Martin, and M. Baggu, "Developing Use Cases for the Evaluation of ADMS Applications to Accelerate Technology Adoption," en, in *2017 Ninth Annual IEEE Green Technologies Conference (GreenTech)*, Denver, CO, USA: IEEE, Mar. 2017, pp. 132–138.

[5] S. Veda, M. Baggu, and A. Pratt, "Defining a Use Case for ADMS Testbed: Data Quality Requirements for ADMS Deployment," en, in *2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA: IEEE, Feb. 2019, pp. 1–5.

[6] A. Pratt, H. Padullaparti, Y. Ngo, and H. Arant, "Defining a Use Case for the ADMS Test Bed: Fault Location, Isolation, and Service Restoration with Distributed Energy Resources," in *2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA: IEEE, Feb. 2021, pp. 1–5.

[7] N. Ainsworth, A. Hariri, K. Prabakar, A. Pratt, and M. Baggu, "Modeling and compensation design for a power hardware-in-the-loop simulation of an AC distribution system," en, in *2016 North American Power Symposium (NAPS)*, Denver, CO, USA: IEEE, Sep. 2016, pp. 1–6.

[8] A. Pratt, M. Baggu, F. Ding, S. Veda, I. Mendoza, and E. Lightner, "A Test Bed to Evaluate Advanced Distribution Management Systems for Modern Power Systems," en, in *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, Novi Sad, Serbia: IEEE, Jul. 2019, pp. 1–6.

[9] A. Pratt, I. Mendoza, M. U. Usman, S. Tiwari, H. Padullaparti, M. Baggu, and E. Lightner, "Using an Advanced Distribution Management System Test Bed to Evaluate the Impact of Model Quality on Volt/VAR Optimization," en, in *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Chicago, IL, USA: IEEE, Oct. 2020, pp. 1–5.

[10] K. Prabakar, B. Palmintier, A. Pratt, A. Hariri, I. Mendoza, and M. M. Baggu, "Improving the performance of integrated power-hardware-in-the-loop and quasi-static time-series simulations," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2020.

[11] K. Prabakar, A. Valibeygi, S. A. R. Konakalla, B. Miller, R. A. De Callafon, A. Pratt, M. Symko-Davies, and T. Bialek, "Remote Hardware-in-the-Loop Approach for Microgrid Controller Evaluation," en, in *2020 Clemson University Power Systems Conference (PSC)*, Clemson, SC, USA: IEEE, Mar. 2020, pp. 1–8.

[12] P. Parikh, I. Voloh, and M. Mahony, "Fault location, isolation, and service restoration (FLISR) technique using IEC 61850 GOOSE," en, in *2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC: IEEE, 2013, pp. 1–6.