STORM-PROOF AUTOMATIC FAULT ISOLATION AND RESTORATION SYSTEM FOR MEDIUM VOLTAGE NETWORKS

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ABSTRACT

The control-center-based automatic fault isolation and service restoration system (called FLIR), which was developed in 2012, has been tuned up for traditional overhead networks [1]. In case of an unknown faulted zone, FLIR has been forced to use a rolling sequence, which could end in numerous control commands. The more control commands the longer it takes and the bigger the risk to run into a telecommunication problem or to face another fault, which may cause the case to be aborted before the original fault has been isolated.

The tightening supply security requirements have forced DSOs to renovate their networks. Replacing overhead lines with underground cables is the most common technique to increase resilience towards natural hazards and extreme weather [2]. This evolution has been started in dense residential areas, which has led to a new structure of feeders, which typically consist of underground sections in the upstream zones and the remaining overhead sections in the rural downstream zones. Because these hybrid (structures of) feeders are not fully resilient towards weather, the question on how to optimally mitigate the impacts of high-impact, low-probability events (later called major events), awakened to think the meaning of fault clearing automation on a new basis.

This paper presents an extended, future-proof FLIR system that matches up both the original operating principles and a new approach for hybrid feeders. Some use cases are presented to compare the reduction of SAIDI and customer interruption cost between the different automation principles. Also, a proof of concept is enclosed to provide an overview, key results and user experiences of the system running at Elenia Oy.

INTRODUCTION

In the 2010s, Finland has faced many storm and snow load conditions, which have caused long outages in electricity supply. Therefore, the Finnish distribution system owners have experienced increased pressure to improve the quality of delivery because of tightening customer expectations and regulation. When the new Electricity Market Act 2013 came into effect, it gave a target according to which climatic conditions after year 2028 are not allowed to cause outages longer than 6 hours in town plan (towns, villages) areas and 36 hours anywhere outside of town plan areas [3]. The majority of DSOs estimate to reach the target by investing heavily in underground cabling [2].

Elenia, the second biggest electricity distribution company in Finland, has only built underground cable network since 2009. Elenia´s plan is to reach the target of the Act in schedule, which means huge investments in cabling. As the underground cabling rate is increasing rapidly, over 1000 km per year in a medium voltage network, fault isolation automation must be optimized in a new way to serve overhead line networks, mixed networks and cable networks, all with different principles. Therefore, Trimble and Elenia together study the issue to come up with a new solution.

RESEARCH QUESTION

FLIR has been widely exploited by several DSOs having rural networks that support automated network reconfiguration by remote-controlled switches (such as load break switches, disconnectors and reclosers) for sectionalizing, and tie points for interconnections. FLIR is based on seamless interoperability between the distribution management system (DMS) and SCADA. The roles of these subsystems are clear: DMS composes switching sequence proposals (later called *sequences*) and SCADA deploys them into real actions in the field and substations, either by being supervised by control-center operators or fully automatically. The automation utilizes detailed information from DMS about the assets in the as-operated network model, and the latest information from SCADA about the status and availability of the remote-controlled switchgear.

The main objective of FLIR is to reduce the outage times by speeding up fault location, isolation and service restoration under the following, often contradictory targets: (1) maximizing the number of out-of-service loads to be restored, and (2) minimizing the number of switching operations. The original FLIR is more inclined towards the first target in each separate FLIR case, as it is not uncommon that the fault isolation ends up with an execution of a relatively slow rolling sequence with numerous trials to restore service to a network segment that is not healthy.

The research question for the extended FLIR system is: Could it be more efficient, especially during major events, to adhere to the targets more comprehensively? In other words, could it be more reasonable to just quickly restore the weatherproof upstream zones and forge ahead to the next FLIR case? This method could reduce the number of switching operations significantly, and rather than maximizing the number of restored loads in each case, it could accelerate the restoration process as a whole.

PRINCIPLE OF EXTENDED AUTOMATION

In an interconnected circuit, the original FLIR is able to isolate the faulted zone and restore the service for the remaining parts using the main feed and top-rated back feed routes. In radial circuits, automation can only use the main feed route for restoration. Originally, the isolation process consisted of two methods called *immediate isolation sequence* and *rolling sequence*. Two additional methods have been added to the extended FLIR, one for restoring the weatherproof upstream of a hybrid feeder and another one for restoring the healthy upstream of a faulted feeder if such a segment can be detected based on computed fault distance.

The case classification (selection of the method to be used) and the main workflow elements of the alternative methods are presented in Figure 1 and Figure 2.

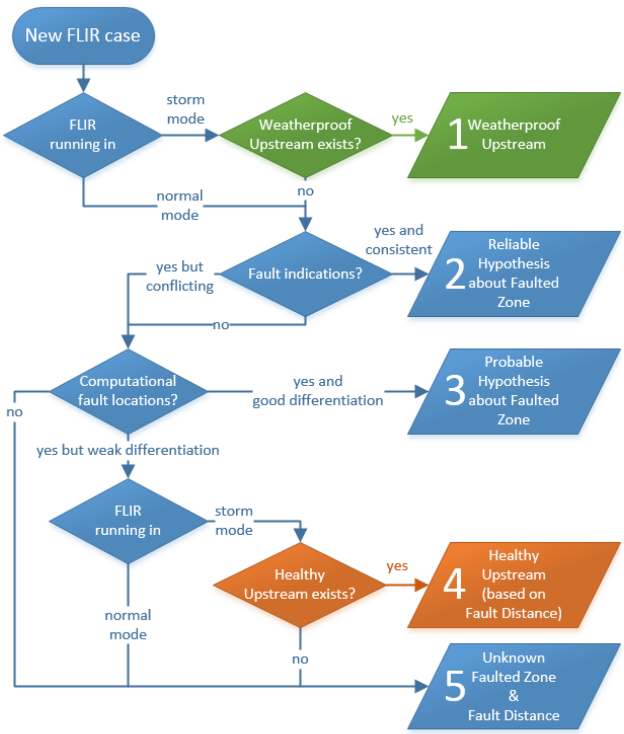

Figure 1. Operating principle – FLIR case classification

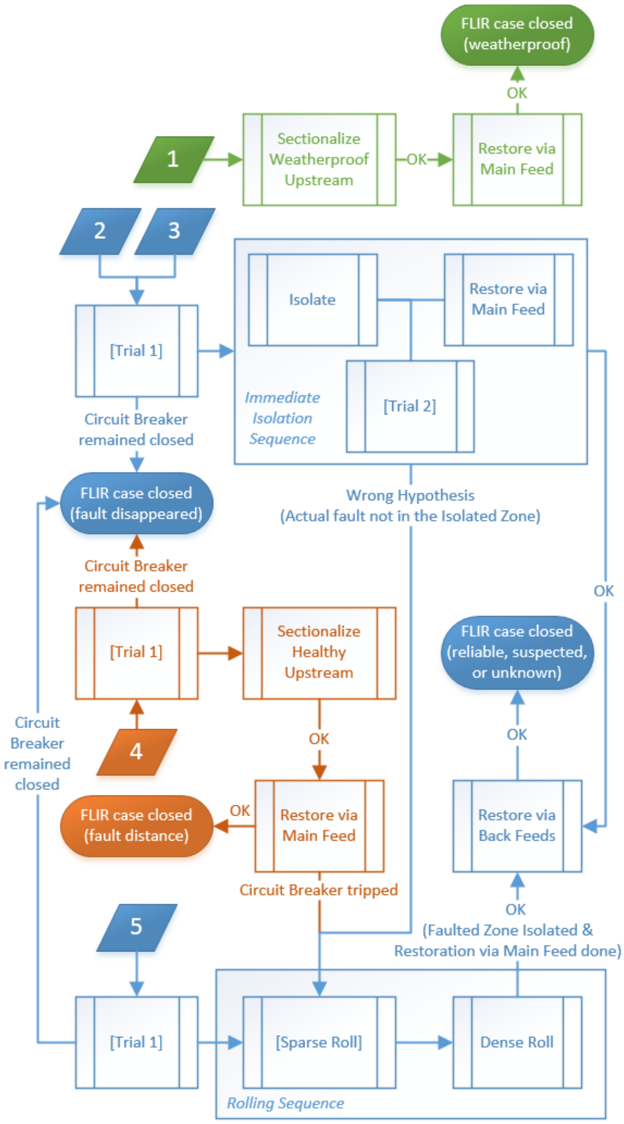

Figure 2. Operating principle – Main workflow elements

The extended FLIR runs either in normal or storm mode. Authorized control-center operators can change the mode if necessary. The next paragraphs summarize the operating principle.

(1) **Weatherproof upstream**. This new storm mode class is selected when the system can find one or many remote-controlled switches so that they border the largest possible resilient area (either the 1st zone or a group of interconnected zones) between the feeder circuit breaker and the switches to be opened. The verification of resiliency is based on the cabling rate.

(2) **Reliable hypothesis about the faulted zone**. This original normal mode class is selected when telemetered fault passage indicators exist in the network, preferably mounted at the interconnection points between the zones, and a consistent and reliable deduction of the faulted zone can be made based on the received indications.

(3) **Probable hypothesis about the faulted zone**. This original normal mode class is selected if the probability calculation function that combines the results of a computational fault location function and a fault frequency analysis, ends up with an evaluation of a certain zone being clearly more likely to be faulted than the others. Note that this and the previous class lead to the same method.

(4) **Healthy upstream based on fault distance**. This new storm mode class is selected when the system, after failing to reach any of the classes 1, 2 or 3, can find one or many remote-controlled switches so that they border the largest possible healthy area (either the 1st zone or a group of interconnected zones) between the feeder circuit breaker and the switches to be opened. The verification of health is based on computed fault distance with the consideration of a certain safety margin.

(5) **Unknown faulted zone and fault distance**. This original normal mode class is the fallback if the case classification does not succeed to reach any other option.

The high-level operating principle of FLIR is described in Figure 2. In this paper we are especially interested in the storm mode operation that is illustrated in the figure with green and orange colors and case classes 1 and 4 respectively.

Both the new case classes of interest differ from the already existing classes by having a totally independent isolation principle with the exception that the case class *Healthy upstream* has a fallback functionality to continue with a rolling sequence after an unsuccessful main feed restoration.

Interaction between SCADA and DMS

The interaction between SCADA and DMS is always initiated by SCADA due to security requirements as SCADA is typically running in the more secure network area. Technically, the FLIR-related communication takes place through a dedicated web service interface having a request-response type of methods, as indicated with blue color in Figure 3. The communication of information that is not directly FLIR-related (e.g. indications of switching state changes) takes place through the traditional communication protocols as before.

FLIR cases are independent of each other and there are no limits on how many cases can be run simultaneously. All cases follow the same communication flow regardless of whether FLIR is run in normal or storm mode. This is illustrated in Figure 3 and elaborated in [1]. Additionally, there is a poll request firstly to make sure that processing in DMS (e.g. the compilation of the isolation sequence) has been done before moving on to the next step and secondly to notify DMS of a case state which can then be visualized in the user interface.

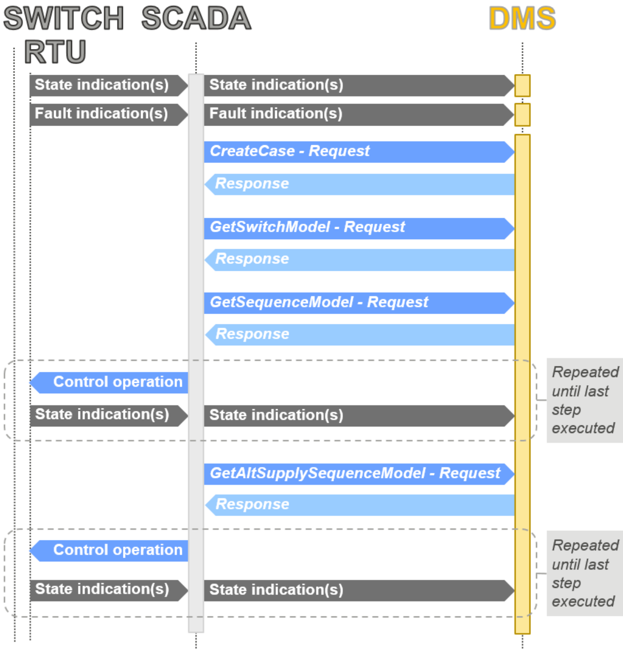

Figure 3. Simplified interaction diagram

IMPLEMENTATION CASE STUDY

Elenia's network area consists of 137 primary substations, 1161 km of 110 kV network, 26 037 km of 20 kV network, 24 941 secondary substations and 44 261 km of 0.4 kV network.

The original FLIR had been in use in Elenia's medium voltage network from October 2011 to March 2018. During this time, it successfully isolated 4400 outages. However, as the cabling rate of the network was constantly increasing, there emerged a need to develop a new approach to the FLIR operating principle, especially for major disturbance situations. Also practical experiences during these major disturbance situations proved that the rolling sequence typically contained too many control commands, which made the abortion probability of a FLIR case significantly higher. This was another main driver for the development work.

The production use of the extended FLIR began in March 2018 as the production use of the new DMS version started in Elenia. During this time, there have been 385 successful isolations. In general, the storm mode is planned to be used during major events when there are several outages ongoing simultaneously. However, the storm mode has also been used during normal operating hours in order to get experiences.

In Elenia, the cabling of urban areas and trunk lines of the network is often prioritized in order to first maximize the benefit for most of the customers. Therefore, the customers in the cabled network typically represent more populated areas. When a fault occurs in these types of fully or partly cabled feeders, the first controls of remote isolation have the most significant effect on customer experience and customer interruption costs. As the storm mode operation aims to quickly restore the power to the healthy network, the SAIDI effect and the customer interruption costs of the outage decrease, which results in better customer experience. In the future, the storm mode operation will concern most of the distribution network as the underground cabling becomes more common also in rural areas.

One of the key ideas of the storm mode is to have fewer and simpler switching operations for completing the fault isolation. There are several reasons supporting this idea. Firstly, FLIR needs to have remotely controllable disconnectors available. It is not possible to control them if they are offline or do not respond to commands. Secondly, certain type of incidents, such as thunderstorms, tend to cause many auto-reclosings for the same feeder. From this perspective, it is beneficial to isolate the cabled part from overhead lines and restore the power only to the weatherproof part. Thirdly, not only does this prevent the circuit breakers and disconnectors from ageing prematurely but also causes less auto-reclosings for customers in the weatherproof network who are justified to expect fewer auto-reclosings.

The advantages of the storm mode operation can especially be seen in a few different feeder topologies. Two simplified feeder topologies are presented in Figure 4, in which the storm mode operation is extremely useful. The dashed line represents the cabled lines, the solid line the overhead line and the vertical parallel lines the remote-controlled switches. In these feeders, the first operation should isolate the cabled section by opening the switches of the overhead line branches and restoring power to the cabled section. It is usually justified to assume that the cabled section is healthy because the fault rate of the cables is lower than with overhead lines and they are much more resilient to storms or snow loads.

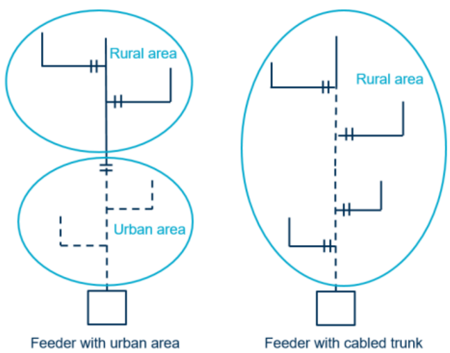

Figure 4. Examples of ideal feeder topologies for storm more operation

Performance comparison

Performance comparison between the normal and storm mode is challenging because their operating principles are somewhat different. In addition, the actual fault history does not contain identical fault cases run both in the normal and storm mode and thus prevents the comparison between these two. However, the difference was illustrated with a few simulations executed in Elenia's testing environment (of SCADA and DMS). A FLIR case of a single fault, located at the end of the feeder, was repeated in three sample hybrid feeders both in normal and storm mode. All three feeders had a cabled trunk in the beginning and remotely isolatable overhead line branches. After the switching sequences were completed, the customer interruption costs were calculated by DMS according to the Finnish regulation. In order to compare the cases, the rolling sequence of the normal mode operation was stopped at a situation identical to the outcome of the storm mode operation. In real use, the normal mode operation would have finished the isolation until the faulted zone was found but the storm mode operation gives the control to the operator. Therefore, the isolation speed would have had too many factors affecting the customer interruption costs.

The results and some basic information of the feeders are presented in Table 1 and Table 2. According to the results, customer interruption costs and customer hours are significantly lower when using the storm mode operation.

Table 1. Basic information of simulated feeders

Feeder	Overhead line length (km)	Cable length (km)	Connection points (pcs)
A	22.4	33.7	479
B	34.8	22.6	983
C	50.0	31.7	208

Table 2. Results from simulated feeders

Feeder	Running mode	Customer interruption costs (€)	Customer hours (h)
A	normal	1829	98
	storm	1175	49
B	normal	5019	141
	storm	4440	116
C	normal	703	30
	storm	487	14

User experiences

The user experiences of the storm mode operation have been promising but the new functionality has also required a new mindset for operators. Because of its novelty, all operators are not yet fully acquainted with the storm mode operation. The process of the isolation is different compared to the normal mode, which takes care of isolating the fault from the beginning to the end. The storm mode operation makes the initial isolation and gives the control to the operator after that. This requires a different type of attention from the operator especially during major events because the operators often need to make actions after a FLIR operation.

There are external factors that cause FLIR to fail its operation for some reason or another. These always happen abruptly and are difficult to be prepared for. A typical situation is the loss of telecommunication connection at the time of the remote control command. After that the only option is to abort the FLIR case.

The production use of FLIR has also revealed other issues related to the quality of network documentation as well as to the system configuration, which have partly hampered the evaluation of the benefits of the storm mode. Because of these issues, some FLIR cases were not completed successfully or they did not start at all.

However, the reasons for relatively low success percentage was investigated in order to reveal the root causes. The task was challenging because the only way to search for reasons is to go through all unsuccessful cases one by one and to manually search for possible reasons. According to the findings, there are several factors promoting unsuccessful cases. Most of the cases are caused by the incomplete SCADA configurations of the circuit breakers and the rest because of missing DMS-SCADA cross-references of switching devices, a changed switching model in SCADA or an interruption made by the operator. All of these issues cannot be fixed directly but the circuit breaker configuration issues were corrected during 2018 resulting in a remarkable increase in the success rate of FLIR cases.

In January 2019, a major event occurred in Elenia's network area causing over 200 outages. During this storm, the number of successful FLIR cases increased by 36%, which is a significant improvement. This also shows that in order to get full advantage of the functionality, the data quality of the system needs to be at a good level in order to provide FLIR the necessary information to function successfully.

CONCLUSIONS

Based on the experiences so far the storm mode operation in FLIR has already proved to offer several benefits compared to the normal mode operation. These include:

- Simpler and quicker supply restoration of the weatherproof part of the network.
- Decreased customer interruption costs and SAIDI.
- Customer experience improvement – e.g. because of reduction in auto-reclosings.
- Less stress for switching devices and the prevention of premature aging.
- Increased rate of successfully completed FLIR cases.

Additionally, the new FLIR also raised a few subjects in which to pay attention in the future as well:

- Maintaining the high quality level of network documentation.
- Increasing the understanding of operators in the new FLIR procedure as they get more responsibility for the isolation.

Development outlook

Even though the storm mode operation has given measurable benefits, there is still room for improvement. The more FLIR cases are successfully run over time the more thorough analysis and thus well-informed conclusions can be done.

Already now it can be stated that there are many, yet quite sophisticated, ideas on how to make FLIR work even more efficiently. One real world case is the situation where the weatherproof part of the network does not exist at the beginning of the tripped feeder. In that case it would be natural to isolate the weatherproof part first and then restore its supply using the main feed or back feed in the non-weatherproof part of the network.

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