RESEARCH ARTICLE

Implementation of a software defined FLISR solution on an active distribution grid [version 1; peer review: awaiting peer review]

Darren Leniston1, David Ryan1, Clem Power2, Paul Hayes3, Steven Davy1

1Programmable Autonomous Systems Unit, Walton Institute for Information and Communication Systems Science, Waterford City, Waterford City, Co. Waterford, Ireland
2Electrification Innovation & Delivery Network Assets, ESB Networks, Rathnapish, Co. Carlow, Ireland
3Electrification Innovation & Delivery Network Assets, ESB Networks, Cork City, Co. Cork, Ireland

Abstract
Background: The resiliency of the distribution grid is of increasing concern to the distribution system operator (DSO) due to factors such as climate change and the resulting faults caused by inclement weather conditions, leading to service disruption to consumers. Loss of service negatively affects key performance indicators (KPI) of the DSO, such as customer minutes lost (CML) and customer interruptions (CI), leading to financial penalties imposed by the regulator.
Methods: In this paper we propose a software-driven Fault Location, Isolation and Service Restoration (FLISR) solution, leveraging modern software and communication technologies married with the DSO’s existing infrastructure, to aid fault detection and resolution, with the aim of reducing CMLs & CIs and curtailing the financial penalties incurred.
Results: The proposed FLISR solution was trialled in an area of south-east Ireland which sees a higher count of service loss as compared to more inland areas, providing an ideal environment to gauge the effectiveness of the solution. It was found that the solution generated outputs that could potentially lead to the resolution of fault events faster than the current systems in place by the DSO.
Conclusions: Based on the results gathered from operating the FLISR solution on an active grid, it has demonstrated that leveraging modern software technologies in tandem with existing grid infrastructure benefits the DSO with reference to grid management and operations and the customer in terms of quality of service site.

Keywords
FLISR, Smart Grids, Self-Healing, Distribution Automation, SCADA
This article is included in the Societal Challenges gateway.

Corresponding author: Darren Leniston (darren.leniston@waltoninstitute.ie)

Author roles: **Leniston D**: Conceptualization, Software, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; **Ryan D**: Software, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; **Power C**: Conceptualization, Methodology, Validation, Writing – Review & Editing; **Hayes P**: Conceptualization, Writing – Review & Editing; **Davy S**: Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no 883710) project EdgeFLEX (Providing flexibility to the grid by enabling VPPs to offer both fast and slow dynamics control services).

Copyright: © 2021 Leniston D et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: Leniston D, Ryan D, Power C et al. Implementation of a software defined FLISR solution on an active distribution grid [version 1; peer review: awaiting peer review] Open Research Europe 2021, 1:142
https://doi.org/10.12688/openreseurope.14115.1

First published: 29 Nov 2021, 1:142 https://doi.org/10.12688/openreseurope.14115.1
Introduction
In an era where climate change is being linked to more frequent and powerful storms, the need for resilient power systems is growing. In recent years the energy sector has been going through a transformation from a hardware to software orientated focus with the emergence of Internet of Things (IoT) technologies and Artificial Intelligence. This is leading to large bodies of research, with an aim to increase grid resiliency, cater for the integration of renewable energy resources (RES), and exploit data gathered from the electrical network to provide analysis techniques that can detect faults on the system and aid in restoring power in a way that will impact fewer consumers. The motivation for this research is centred on economic and quality of service grounds, focusing on how the restoration of supply to as many consumers in the shortest time period possible obviously benefits the consumer, but also saves the distribution system operator (DSO) from the imposition of financial penalties for customer minutes lost (CMLs). FLISR is one such technique, and in this paper we present a software based approach that utilises grid models coupled with real-time data gathered from certain existing pole-mounted grid components, namely electrically and remotely operable switches & reclosers. The following sections frame the research, expand on the motivation and background work that formed the basis of the software implementation, and how the proposed technique leverages existing data sources and hardware components. The results are presented, followed by the future work and conclusion where the potential of the research in the DSOs operations is discussed with the next steps needed to realise the potential of the proposed solution.

The FLISR solution described in this paper was tested on sections of the distribution grid located in key locations in Ireland, where the effect of adverse weather conditions on exposed and vulnerable networks causes higher occurrences of loss of supply to the consumer. The trial sites in question employ grid resilience strategies on the medium voltage (MV) network to curtail the effect of faults on consumers and the financial penalties imposed on the DSO, these strategies take the form of manual and automated schemes operated by pole-mounted switches and reclosers. While these strategies go some way to reducing the impact of faults, they possess certain limitations. For example, the pole-mounted switches are load break fault make (LBFM) remotely operable switches, and as such they do not open/close autonomously. The switches communicate with the DSOs supervisory control and data acquisition (SCADA) system, assisting control room operators (CRO) in identifying the faulted section of network. Subsequently, the manual opening and closing operations are performed remotely from the National Distribution Control Centre (NDCC) to sectionalize and restore supply. This requirement for manual intervention on the part of the CRO to operate the switches introduces bottlenecks in the speed of fault resolution and ultimately increases the cost to the DSO. The introduction of loop automation through pole-mounted reclosers goes some way in mitigating the efficiency concerns observed with manual intervention. Within this configuration, reclosers operate as their own autonomous islands with no requirement for intervention from the central control room. In the event of a fault, reclosers operate autonomously based on timers and loss of voltage. This approach has some disadvantages however, as the faulted section can at times be re-energised by alternative supply before it is isolated from the network. Additionally, the pole-mounted reclosers only operate autonomously when part of a loop automation scheme. In relation to the Irish distribution grid, the DSO observed that earlier versions of pole-mounted reclosers required re-commissioning, as their firmware did not originally support loop automation functionality, thus leading to a large financial investment. Though the autonomous nature of this scheme resembles some characteristics of self-healing, it does not meet the requirements of the self-healing concept. In relation to the smart grid, self-healing describes the capacity for the systems existent on the distribution network to act autonomously to restore themselves in the event of a sustained or permanent fault and such systems should leverage information and communications technology (ICT) to enable monitoring, control and data management. These factors provided the motivation to explore the development and implementation of an autonomous, software-driven solution for the Irish distribution grid. The solution applies the concept of FLISR and is supported by back-bone services to collect and analyse data streams from pole-mounted devices in the field. The goal of the FLISR concept is to optimally restore supply to the largest number of consumers as possible, by intelligently and autonomously isolating and reconfiguring the affected parts of distribution grid.

Methods
Proposed FLISR solution to enable grid awareness and restoration
The implementation of the proposed FLISR system commenced with devising a series of fault restoration steps for a portion of the distribution grid located in the south-east of Ireland. The site was selected for its proximity to the coast resulting in a higher occurrence of fault events and service disruption compared to inland areas, its structure as a complex radially fed network of single and three phase lines, shown in Figure 1, and a lack of an existing loop automation scheme.
The trial site network is divided into four primary sections, supplied by one of three 38kV substations with a total of five MV feeders. Each section contains a number of assets, including pole-mounted switches and reclosers that are identifiable through a unique SCADA ID, with select devices designated as normally-open (N/O) points to facilitate interconnection to adjoining outlets. Figure 2 describes in more detail the circuitry of the trial site distribution grid. A subsection of this network was selected as a starting point for developing the FLISR solution, presented in Figure 3.

The selected subsection E11 is fed supply from a 38kV substation, with connection to an adjoining circuit and sections E13 and E31 through interconnecting normally-open devices, providing a source of back-fed supply if necessary. Pole-mounted devices on the line communicate two key data points in the event of a fault; a fault passage indicator (FPI) and a loss of voltage indicator (LVI), which are used by the CRO to determine the
approximate location of the fault, after which the faulted section is isolated and supply is restored from an adjoining section or circuit through closing a normally-open device. The DSO used their in-house expertise to investigate the E11 line and determine all permutations of fault events that could occur, and the effective resolution steps for each, and these were correlated into “fault cases” as presented in Table 1.

The automatic statuses of the pole-mounted devices were contrasted against recommended operations which were formulated to resolve each of the fault cases in the most efficient manner. Taking the fifth fault case as an example, where a fault has occurred between recloser R518 and switch S509, as illustrated in Figure 4.

The following Table 2 describes the status of each device (FPI and LVI) and its automatic status in the event of a fault before manual intervention, with the recommended operations contrasted.
In the above case, the recommended actions result in isolating the fault by opening switch S509 and closing the N/O point, thereby back-feeding from line E13 and restoring supply, as illustrated in Figure 5.

To aid the development of the FLISR software algorithm, a decision tree was created based on the fault cases described in the above table. This decision tree provided a graphical representation of the processing logic for the fault cases, a portion of the decision tree is presented in Figure 6.

**Operation of the FLISR Solution on an Existing Distribution Grid**
The FLISR algorithm developed as an output of the above research requires real-time data from pole-mounted devices that match the FPI and LVI values outlined previously. Switch and recloser devices each have a set of unique data points which correspond to the asset’s current operational status, communicated to the DSO’s SCADA system via a wirelessly enabled Remote Terminal Unit (RTU) employing the International Electrotechnical Commission (IEC) protocol standard, IEC 60870-5-101/104. Through this protocol, the data points map to an information object address (IOA), and the devices are identifiable through a unique application service data unit (ASDU) type. Two data points that match FPI and LVI were identified for both switches and reclosers, described with their corresponding IOA value in Table 3.

| **Table 1.** List of fault cases for the E11 line. |
|-----------------|-----------------|-----------------|
| **Fault case** | **Fault location** | **Recommendation** |
| 0              | No fault        | No recommendation |
| 1              | Between E11, S696, S507 and S696 | Open S696, Close N/O (S697 or R584) |
| 2              | Between S696, S507 and R584 | Open S696, S507, Close E11, Close N/O (S697) |
| 3              | Between S507 and S508 | Open S508, S508, Close E11, Close N/O (S697) |
| 4              | Between S508 and R518 | Open S508, R518, Close E11, Close N/O (S697) |
| 5              | Between R518 and S509 | Open S509, Close N/O (S697) |
| 6              | Between S509 and S697 | Open S509, Close R518 |
| 7              | Fault detected  | Inconclusive reading - investigate further |

**Figure 4.** Fault case circuit.

**Table 2.** Fault case device status and recommended operation.

<table>
<thead>
<tr>
<th><strong>E11 Line</strong></th>
<th><strong>E11 CB</strong></th>
<th><strong>S695 N/O</strong></th>
<th><strong>S696</strong></th>
<th><strong>R584 N/O</strong></th>
<th><strong>S507</strong></th>
<th><strong>S508</strong></th>
<th><strong>R518</strong></th>
<th><strong>S509</strong></th>
<th><strong>S697 N/O</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>FPI</td>
<td>false</td>
<td>N/A</td>
<td>false</td>
<td>false</td>
<td>true</td>
<td>false</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVI</td>
<td>false</td>
<td>false</td>
<td>false</td>
<td>false</td>
<td>true</td>
<td>true</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto status</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recommended ops</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td>open</td>
<td>close</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. FPI and LVI mapping to switch and recloser devices.

<table>
<thead>
<tr>
<th>Data point</th>
<th>Switch data</th>
<th>Recloser data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault passage indicator</td>
<td>Fault current - IOA 4</td>
<td>End of protection sequence - IOA 27</td>
</tr>
<tr>
<td>Loss of voltage indicator</td>
<td>AC supply fail - IOA 2</td>
<td>Controller locked out - IOA 34</td>
</tr>
</tbody>
</table>
The devices communicate operational data when triggered by an event on the distribution grid; in the case of a fault, all affected devices communicate a combination of data points. Devices on the faulted section communicate FPI and LVI, while devices on sections which have lost supply but are otherwise undamaged, communicate LVI. Device data is collected through supplementary communication hardware installed within the existing pole-mounted devices on the trial site grid. This new communication hardware utilises IEC 101 to MQTT (message queueing telemetry transport) communications, a lightweight messaging protocol suitable for systems with large numbers of IoT enabled assets, due to its speed, scalability and network bandwidth efficiency\(^4\).

Device operational data captured from the field is accessible to the FLISR solution and used to generate fault location and restoration outputs. The FLISR solution is also supplied with a grid model of the trial site, containing asset data for pole-mounted devices including SCADA and ASDU identifiers, device type (switch or recloser) and N/O status. As a result, the FLISR solution is aware of each pole-mounted device and its position relative to other devices, thereby achieving a system awareness that did not exist previously.

**FLISR algorithm operation**

In operation, the FLISR solution constantly monitors activity from the pole-mounted devices. When a fault occurs on a section, each pole-mounted device affected will communicate their status (FPI and LVI). The FLISR solution uses the detected device’s ASDU identifier, referenced against the grid model, to identify the section in which the fault has occurred. From this point, the FLISR solution retrieves all last available readings from pole-mounted devices on the affected line to build a fault case, which takes the form of a data structure that is parseable by the FLISR algorithm. The fault case contains the faulted device’s ASDU identifier, FPI/LVI IOA address and value. an example for the fifth fault case and the translated meaning is presented in Figure 7.

The assembled fault case is processed by the FLISR algorithm. Working backwards from the end of the line, the algorithm locates the faulted section by identifying occurrences of FPI and LVI readings from devices. The FLISR algorithm will then determine recommended restoration steps, suggesting which devices to open in order to isolate the fault, such as the two devices at either end of the fault and, depending on the position of the normally-open points on the line, which devices to close in order to return supply. The algorithm operates in two parts: first, it uses measurement data to create a resulting set of devices in the grid model that communicated a fault reading (FPI and LVI). This result set is then passed to the main FLISR algorithm to determine fault location and recommend the appropriate restoration steps. The algorithms described for the FLISR solution have been developed to be generic so as to apply to any section of network, with the fault cases highlighted previously serving to validate the algorithm outputs. The operation of the FLISR algorithm is illustrated in Figure 8.

**FLISR solution output to DSO operations**

While it is possible to enable bi-directional communications and enact opening/closing operations on the polemounted devices through the FLISR solution, to mitigate the DSO's concerns relating to full automation, this is not enabled. Once the FLISR solution has completed processing a fault event, the DSO’s operations staff is notified via email, reporting details of the faulted devices, the approximate location of the fault as identified by the FLISR algorithm and the recommended restoration steps. This allows for a human operator to be included in the loop and verify that the FLISR solution has recommended reasonable steps to isolate and restore the detected fault, Figure 9 illustrates an email report generated by the FLISR solution in reaction to a fault on the trial site, with the fault location identified highlighted on a geographical map.

\[
\text{[} \{41816, 4, 1(ON)\}, \{41816, 2, 1(ON)\} \text{]}
\]

\[
\text{[} \text{Device R518, End of Protection Sequence (FPI), True}, \{ \text{Device R518, Controller Locked Out (LVI), True} \} \text{]}
\]

**Figure 7.** Generated fault case translated.
Figure 8. FLISR algorithm operation.

Figure 9. FLISR solution output and location on geographical map.
Results
Results from the trial site

The FLISR solution was deployed to monitor the chosen trial site distribution network over a period of four months, and during this time a number of fault events were captured by the system. However, during the initial operation of the solution, it became clear that fine-tuning of the software algorithm was necessary, as it was found that the system was generating a number of email reports per fault. The reason for this is due to the mechanics of how fault events propagate on the network from their point of origin. In the event that a fault occurs, the pole mounted switch that initially detects the fault communicates a data payload of FPI and/or LVI to both the DSO’s SCADA system and also to the FLISR solution. As the loss of supply is detected along the line by the switches following the faulted section, they in turn also send an individual FPI and/or LVI data payload as illustrated in Figure 10. In theory, each switch should detect and communicate the loss of supply instantaneously, though in practice a very slight delay was observed between data payloads communicated from each faulted switch.

As a consequence, the FLISR solution was detecting each data payload as a separate fault event due to the speed of the solutions operation, therefore generating incorrect results. To mitigate this, the solution was refactored slightly to ensure an email report was generated only after a fault event had completely propagated throughout a line, leading to an increase in the amount of time between the detection of fault event and generating an email report, though only by a fraction of a second. Exploring the results subsequent to the refactor, the average time from fault detection and an email report received fell within a one minute bracket. Table 4 presents a selection of fault results detected by the FLISR solution, including the time of fault detection and receipt of email report.

For this first iteration of the system, the intention is for the generated email report to be forwarded to the DSO’s central control room, whereby a human operator would verify the validity of the report and the fault resolution steps suggested and act on these recommended steps according to their judgement, thereby reducing the amount of time for an operator to manually locate the fault, verify it is a true fault event and finally decide on and enact a set of steps to resolve the fault. From the results presented above, the timing between fault detection and

![Figure 10](image_url) Propagation of fault through a line.

<table>
<thead>
<tr>
<th>Faulted devices</th>
<th>Fault detected</th>
<th>Email report received</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11 - S508, R518</td>
<td>19/06/2020 - 17:57:17</td>
<td>19/06/2020 - 17:57</td>
</tr>
<tr>
<td>E11 - R584, R518</td>
<td>25/06/2020 - 11:40:05</td>
<td>25/06/2020 - 11:40</td>
</tr>
<tr>
<td>C19 - S716</td>
<td>28/06/2020 - 01:11:00</td>
<td>28/06/2020 - 01:11</td>
</tr>
<tr>
<td>E13 - S699, S698</td>
<td>08/07/2020 - 16:28:56</td>
<td>08/07/2020 - 16:29</td>
</tr>
</tbody>
</table>
reporting from the FLISR solution is minimal, potentially leading to a substantial reduction in the delay from fault detection and resolution when complete human intervention is required, and therefore a significant saving in terms of penalties incurred by CMLs.

Relevance to the DSO
This is significant as looking to the DSO’s performance reports, in 2019 service loss stood at 87.47 CML per customer (excluding storm events), resulting in a total financial penalty of 2.79m€. Within certain EU territories, the relevant energy regulator imposes financial penalties on the DSO for the number of CMLs or CIIs accrued per customer. In relation to Ireland, such regulatory policies are enforced by the Commission for Regulation of Utilities (CRU). For the Irish DSO this means that fines begin to accumulate once a fault event breaches an amount of CMLs that exceeds three minutes. With this in mind then, it is not only vital for the DSO to resolve faults in a timely fashion for the sake of the customer, but also to reduce the financial implications to the DSO to as high a degree as is possible. In practice, due to the manual operation required to operate pole mounted switches discussed previously, it may take well beyond the three minute threshold for a fault event to be detected and ultimately resolved on a distribution grid.

The potential benefits of a FLISR solution such as the one described in this paper is compounded further when taking the effects of climate change and extreme weather events and their effect on the distribution network into account. Such disastrous effects were demonstrated in Ireland in 2017 by the enormous negative impact caused by ex-hurricane Ophelia, which resulted in almost 400,000 customers without power and a total of 11.7 million customer hours lost (CHL) according to the DSO’s 2017 performance report. As climate change and the resulting weather events continue to increase in size and severity in the future, the need for intelligent, automated systems to be made available will inevitably increase, exemplified by the Irish DSO’s own plans to increase the self-healing capabilities of the distribution network by 2027 by introducing new smart technologies and systems. The FLISR solution and related research described in this paper has the potential to meet the needs of the DSO and with further development has the capability to benefit both the DSO and energy consumer by not only aiding operations in the here and now, but also hardening the distribution grid against future challenges.

Potential improvements
While the FLISR solution algorithms were developed, tested and implemented using predefined test cases to validate the solution outputs, such validation could have been further enhanced with the use of a simulated environment. As the structure of the distribution network is known, it would be possible to create a software simulator which would generate simulated fault events that would then trigger the FLISR solution to generate outputs. This would enable another layer of validation before implementing the solution on the trial site. Additionally, such a simulator would also enable the capability to simulate distribution grids located in a number of diverse locations, offering insight into the potential benefits of the FLISR solution in locations with unique operational challenges or network configurations. Although the development and implementation of such a simulator was outside the scope of work for this particular piece of research, further iterations would greatly benefit from its introduction.

Conclusions
In this paper we have discussed how the DSO’s research on the best steps to isolate and resolve faults on part of an active distribution grid informed the development, implementation and testing of a novel software-driven FLISR solution. The proposed solution utilizes modern software and communication technologies in conjunction with existing grid models and pole-mounted devices on the trial site to provide system awareness, monitoring of fault events, and the generation of recommended steps to isolate and restore service, communicated to DSO system operators for enactment. From the results gathered, the delay in fault detection and reporting is minimal, leading to a potential reduction of the negative financial impact of CMLs as a result of fault events. The proposed FLISR solution could be enhanced further with the aid of network operators, validating the FLISR recommendations and suggesting changes to FLISR reporting. With such validation in place and further development, an intelligent, fully autonomous version of the FLISR solution could be realised, enabling bi-directional control of pole-mounted devices and achieving full self-healing capability, further reducing the delay in fault resolution. Given the increasing disruption to the grid by climate change and the introduction of RES and distributed energy resources, the need for solutions that lever existing DSO data streams is apparent. The application of back-bone services and communication technologies explored in this research can be further leveraged for other use-cases in the energy space to meet this need, such as ancillary services for grid stability and interactions between the energy grid and market to facilitate intelligent energy flexibility.
Data availability
Underlying data

This repository contains the following data and resources:

- E11_circuit_decision_tree.xlsx (decision tree for E11 circuit which informed the development of the FLISR solution algorithm, it represents graphically the conditions under which certain fault cases occur)
- E11_circuit_CIM.json (Common Information Model (CIM) representation of the E11 circuit, one of the lines on which the solution was trialled. This file is written in JavaScript Object Notation (JSON) format and contains metadata relating to nodes on this circuit and their location relative to other assets. These models were utilised to provide system awareness in terms of where pole mounted switches are located relative to one another to enable the FLISR solution to produce meaningful outputs)
- E11_circuit_sample_fault_data.csv (Sample data set of fault readings for the E11 circuit is provided in a comma-separated values (CSV) file for investigation or importing into a time series database)
- E11_circuit_test_case_seeds (Contains individual files to seed a time series database with fault data for each fault case scenario as described in the paper)

Data are available under the terms of the Creative Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).

The underlying data outlined relates to one of the circuits described in the paper and was provided by the Irish DSO. As the full trial site grid model contains information relating to real, live grid assets and customer details, it has not been made publicly available as part of this paper. Further information, including contact information to request additional data directly from the DSO, is available at the following resource:

ESB Networks: SOGNO H2020 Project Close-Out Report

References


17. ESB Networks: ESB Network 2027. 2015. Reference Source