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FUSE – using artificial intelligence in the energy grid of tomorrow

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Abstract: The objective of Future Smart Energy (FUSE), a Finnish-German research and development project, is to develop methods based on artificial intelligence (AI) that will help to increase the resilience of future energy distribution grids. The use cases that are investigated include both condition monitoring/predictive maintenance, and distributed demand-side management in medium-voltage and low-voltage grids. The FUSE concept foresees a hierarchical infrastructure of sensing- and data processing nodes that use AI to transform raw data into information on asset and grid status and performance. FUSE supports the upward flow of data and aggregation of information into high-level visualisations for grid operators, as well as the downward flow of soft control signals that trigger the distributed self-control of assets. This study outlines the FUSE concept and presents the first results.

1 Introduction

A well-functioning distribution grid able to deliver energy reliably and with high quality is the backbone of modern society. For distribution system operators (DSOs), keeping the grid operational and efficient requires considerable efforts for monitoring and maintenance. These efforts will have to increase in the future because the growing contribution of renewable energy sources will lead to new, cellular local grid topologies (with the possibility of bi-directional energy flows), more long-distance energy transmission from producers to consumers, and more fluctuations in energy production.

- Condition monitoring (CM) and predictive maintenance (PM), i.e. the optimisation of maintenance and repair of assets based on predictions of their behaviour and the occurrence of faults, can offer a tool to retain today's high quality of service in the distribution grid without exploding the maintenance costs.
- Distributed demand-side management (d-DSM), i.e. the (automated) adaptation of the energy demands of distributed loads to variations in energy production help to improve the stability of energy grids that include a high percentage of renewable energy sources.

The bi-national Finnish-German research project FUSE (Future Smart Energy) investigates the applicability of artificial intelligence (AI) for both concepts. The goal is to develop methods that improve the resilience of power grids, both on a medium-voltage (MV) and on a low-voltage (LV) level. In FUSE, both grid domains are connected through a hierarchical Information and Communication Technology infrastructure, with use cases, demonstrated both in Finland and in Germany.

In CM and PM, FUSE follows the concept to improve existing methods for asset-monitoring and fault detection with machine learning (ML). The objective is to identify potential problems earlier and with more confidence, and to enable grid operators to implement a flexible maintenance schedule based on actual risks and needs, thereby reducing costs.

In d-DSM, the project evaluates an innovative approach for the dynamic, automated and decentralised control of energy consumers based exclusively on (real-time and predicted) energy availability [1].

2 Methodology

2.1 FUSE architecture

FUSE implements a hierarchical infrastructure of nodes equipped with AI-based data processing and reasoning capabilities. The leaves of this tree (Level 1) are smart sensors that use lightweight algorithms for data-driven ML and data processing on embedded hardware. Level 1 nodes pre-process massive raw data (e.g. high-frequency measurements of grid parameters) and convert them into labelled information (e.g. on critical events, irregular system behaviour), which is propagated upward in the hierarchy.

Higher up in the hierarchy (e.g. Level 2), the information is aggregated and further processed, using a combination of data-driven and knowledge-driven AI methods. More complex information is generated, and suggestions are formulated by user-friendly visualisations to empower grid operators to understand the current and future state of the grid and to initiate appropriate management and maintenance measures.

The FUSE infrastructure supports CM and PM in both MV and LV grids. In the LV grid, the algorithms are also used for d-DSM to cope with energy congestion or shortage as a result of malfunctions and shut-downs in the MV grid.

While the FUSE demonstrator implements only a three-tier hierarchy (Fig. 1), the infrastructure is in principle fully scalable and can be extended with as many levels as required.

2.1.1 Level 1: On Level 1, raw data on system performance are collected, processed and analysed by smart sensors. The embedded sensor hardware consists of a processor for high-level data analysis, plus a programmable FPGA for low-level data pre-processing and parallel computations, such as the ones required in artificial neural networks. Both HW components are interconnected in a compact system-on-chip module, which enables the fast exchange of data.

In the MV grid, these smart sensors are used to identify and localise anomalies in power lines, transformers and feeder bays. Here, deviations from the standard condition are caused, e.g. by partial discharges (PDs). Temporal PD patterns are analysed to predict faults in the MV grid (e.g. in power lines) [2].

In the LV grid, physical interferences, such as harmonics, transients, voltage deviations and sags can cause poor power quality, affecting the network and its efficiencies, and even causing asset damages. The smart sensors on Level 1 can measure and even forecast these anomalies, as long as they are caused by specific loads in the grid. From both measurements and forecasts, features can be extracted to identify which device type and device condition is causing a specific change in power quality.

Other common grid-state values (e.g. main frequency or power consumption) are measured and forecast to support optimised demand-side management. The information is used to generate soft-control signals that are distributed through the grid infrastructure to the appliance controllers on Level 1. Here, they trigger a response, i.e. regulate the energy consumption of each individual appliance and thus make optimal use of its current flexibility reserve. Such is decentralised optimisation is expected to help stabilise the grid and reduce costs for the consumer – this will be further investigated in FUSE with future results.

The flexibility reserve of an appliance can be predefined or dynamically defined according to individual usage patterns. In FUSE, such patterns are learned on the Level 1 nodes from user behaviour, based on data recorded in the smart sensors and using ML algorithms on the Level 1 embedded hardware.

2.1.2 Level 2: Each Level 2 node represents a specific grid section or sub-system of which data are collected and pre-processed in multiple Level 1 nodes.

- In the MV use case, the objective on Level 2 is to achieve an overview of the state of the respective MV grid section and to identify and localise existing or pending system malfunction events. If possible, this includes the prediction of when and where this malfunction may happen.
- In the LV use case, we look at multiple Level 1 nodes that perceive the same power quality event generated by a device, but with different magnitudes. The algorithms on Level 2 use the Level 1 data to localise and create a map of all events.

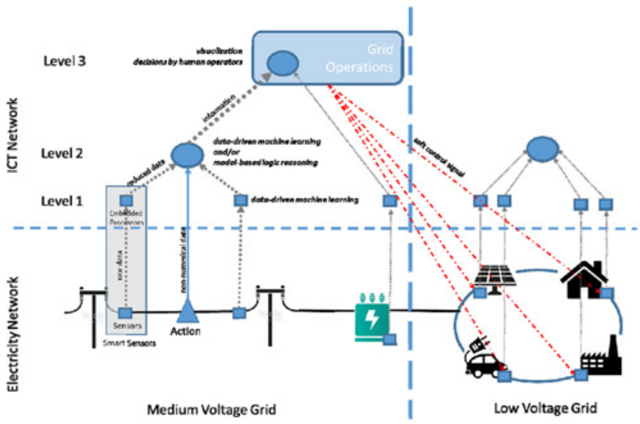

Fig. 1 *FUSE hierarchical infrastructure*

On Level 2, both present and future events are mapped by using direct measurements and forecasts, respectively. With this information as training data, the state of the grid section or sub-system is learned and used for both energy management and PM.

On Level 2, we investigate the combination of ML and rule-based reasoning. By using rule-based reasoning, implicit expert knowledge can be leveraged without the need to deduct this knowledge from training data. This is particularly useful for the identification and prediction of large-scale and serious fault events, which do not happen very often and thus are not well documented.

The hardware of Level 2 supports data fusion and real-time big data, ML and simulation algorithms. This allows us to make predictions about the functioning of individual assets and of the respective grid segment in real time.

2.1.3 Level 3: On Level 3, data and information from multiple Level 2 nodes are brought together and visualised in a user-friendly manner, using the Thingsboard framework [3]. Grid operators are enabled to view and evaluate the information created by the Level 2 nodes, to make decisions regarding maintenance measures, and to transmit respective soft control commands (e.g. to trigger the d-DSM controllers to reduce the power demand in the LV sub-grid) if needed.

2.1.4 5G communications: For the communication and data exchange between the nodes on Level 1 and Level 2, FUSE investigates the use of 5G technology.

Level 1 communication requires 5G user equipment (UE) capability. This can be implemented with 5G modems attached to the Level 1 embedded devices. Level 2 nodes correspond to both the 5G access network and the 5G core network, which are services provided by a telecommunications operator. In addition, other 5G services like mobile edge/fog computing may be used.

The 5G security mechanisms are an important part of the FUSE system functionality. These mechanisms include, e.g., device identity management, communication encryption and security monitoring with anomaly detection. In order to provide more advanced 5G communication services also micro-segmentation and slicing techniques can be used.

2.1.5 Tests and validations: The FUSE ICT infrastructure is tested and validated both in Vaasa, Finland, and with a pilot implementation in the SENSE Smart Grid Laboratory of TUB in Berlin, Germany [4]. Testing includes the integration of embedded hardware as well as the configuration of data interfaces and digital twins for selected assets.

3 Results

FUSE is an ongoing project. First results were achieved regarding the selection of data and algorithms that can be used for CM/PM and d-DSM in the MV and LV use cases.

3.1 CM/PM in the MV grid

In the MV grid, we looked at event data (e.g. control events, warnings, alarms) from protective relays, which operators had registered for concurrent fault monitoring [5]. To prevent damages to MV power equipment, faults need to be anticipated with enough lead time, and their root causes need to be identified and localised. To harness the full potential of the event data for fault prediction and root cause analysis, extensive persistence and a central collection of high-volume data are required. Also, the

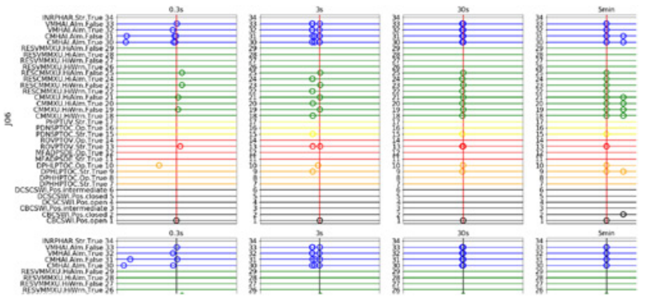

Fig. 2 *Fault visualisation for pre-indication pattern discovery by domain experts*

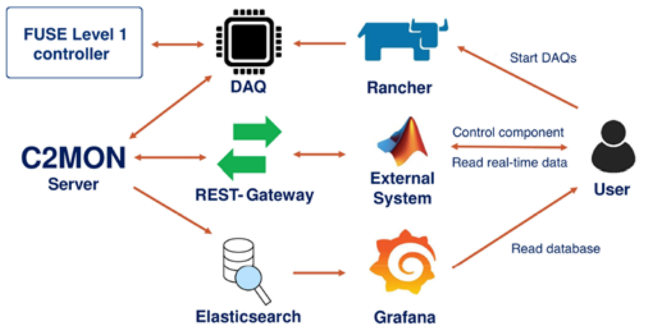

Fig. 3 *Integration scheme of the Level 1 controller into the control framework of the SENSE Smart Grid Laboratory*

sensitivity of thresholds for alarms and warnings needs to be calibrated (further increasing the number of data points) to allow the tracking of gradual fault evolution over long time periods.

We explored the potential of event data from protective relays for fault prediction by analysing a dataset of 80,000 data points recorded between May 2017 and September 2019 at a substation with 13 bays in the Finnish Noormarkku area. During this time period, 250 fault events (short circuits and earth faults), which can be categorised in 14 event types in 8 groups were registered.

The results are visualised in Fig. 2. For each fault event, we plotted all signals that occur in the fault's neighbourhood, both topologically (signals at neighbouring bays), and temporally (signals before and after the event). Signals are colour-coded by an event-type group to facilitate manual pattern recognition. The time resolution ranges over seven orders of magnitude, between 0.3 s and 3.5 days before and after the fault. This reflects the fact that characteristic event patterns, indicating the evolution of specific fault types, may occur on multiple time scales.

This visualisation allows domain experts to explore the data in various dimensions simultaneously to discover patterns of fault pre-indications. Such patterns may subsequently be formalised into rules for automated fault forecasting.

While the current data density proved to be too low to support the extraction of such rules purely based on data mining and ML, this may be possible – and will be explored in FUSE – with more dense data in the future.

3.2 LV network pilot implementation

The FUSE pilot for the LV grid was implemented in the SENSE Smart Grid Laboratory of TU Berlin. It comprises Level 1 embedded hardware and data interfaces to selected assets (LV energy consumers), as well as their parametrised digital twins in the lab, and interfaces to the FUSE ICT infrastructure. The pilot covers both the CM/PM and the d-DSM use case.

3.2.1 CM/PM application: For the CM/PM application, high-frequency data are recorded and used to train suitable ML algorithms. Using the EtherCAT protocol [6] according to IEC 61158, the data are recorded in hard real time to ensure a very high quality of the input data for the ML.

As of today, the first set of CM/PM training data has been recorded as the basis to develop the ML conceptual design. The data set includes current and voltage measurements with a resolution of 20 kHz and will be used for detecting power quality events, occurring in the LV network.

3.2.2 d-DSM application: For the d-DSM application, the Level 1 embedded hardware was integrated into the SENSE Lab control system architecture. This allows evaluating the behaviour of multiple assets controlled by the d-DSM controllers as a function of an external soft control signal. In the demonstrator, the signal is caused by a partial shutdown of the MV grid feeding the LV grid (Fig. 3).

The d-DSM pilot was implemented using three different application schemes for the investigated LV network cell:

(i) grid-connected cell with a high degree of self-sufficiency (non-congested PoCC),
(ii) grid-connected cell with frequency stabilisation and congestion management (congested PoCC),
(iii) islanded cell (grid-de-coupled PoCC).

The Level 1 controllers were fully integrated into the laboratory's SCADA system and are now subjected to stress testing for stability and reliability. Currently, they are controlling digital twins of energy assets before successful testing results will allow for control of physical devices in the lab. The first results look promising, but more detailed analysis is still needed [7].

4 Conclusion

FUSE, a bi-lateral Finnish-German R&D project, investigates the use of AI for CM/PM and d-DSM in both the MV and LV grids. The objective is to implement a hierarchical data processing infrastructure, enabling the distributed processing of data, generation of information and self-control of assets.

So far, the first data sets have been gathered in an MV demonstrator in Finland and the LV SENSE Lab in Germany, and tests with ML algorithms and visualisation tools were performed. The preliminary results are promising and support the FUSE concept. However, a further collection of data and optimisation of AI-based data processing, combining ML with rule-based methods, will be needed to achieve the objectives of FUSE.

5 Acknowledgments

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