Asset Performance Management application for power system condition monitoring in an Internet of Things platform

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Abstract of the master's thesis

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Abstract

Fingrid is making the transition from time-based maintenance to condition-based maintenance in order to increase the cost-efficiency of substation asset condition management and to prevent equipment failures. Digitalization improves real-time visibility to asset condition as Fingrid is developing an Internet of Things (IoT) concept for online asset condition monitoring.

The objective of this Thesis was to specify Fingrid's requirements for asset condition data visualization in an Asset Performance Management (APM) application. A secondary objective was to document Fingrid's IoT concept and existing condition monitoring practices. Asset maintenance strategies, digitalization and Internet of Things were discussed as a background. For the IoT data of switchgear, simple illustrations of dashboards were drawn to show how the data could be visualized in an APM application. Regarding power transformers, the necessary basic elements for condition data visualization were reviewed. Specifications for visualization of all the available condition data were listed in Appendices.

Online condition monitoring is currently concentrated on switchgear, power transformers and substation buildings. The IoT solution for switchgear consists of low-cost sensor units installed in switchgear control cabinets and bay marshalling cabinets. Power transformers are equipped with online DGA (Dissolved Gas Analysis) instruments which is a well-established practice. In substation buildings, the climate is monitored with low-cost IoT sensors.

The conclusion of the study was that there are two types of condition data that determine Fingrid's requirements for data visualization in an APM application: time series data and event data. Monitoring of continuous processes produces a large amount of continuous time series data. A tool with efficient functionalities for time series data presentation and analysis is needed. Switchgear operations and oil sampling produce event data that require visualization in forms of data reporting and special analyses. The amount of event data is small even though it will increase due to IoT.

Keywords IoT, Internet of Things, Condition Monitoring, Switchgear, Asset Performance Management, Data Visualization

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Tiivistelmä

Fingrid on siirtymässä aikaperusteisesta sähköasemien kunnossapidosta kuntoperusteiseen kunnossapitoon kustannustehokkuuden parantamiseksi ja laitevikojen ennalta ehkäisemiseksi. Reaaliaikaista näkyvyyttä omaisuuden kuntoon parannetaan kehittämällä "Esineiden Internet"(*engl. Internet of Things, IoT*) -konsepti omaisuuden käytönaikaiseen kunnonvalvontaan.

Tämän diplomityön tavoitteena oli laatia määrittelyt kunnonvalvontadatan visualisoinnille omaisuuden kunnonvalvontajärjestelmässä. Toisena tavoitteena oli dokumentoida Fingridin IoT-konsepti ja käytössä olevat perinteiset kunnonvalvontamenetelmät. Taustana työlle esiteltiin omaisuuden kunnonhallintamalleja, digitalisaatiota ja Esineiden Internetiä. Kytkinlaitteiden IoT-datan visualisoinnin tarpeiden hahmottamiseksi laadittiin luonnoksia kunnonvalvontajärjestelmän näkymistä. Muuntajien kunnonvalvonnan tarpeelliset osa-alueet kunnonvalvontajärjestelmässä käytiin läpi käytössä olevia ratkaisuja tutkimalla. Määrittelyt kaiken käytettävissä olevan kunnonvalvontadatan visualisoinnille listattiin työn liitteissä.

Käytönaikainen kunnonvalvonta keskittyy tällä hetkellä kytkinlaitteisiin, muuntajiin ja sähköasemarakennuksiin. Kytkinlaitteiden IoT-ratkaisu koostuu kytkinlaitteen ohjainkaappiin sekä kytkinkentän jakokaappiin asennetuista kustannustehokkaista sensoriyksiköistä. Muuntajat on varustettu jatkuva-aikaisella vikakaasujen seurannalla, mikä on toimivaksi todettu ja vakiintunut kunnonvalvontamenetelmä. Asemarakennusten olosuhteita valvotaan huoneisiin sijoitetuilla IoT-sensoriyksiköillä.

Työn johtopäätöksenä voidaan todeta kunnonvalvontadatan jakaantuvan pääasiassa kahteen muotoon, jotka määrittelevät Fingridin tarpeet kunnonvalvontajärjestelmälle. Jatkuva-aikaisten prosessien valvonta tuottaa suuren määrän jatkuvaa aikasarjadataa, minkä vuoksi tehokkaat työkalut aikasarjadatan esittämiselle ovat tarpeen. Kytkinlaitteiden ohjaukset ja muuntajien öljynäytteet puolestaan tuottavat tapahtumaperusteista dataa, jonka visualisointi muistuttaa datan raportointimenetelmiä. Tarvitaan erilaisia datan esitystapoja ja mukautettuja analysointimenetelmiä. Tapahtumadatan määrä on pieni siitä huolimatta, että sen määrä kasvaa huomattavasti IoT:n myötä.

Avainsanat IoT, Esineiden Internet, kunnonvalvonta, kytkinlaite, omaisuuden hallinta, datan visualisointi

Preface

This Thesis was made for the Transmission System Operator of Finland, Fingrid Oyj, as a Master's Thesis of the School of Electrical Engineering in Aalto University. I want to thank Professor Matti Lehtonen for supervision and academic overview of this Thesis. I want to thank my Thesis advisor Juhani Tammi and his colleague Tuomas Laitinen for their guidance.

This Thesis was a great opportunity to familiarize with industrial asset condition management, Internet of Things and technology of high voltage equipment. Fingrid's development of IoT solutions for online condition monitoring is pioneering work in the field of power systems. I will be interested in contributing the work in the future to find out how the potential of this promising concept can be realized.

Espoo, 31.3.2019

Janne Lappi

Contents

Abbreviations

AC	Alternating Current
AI	Artificial Intelligence
AIS	Air-Insulated Switchgear
APM	Asset Performance Management
BI	Business Intelligence
CIC	Customer Interruption Costs
DB	Database
DBFS	Databricks File System
DC	Direct Current
EAM	Enterprise Asset Management
FOCS	Fiber optic current sensor
GIS	Gas-Insulated Switchgear
GW	Gateway
GPRS	General Packet Radio Service
HMI	Human-Machine Interface
HVDC	High Voltage Direct Current
IED	Intelligent Electronic Device
IoT	Internet of Things
LAN	Local Area Network
LoRaWAN	Long Range Wide Area Network
MPLS	Multiprotocol Label Switching
MPLS-TP	Multiprotocol Label Switching - Transport Profile
MSM	Modular Switchgear Monitoring
OLTC	On-Load Tap Changer
PD	Partial Discharge
QR	Quick Response
RFI	Radio-Frequency Interference
RMS	Root Mean Square
SCADA	Supervisory Control And Data Acquisition
SF_6	Sulfur Hexafluoride
SFRA	Sweep Frequency Response Analysis
TDCG	Total Dissolved Combustible Gases
TSO	Transmission System Operator
UI	User Interface
WiFi	Technology for wireless local area networking of devices
WTI	Winding Temperature Indicator

1 Introduction

1.1 Background

Fingrid is the Transmission System Operator (TSO) of Finland. It operates at voltage levels of 400 kV, 220 kV, and 110 kV. Fingrid's asset fleet consists of over 14 000 kilometers of transmission lines and more than 100 substations. Fingrid manages its assets aiming to provide reliable and cost-effective electricity transmission between production facilities and distribution networks.

Failures of the high voltage primary equipment in electricity transmission substations are relatively rare but one may result in high costs and in a significant impact on the electricity supply. Thus, a preventive maintenance strategy is preferred, meaning that the equipment is overhauled prior to a failure. Until now it has been mostly time-based maintenance which refers to maintenance actions executed at pre-defined regular time intervals. Occasionally this results in unnecessary maintenance actions for healthy assets. Respectively, emerging faults may not be detected in time because of long maintenance periods. This may lead to equipment failures.

Equipment in high voltage substations is expensive assets of a long lifecycle. Fingrid's substations are designed for a lifespan of 40 years. A long asset renewal cycle leads to slow penetration of new technologies. Accordingly, no major reformation of asset maintenance techniques has taken place during the past decades. In the modern World changes are fast and considering a major challenge, the climate change, there is a demand for rapid actions. As a part of the energy sector, electricity transmission plays a major role in climate change mitigation. It is time to revise the asset maintenance techniques and take them to a new level in terms of cost-efficiency and equipment reliability. To respond to the challenge, Fingrid is currently making the transition from time-based maintenance to condition-based maintenance.

It is cost-effective to overhaul equipment only when it is technically necessary. Preventive maintenance based on asset condition optimizes the lifecycle of an asset. The implementation of the condition-based maintenance technique requires up-to-date information on asset condition. [**1**] Current time-based substation inspections dispatched by service personnel don't provide frequent enough data. Online condition monitoring is not a recent innovation but it is still at a primitive level in electricity transmission. Online condition monitoring solutions are necessary to provide real-time condition data for preventive maintenance decision-making.

"The upcoming five years will bring more change in terms of maintenance than the previous 50 because of digitalization," stated Marcus Stenstrand, Fingrid's Digitalization Manager [**2**]. Fingrid is running a project "Digital Substation". As a part of it, Fingrid is developing an Internet of Things (IoT) concept for online asset condition monitoring. Using low-cost sensor technology, commercial cloud services and edge computing, the IoT system is completely separated from the Local Area Network (LAN) of a substation, referring to the critical substation control environment. Measurement data is transferred to the cloud to be analysed and visualized. The main idea behind this approach is low-cost retrofitting in old substations and thus completing the transition to condition-based maintenance in a timespan of years instead of several decades.

The asset condition data needs to be efficiently visualized. Pinpointing outliers, detecting alarming trends and assessing the overall health of asset groups is essential regarding efficient maintenance decision-making. This thesis will specify the requirements of an Asset Performance Management (APM) application in terms of asset condition data visualization. It will allow Fingrid to evaluate the feasibility of commercially available products or to implement a custom solution.

1.2 Objective of the Thesis

The objective of this Thesis is to specify requirements for asset condition data visualization in an Asset Performance Management (APM) application. It is a general term of an application that is dedicated for condition data visualization and health assessment of industrial assets. There are competing commercial products available that are at early stages of development. To evaluate the feasibility of an APM application it is necessary to figure out first what kind of functionalities are required to meet the user's needs. This Thesis is made for Fingrid but it will be useful also for other electricity transmission companies willing to improve their asset condition management and online condition monitoring. The emphasis of this Thesis is on visualization of switchgear and power transformer condition data. Successfully designed dashboards in an APM application allow efficient usability and data-based decision-making in asset condition management. Some other relevant functionalities are studied, too. Important aspects are for example alarm functionalities, asset risk assessment and integration of multiple data sources.

An important objective of this Thesis is also to document Fingrid's IoT concept and involved online measurement solutions as well as existing condition monitoring practices. Globally, IoT is a new developing trend at its early stages in online condition monitoring of industrial assets. Fingrid's development of an IoT concept for switchgear is pioneering work in the field of power systems. In general, digitalization is currently a hot topic in heavy industry.

The nature of substation maintenance and the motives behind Fingrid's IoT concept have to be understood in order to succeed in specifying the requirements of condition data visualization. Thus, these topics are discussed in the beginning.

Chapter 1 is an introduction providing background for this Thesis. In Chapter 2 asset maintenance and condition monitoring are discussed in general. Chapter 3 introduces a digital high voltage substation and Fingrid's IoT concept for online asset condition monitoring. Chapter 4 reviews condition monitoring solutions and practices of different asset types, including new IoT solutions and existing conventional solutions. The focus is on condition data acquisition. In Chapter 5, visualization of the new IoT condition monitoring data is planned and necessary elements of the existing data visualization solutions are specified. Other essential functionalities of an APM application are specified, too. Finally, Chapter 6 concludes the study. In addition, specifications of condition data visualization in an APM application for Fingrid are summarized in Appendix B.

2 Substation Asset Condition Management

2.1 Maintenance strategies

Maintenance is defined as a set of activities or tasks used to restore an item to a state in which it can perform its designated functions. It can be classified into two main strategies: Corrective Maintenance and Preventive Maintenance. Corrective maintenance is reacting to an equipment failure once it has happened. This results in equipment downtime and costs of repair or replacement. Preventive maintenance involves performance of maintenance actions prior to an equipment failure. Preventive maintenance reduces the failure rate, failure costs and equipment downtime. [**1**]

The equipment in electricity transmission substations are expensive assets of a long lifecycle. Fingrid's substations are designed for a lifespan of 40 years. Failures are relatively rare but one may result in high costs and in a significant impact on the electricity supply. In case of the power system, the downtime is an important quantity to be minimized from the end-user's point of view. An equipment failure may also lead to destruction of the equipment and further damages to other equipment, whereas reasonable maintenance activities might have extended the lifespan of the equipment for even decades. Thus, regarding both aspects, transmission system reliability and cost efficiency, preventive maintenance is preferable over corrective maintenance.

Time-Based Maintenance is the preventive maintenance technique traditionally used for electricity transmission equipment. Fingrid's substations are visually inspected several times in a year. Maintenance actions are performed according to the detected defects such as oil leakages or fragmented insulators. [**3**] Equipment-specific measurements and periodic maintenance are performed at pre-defined time intervals, regardless of equipment condition. The time intervals depend on the asset model, varying between several years and two decades for example in case of the switchgear. [**4**],[**5**]. However, a Master's Thesis conducted in 2007 concluded that Fingrid's switchgear is mainly in a good condition at the end of the maintenance period [**3**]. Time-based maintenance inevitably results in unnecessary maintenance actions for healthy assets. Respectively, emerging faults may not be detected in time because of long maintenance periods. This may lead to equipment failures.

Condition-Based Maintenance is preventive maintenance based on asset condition. It is cost-effective to overhaul equipment only when it is technically necessary. [**1**] Fingrid's primary equipment is mostly under a light load in respect of the loadability limits whereas in many countries the transmission network is heavily loaded. The Nordic weather conditions are harsh and the equipment must be able to operate at low temperatures, even at -50 degrees Celsius. The operations count of a circuit breaker switching a regulating shunt reactor is multiple compared to one switching a transmission line [**3**]. These are examples of factors that contribute to the asset lifecycle. It is not possible to determine an optimal asset renewal time or maintenance period by default which would apply even to all assets of an equal model. Therefore the key to improve the lifecycle optimization of an asset is condition-based maintenance.

In condition-based maintenance, the decision-making is based on information on asset condition [**1**]. The four key steps of the condition-based maintenance strategy are presented in Figure 1.

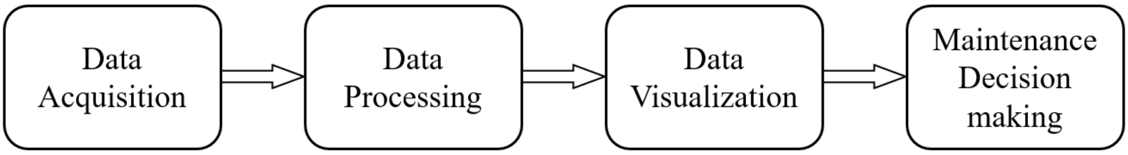


Figure 1: Four steps of the Condition-Based Maintenance strategy. Modified from [**6**].

In 99 per cent of equipment failures cases in industrial applications, certain indications occur prior to a failure [**1**]. To detect these indications, which may be either of a short-term nature or longer-term trends, appropriate condition monitoring solutions are required. Thus the first step of the process is condition data acquisition. The second step is data processing. The raw data must be analysed in order to reveal phenomena that might be indications of emerging faults [**6**]. The third step, data visualization, is the tool that a maintenance specialist uses for the final step, the decision-making. Efficient decisions to allocate maintenance actions can be made according to the data only if the data is visualized in a manner that clearly highlights all the relevant information included in the data.

The condition-based maintenance technique is already used in some industries, for example in elevator industry and forestry [**7**], [**8**]. It has been discussed since a long time in electricity transmission, too, but it has never been comprehensively implemented [**3**]. The challenge is the lack of real-time visibility to asset condition, in other words condition monitoring. More accurately the root cause is the first step in Figure 1, data acquisition. Conventional high-voltage equipment is mostly not equipped with sensors for condition monitoring.

Fingrid is currently making the transition from conventional time-based maintenance to condition-based maintenance. To overcome the challenge of condition monitoring, Fingrid is developing an IoT concept which is introduced in Section 3.2. First, condition monitoring is briefly discussed in general.

2.2 Condition monitoring

Condition monitoring is a process which intends to indicate the actual state of an asset. It collects condition data that reveals equipment failure mechanisms and deterioration patterns. Condition monitoring can be either online or offline. Online monitoring takes place while the monitored equipment is operating whereas offline monitoring is carried out when the equipment is not in use. [**1**]

Electricity transmission equipment is operating all the time and outages are basically avoided. Therefore, the focus must be on online monitoring. However, current online monitoring methods for high voltage equipment are quite limited. The most expensive single component of a high voltage substation is a power transformer which is worth several millions of euros. They are equipped with real-time online condition monitoring systems, measuring oil and winding temperatures and analysing dissolved gases. In the switchyard, the only online condition monitoring feature is gas pressure monitoring of SF_6 (Sulfur Hexafluoride) circuit breakers. Old circuit breakers are only equipped with low pressure alarm systems that cannot provide actual monitoring data.

General inspections are performed in a substation several times in a year. [**4**] For switchgear, offline measurements are performed at time intervals of 8-10 years. Some circuit breakers can be test-operated online at a time interval of 5 years but all measurements cannot be performed online. The online inspections require a considerable number of work hours even though it is more efficient than an offline inspection. [**9**] In conclusion, manual work is currently needed frequently and only the most critical processes are automatically monitored online.

In industrial applications the challenge with continuous online monitoring is often the cost of special monitoring devices and solutions [**1**]. This is the case for a TSO as the number of monitored equipment would be high. For example Fingrid has more than 10 000 high voltage primary equipment in unmanned substations spread all over the country [**10**]. Technically, online condition monitoring of switchgear and instrument transformers could have been already implemented. In addition to the costs, another inconvenience of a conventional solution would have been extensive amount of cabling required across a switchyard. Thus, a wireless online condition monitoring concept is needed and the main priority is low-cost scalability.

3 Digitalization

3.1 Digital substation

Subsystems and components of electricity transmission substations have been gradually digitalized over time. Figure 2 shows a simple illustration of the difference between a digital and a conventional substation. Data communications in a substation have been changed from manufacturer-specific hard-wired communication to buses using communication protocols standardized in the international standard IEC 61850.

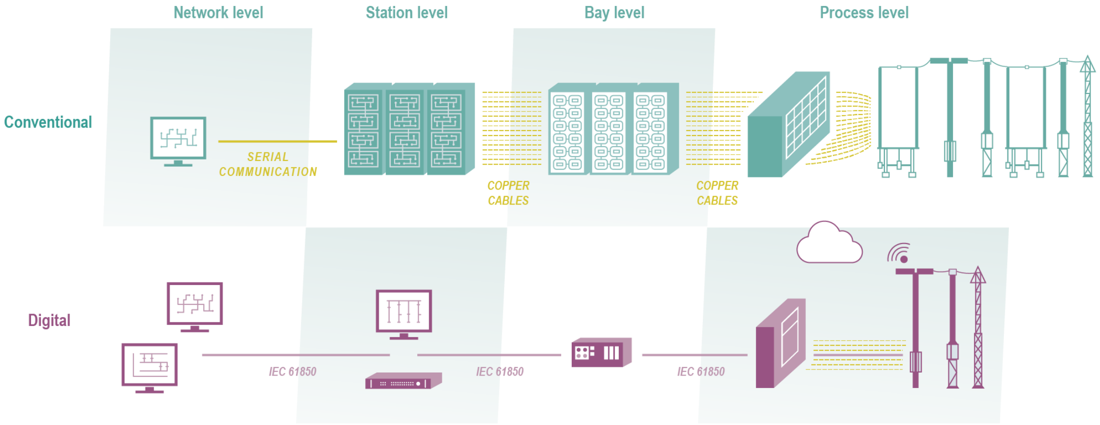


Figure 2: Fingrid's illustration about the difference between a conventional and a digital substation in terms of data communications design. [**11**]

Station level refers to the communication between protection relays and other automation systems in the substation building. Process level refers to the communication between primary equipment and secondary equipment, in other words between the outdoor switchyard and the substation building. [**12**]

Because of the long lifespan of a substation, Fingrid's substations are at different stages of digitalization. Figure 3 presents more detailed illustrations of the substation evolution from conventional to digital. Fingrid's substations are similar to the conventional design or the modern design of Figure 3, or a combination of both [**13**]. Old substations still have hard-wired systems in the station level whereas systems in modern substations communicate using IEC 61850 station buses [**13**].

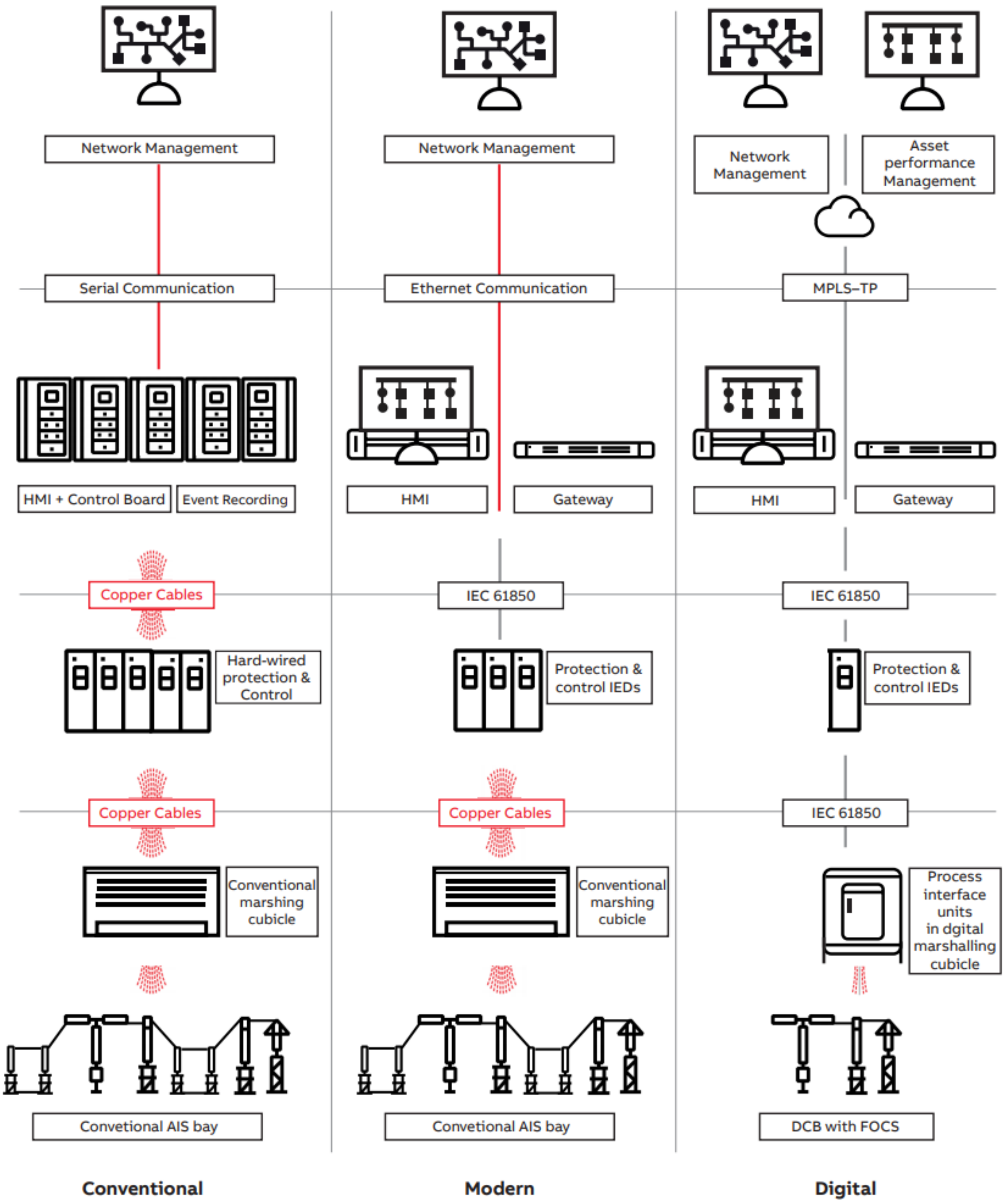


Figure 3: ABB's illustration about the evolution of high voltage substations from conventional to digital. [**14**]

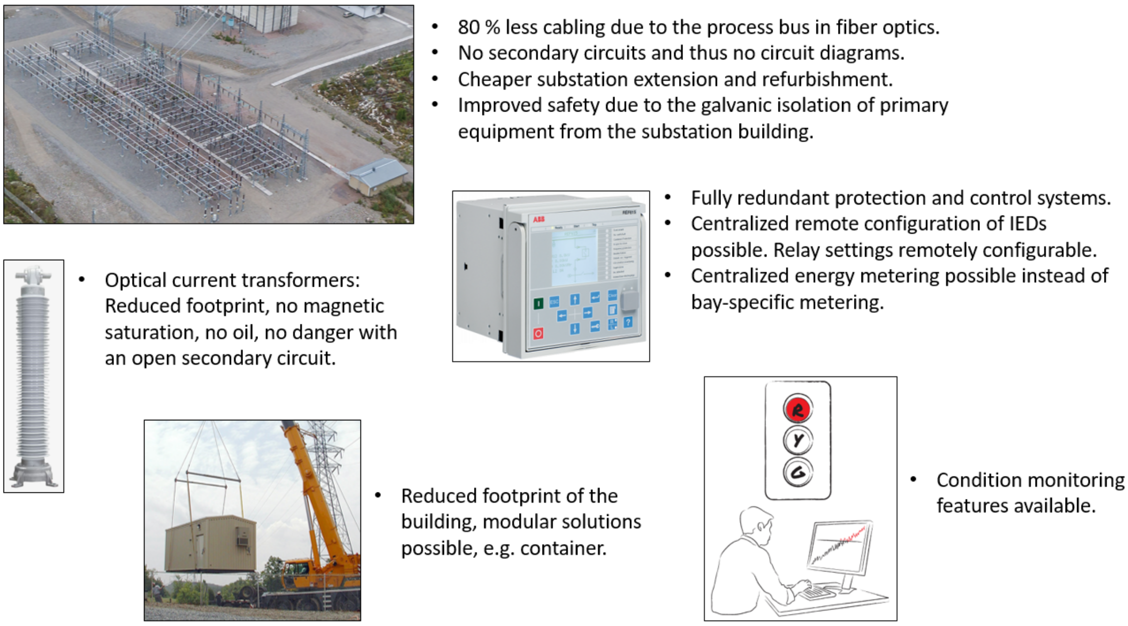
Currently, the definition of "Digital substation" refers to the digitalization of the process level [**15**], [**12**]. It is being experimented by transmission companies but it hasn't been comprehensively implemented yet [**16**]. Control commands and position information of switches and secondary quantities of instrument transformers are conventionally hard-wired between the substation building and the switchyard. There are a lot of copper cables in the process level as the distance may be more than 100 meters in a high voltage substation. A digital process bus connects the switchyard and the secondary equipment via fiber optics. Intelligent Electronic Devices (IED) in the marshalling cabinet of each bay are the interface between the process bus and the primary equipment. According to IEC 61850, the process bus and the station bus shall be separated. [**12**]

Fingrid is currently running a project called "Digital substation" which consists of digitalization of two 110 kV bays in Pernoonkoski substation. It is a pilot project in order to gain experience of new digital substation technology. Thus, a digital process bus is implemented in parallel with the conventional hard-wired system. Control and protection functions are primarily operated in the conventional system to avoid possible unexpected malfunctions. Circuit breaker tripping commands will be monitored in the digital process bus to ensure appropriate operation of the new system regarding protection.

Another special feature in the project is the experiment with optical current transformers. They are connected in series with the conventional ones, with a similar idea to the digital process bus parallel with a conventional hard-wired system. There are several benefits which make an optical current transformer superior to a conventional one. Firstly, there is no insulation oil or gas which eliminates the risk of an environmental damage. A fault in a conventional current transformer may also increase the oil temperature and pressure, possibly resulting in an explosion. It can no longer occur with optical current transformers. An improvement from functional point of view is that magnetic saturation followed by protection misoperation cannot occur due to the optical technology. Physically, an optical current transformer is more compact. Concerning work safety, there is no secondary circuit to induce a dangerous open circuit voltage. [**17**], [**18**]

In general, primary equipment compatible with a digital process bus will be able to communicate a lot of data to the substation building and to cloud. Online condition monitoring can be a built-in feature in a digital substation in the future whereas the currently developed IoT concept presented in Section 3.2 is designed for retrofitting to existing primary equipment.

The benefits and challenges of a digital substation according to Fingrid are presented in Figures 4 and 5. This Chapter is only an introduction to digitalization and digital substation is not further discussed in this Thesis.



- 80 % less cabling due to the process bus in fiber optics.
- No secondary circuits and thus no circuit diagrams.
- Cheaper substation extension and refurbishment.
- Improved safety due to the galvanic isolation of primary equipment from the substation building.

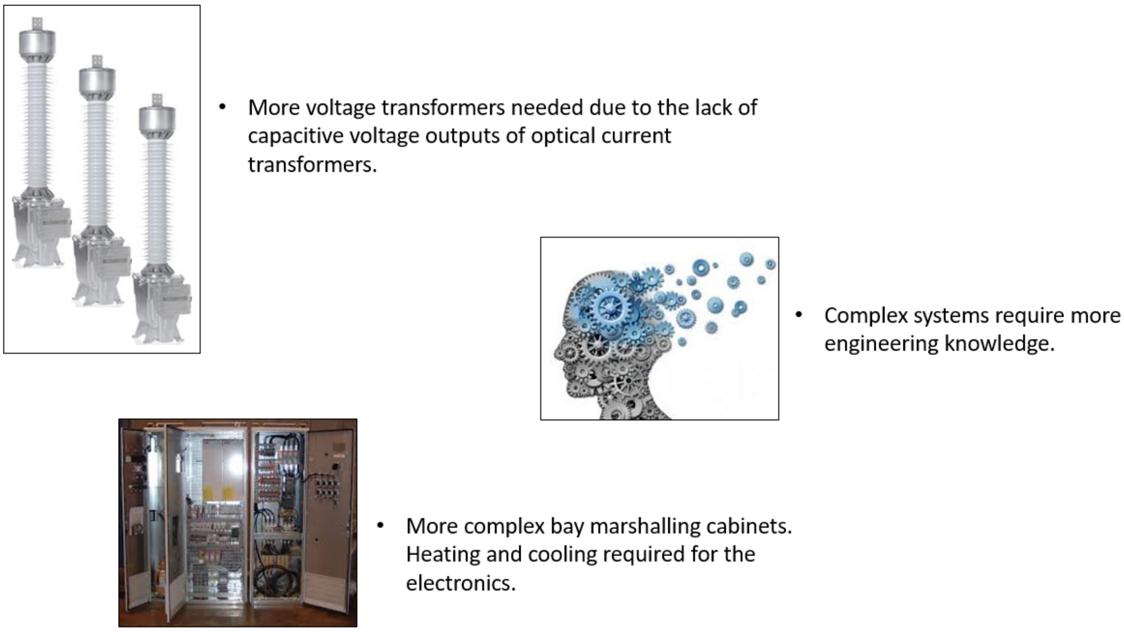
- Fully redundant protection and control systems.
- Centralized remote configuration of IEDs possible. Relay settings remotely configurable.
- Centralized energy metering possible instead of bay-specific metering.

- Optical current transformers: Reduced footprint, no magnetic saturation, no oil, no danger with an open secondary circuit.

- Condition monitoring features available.

- Reduced footprint of the building, modular solutions possible, e.g. container.

Figure 4: Benefits of a digital substation [**16**]. Modified from [**19**], [**20**], [**21**], [**22**].



- More voltage transformers needed due to the lack of capacitive voltage outputs of optical current transformers.

- Complex systems require more engineering knowledge.

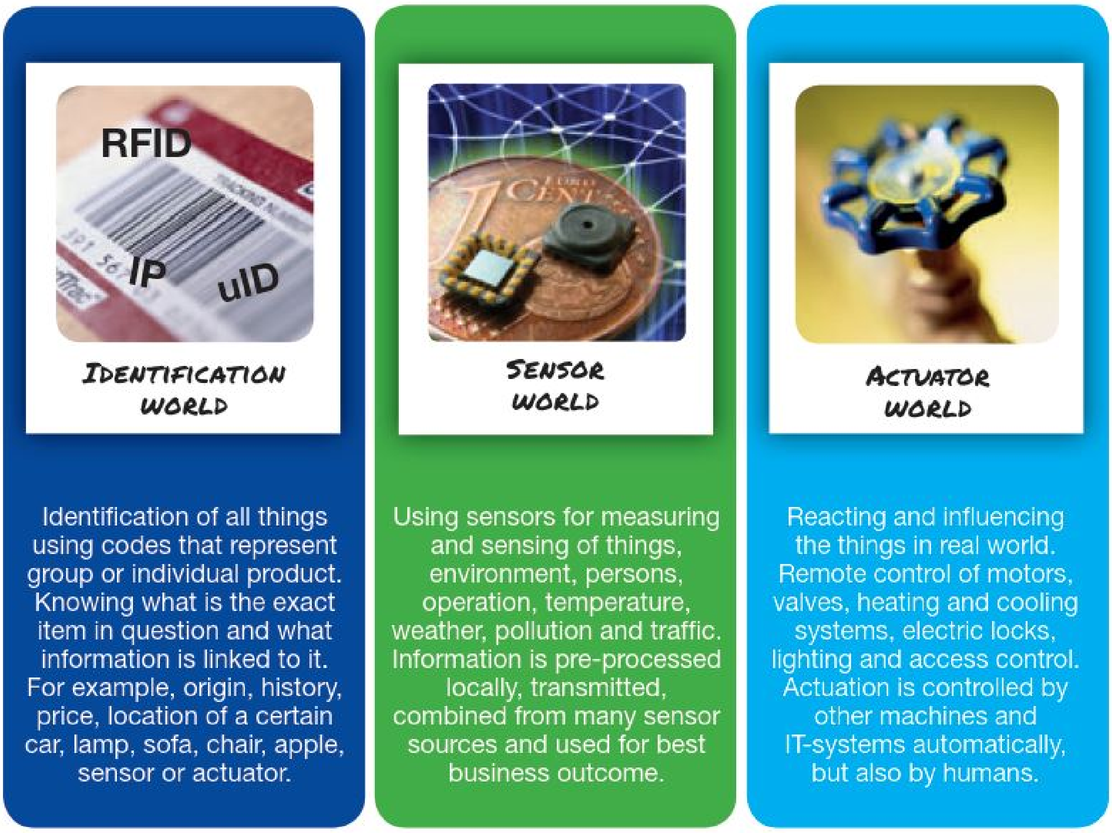
- More complex bay marshalling cabinets. Heating and cooling required for the electronics.

Figure 5: Challenges of a digital substation [**16**]. Modified from [**23**], [**24**], [**25**].

3.2 Internet of Things in Asset Condition Management

Internet of Things

There is no established and clear definition for Internet of Things (IoT). Despite its meaning to private consumers and industrial business may be different, the core idea is to bring together the physical and digital worlds. [**20**] IoT is a network which enables physical objects to connect, collect data and exchange data [**26**].



Identification of all things using codes that represent group or individual product. Knowing what is the exact item in question and what information is linked to it. For example, origin, history, price, location of a certain car, lamp, sofa, chair, apple, sensor or actuator.

Using sensors for measuring and sensing of things, environment, persons, operation, temperature, weather, pollution and traffic. Information is pre-processed locally, transmitted, combined from many sensor sources and used for best business outcome.

Reacting and influencing the things in real world. Remote control of motors, valves, heating and cooling systems, electric locks, lighting and access control. Actuation is controlled by other machines and IT-systems automatically, but also by humans.

Figure 6: The three interconnected "worlds" of IoT. [**20**]

Figure 6 presents the three interconnected "worlds" of IoT. A physical object, a product, has a unique digital identifier linking it to digital information that represents the location, the condition and the properties of the object. Sensors measure physical phenomena and communicate the collected information to be digitally stored. Remotely controlled actuators will physically affect the real world according to algorithms making use of collected data. [**20**] There is nothing new in any of these three aspects in itself, but IoT enables efficient up-scaling of their combination [**27**], [**20**]. The number of connected devices in 2020 is estimated to be 50 billion. [**20**]

In industry, the disruption of business models originated from IoT will remarkably enhance productivity. From this point of view, a definition of IoT could be as follows:

"The Internet of Things is a digital representation of the real world, enabling productivity enhancement through optimal use of real-world assets." [**20**] An electricity transmission company does not produce a physical product. Instead, productivity is efficiency of the activities such as asset management. A step towards the "Optimal use of real-world assets" is the condition-based asset maintenance technique discussed in Chapter 2.

Fingrid's Internet of Things concept

Fingrid is developing an online condition monitoring system in an IoT platform. Figure 7 illustrates the system that covers the first three steps of Figure 1 in Chapter 2, from Data Acquisition to Data Visualization.

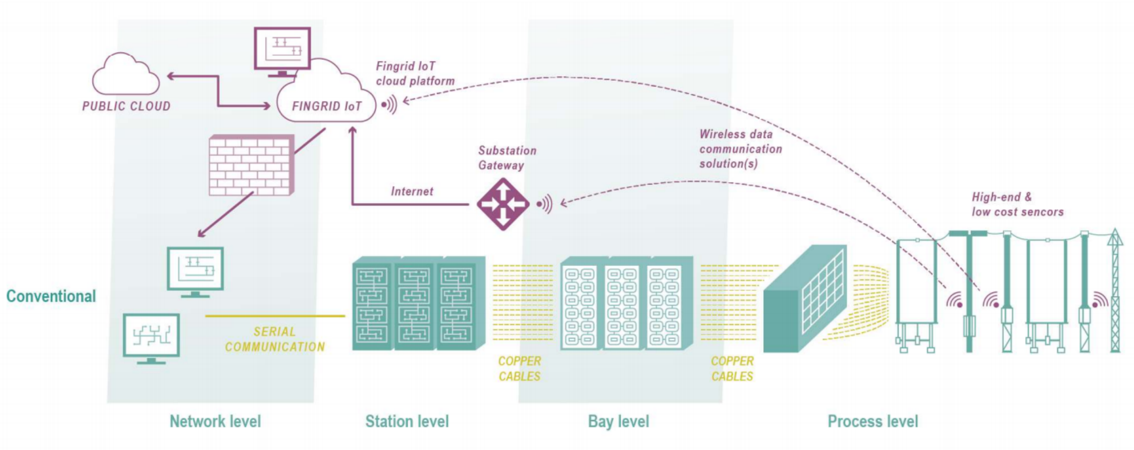


Figure 7: Fingrid's IoT concept. [**11**]

Referring to the first step of Figure 1, substation assets are being equipped with sensor units developed in cooperation with external partners specialized in metering. Current, temperature, humidity and vibration sensors, microphones, thermal cameras, etc. are used. The sensor units measuring the primary equipment is installed in switchgear control cabinets, bay marshalling cabinets and directly attached to the external surface of the equipment. Measurements are either continuous or event-based, depending on the nature of the measured phenomenon. For example temperature measurement is continuous whereas microphones record distinct operations of switchgear.

Regarding the high voltage primary equipment, the focus is primarily on switchgear, the largest asset group in number of equipment. Switches consist of moving mechanical parts that wear out over time. Each operation of a circuit breaker or a switch is recorded by using multiple sensor technologies. The measurement data of each sensor unit is transferred wirelessly to a router or a gateway for further transfer to a commercial cloud service. WiFi and Long Range Wide Area Network (LoRaWAN) are experimented as wireless communication technologies between the sensor units and the gateways. 4G mobile network is used for the cloud transfer.

Fingrid's IoT platform is built on Microsoft Azure cloud service. It is a cloud platform with a great number of optional components that the user can include in its solution and customize for its needs [28]. The current architecture of Fingrid's IoT platform is presented in Figure 8.

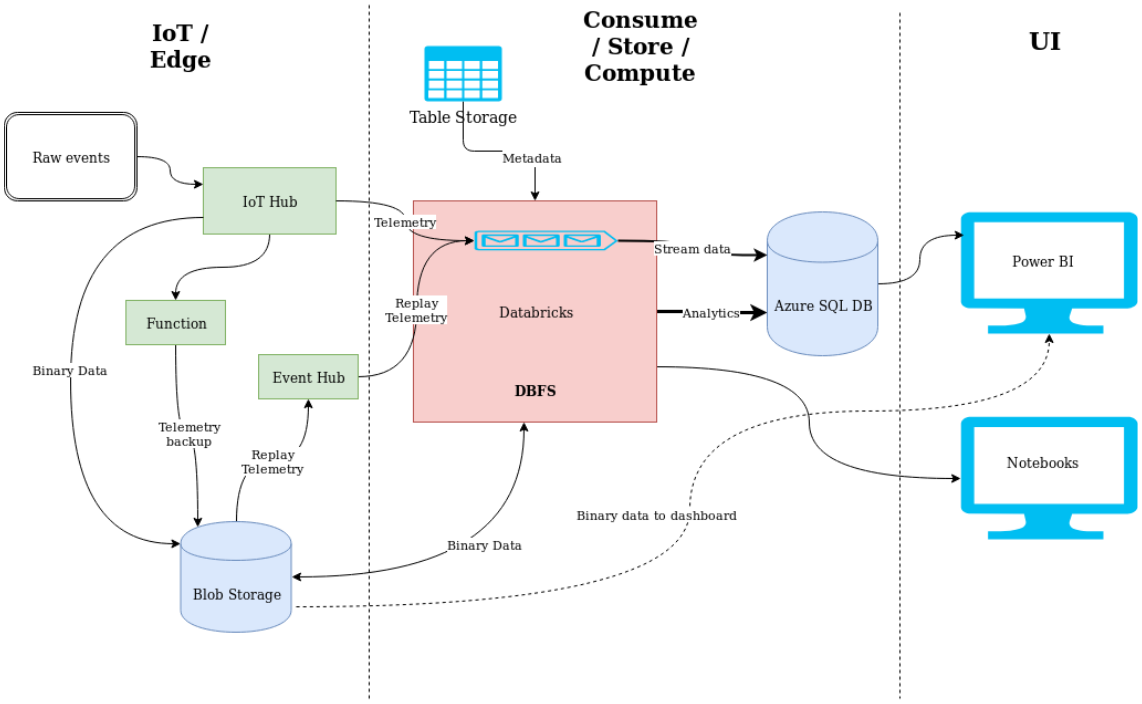


Figure 8: The current architecture of Fingrid's IoT platform.

The sensor data is received by an "IoT Hub" component. "BLOB Storage" and "SQL DB" are data storages, each having different capabilities in terms of real-time accessibility and supported data formats [28]. The component "Function" offer serverless computing resources for custom programs that can be coded by the user, for example for data processing and transfer in this case [28]. As the second step of Figure 1, the sensor data is processed and analysed in the cloud by custom algorithms to reveal the phenomena that will be visualized. For example start and end timestamps of event phenomena like switchgear operations can be obtained from a sound spectrogram to quantify the time duration of the event.

Databricks is an Apache Spark -based analytics service. It takes programs written in high-level languages, distribute the execution onto many machines and optimizes the usage of databases. [29] Databricks is used in Fingrid's IoT platform to allow fast data processing.

The third step of Figure 1, Data Visualization, will be implemented using an Asset Performance Management (APM) application which is the User Interface (UI) to asset condition monitoring, asset health assessment and asset risk assessment. All Fingrid's sources of condition monitoring data, including the new IoT platform, existing online monitoring systems and existing offline measurement databases, will be integrated to an APM application. Additional value of condition data is gained by combining data from many sources [**20**]. By using an APM application, grid maintenance responsibles will be able to comprehensively monitor and evaluate the condition of the asset fleet. In Figure 8, the section "UI" represents the component for data visualization that can be an APM application or a custom solution. A custom solution could make use of a Business Intelligence (BI) reporting application such as Microsoft Power BI.

An important element of IoT is "Edge". Edge computing is defined as performing computation on device nodes that are usually geographically distributed [**30**]. It is also the idea of another current hot topic, the Blockchains [**31**]. In IoT, edge is the endpoints where sensors measure the physical world [**32**]. IoT edge is illustrated in Figure 9.

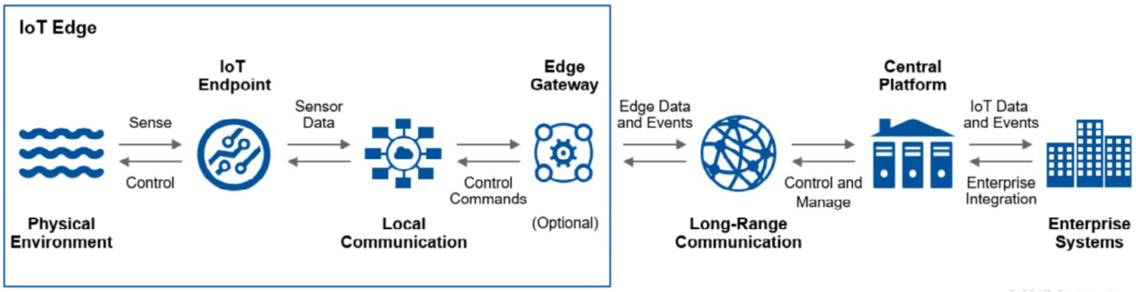


Figure 9: IoT Edge in a complete IoT system. [**32**]

Computing, meaning data processing and analysis in this case, could be performed in a substation gateway instead of the cloud platform. This is something that will probably be experimented later in the IoT project. For the time being however, the edge is used for the remote management of the IoT devices. Only a bay in a switchyard will be equipped with a few dozens of sensor units. The number of bays in Fingrid's substation ranges from a few to a few dozens. The resulting number of devices in the entire IoT system will be in a scale of thousands. The management of software updates, device drivers, and sensor settings needs to be performed in an efficient way. It is currently being studied what kind of a remote management solution for IoT devices would be appropriate and cost-efficient. "Azure IoT Edge" component could be used but there are also systems available outside Fingrid's IoT platform that could manage the operating systems of IoT devices [**33**], [**34**].

The key elements of the concept

The ultimate goal is to create a low-cost IoT concept for condition monitoring in order to improve the cost-efficiency of asset management. The key elements of Fingrid's IoT concept are listed below and explained in this subsection.

- Low-cost sensor technology available.
- IoT platform built on a commercial cloud service by using available components.

- Private platform combining promising solutions of different providers.
- IoT platform isolated from substation LAN to ensure information security.
- Retrofitting of IoT sensor units into existing substation equipment.
- Quick online installation and commissioning of a large number of IoT sensor units.

Sensor technology and cloud services have evolved rapidly. There are a lot of low-cost sensors available and several giant IT companies are competing in cloud service business. There are companies, including startups, that are specialized in sensors and metering. Data analytics is a vast market today and there is a growing number of asset performance management tools available, too. A wide range of new interesting products are being developed in these fields. IoT business is at early stages especially in electricity transmission, meaning that the leading manufacturers in the field don't have yet a lot of finished products in their catalogues. Thus, the development of an efficient IoT concept requires an open-minded approach and ability to involve numerous parties in the project. It is essential to combine the most promising innovations of different providers instead of relying on a single major service provider. Technical limitations due to manufacturer dependency has to be avoided. It has proved to be a challenge that major manufacturers aim to provide a complete IoT service including sensors, a cloud platform and data management. Besides being expensive, this idea is not compatible with Fingrid's concept of a private platform combining competitive solutions of different parties.

Information security plays a major role in the IT architecture of power systems. Crucial information for power system control is transferred in Fingrid's private telecommunications network basically consisting of fiber optic cables all around the country. This network must be kept secure and reliable. Commercial cloud services and common wireless communication technologies offer efficient and flexible solutions for data management and transfer but they are more vulnerable to information security threats. One of the most important characteristics of Fingrid's IoT concept in Figure 2 is the isolation from the substation LAN. To ensure security, condition data is not transferred in the same channels with crucial control data and the IoT platform is not connected to the SCADA (Supervisory Control And Data Acquisition) environment where the power system is controlled. In the worst case, manipulation of condition data could lead to unnecessary planned outages as equipment indicating a false emerging fault would be disconnected from the primary circuit. However, the scenario is unlikely because credible manipulation of condition data requires a major effort and solid professional knowledge of high voltage equipment.

Retrofitting is another fundamental driving force for Fingrid's IoT concept. Fingrid's substations are designed for a lifespan of 40 years. There are condition monitoring features available for switchgear in the market today, but the asset renewal cycle being very long, new technologies will penetrate into the asset fleet slowly. The transition from time-based maintenance to condition-based maintenance is realistic in a timespan of years only provided that the existing equipment can be efficiently retrofitted with an online condition monitoring system.

A quick on-site installation and commissioning routine for the monitoring equipment is being designed. Hall-effect current sensor clamps, electret and contact microphones, temperature sensors with adhesive, etc. make the battery-powered sensor units a completely external setup in respect of the primary equipment itself. The installation is quick and it is supposed to be performed online, without an outage of the primary circuit. A custom mobile application making use of QR (Quick Response) codes is developed for managing the commissioning of the sensor units that need to be mapped to corresponding primary equipment. To make the IoT concept cost-efficient, a lot of effort is put into the implementation of an easy commissioning and maintenance routine. In addition, thousands of new devices in the power system are a major concern regarding their maintenance over time. Allocation of maintenance actions based on asset condition and possible reduction in the number of equipment failures improve cost-efficiency. It is however essential to ensure that this improvement is not negatively compensated by the maintenance load of the new monitoring equipment. Quick installation of low-cost sensor units at commissioning leads to cost-efficient maintenance in the way that the replacement of units is cheap, too, regarding required work hours and costs of the physical product.

Future vision of power system asset condition management

What does the digital future of asset condition management look like? Figure 10 summarizes the current trend.

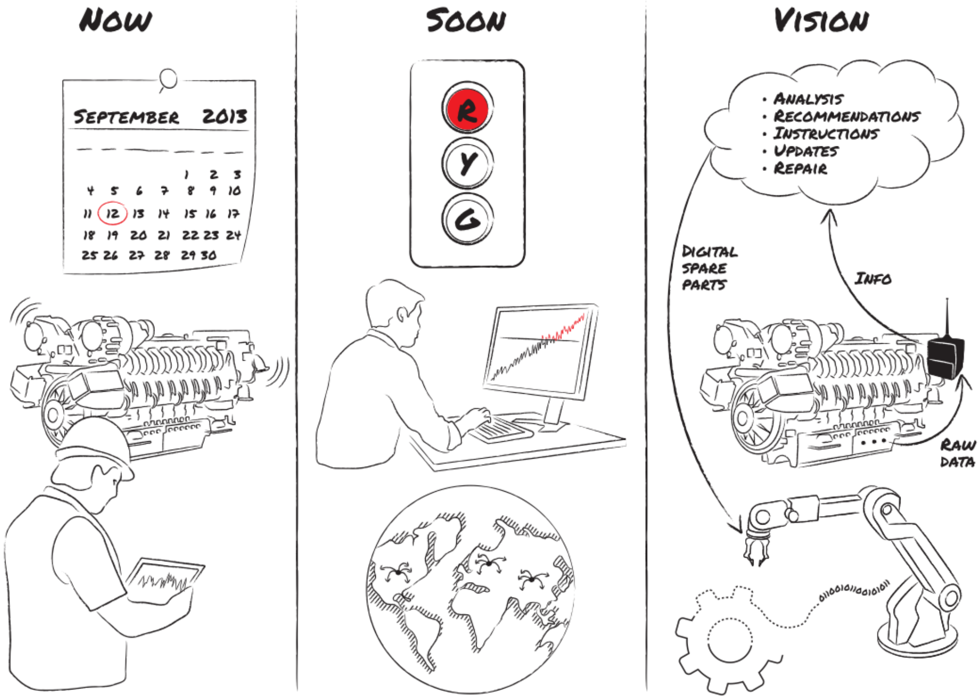


Figure 10: The phases of digitalization in industrial asset condition management. [20]

In electricity transmission, the next step is the ability to remotely monitor the geographically distributed asset fleet and reveal indications of emerging faults. Service personnel is deployed to perform maintenance to equipment of alarming condition, instead of time-based inspections and maintenance. A long term vision could incorporate robotics and Artificial Intelligence (AI) for automatic maintenance. 3D printing or similar small-scale manufacturing technologies could be used for quick local production of spare parts [**20**].

What are the benefits Fingrid is aiming to gain with the IoT concept and online condition monitoring? The following list of aspects are answers to this question.

- Real-time visibility to asset condition.
- Efficient allocation of maintenance work hours and reduction of time-based maintenance costs.
- Less planned outages.
- Improved work safety in substations.

Real-time visibility to asset condition allows efficient maintenance planning, as it was discussed in Chapter 2. Work hours form a major portion of maintenance costs. Cutting out unnecessary time-based work on site, which may be at a remote location, will bring savings.

Another main benefit of real-time visibility to asset condition is presented in the column "Soon" in Figure 10. The ability to detect and prevent a fault is strongly linked to cost-efficiency, too. Besides social impacts, a network disturbance due to an equipment failure may cause significant losses to the society in a short time. A current transformer failure in summer 2018 incurred costs of more than 5 million euros to Fingrid, mostly because of reserve power production and countertrade [**35**]. The costs were very high even though the power supply of customers was not interrupted. Prevention of even one or a few such failures would save a TSO costs that may be well more than the cost of implementing an efficient online condition monitoring system.

The third benefit of real-time visibility to asset condition is optimization of asset lifecycle. At the end of the predicted substation lifespan, a major refurbishment is performed in case the substation is still necessary in the transmission network. Primary and secondary equipment is mostly replaced, depending on the situation and on the age of equipment. Fingrid has more than 100 substations which sometimes leads to a situation where multiple major refurbishment projects are scheduled to overlap. With limited work resources, projects have to be prioritized. Up-to-date information on asset condition enhances the decision-making and lowers the risk of equipment failures when the priorities of refurbishment projects are scheduled based on asset condition.

Reduction of planned outages is an obvious benefit gained by cutting down time-based maintenance. In a normal state, the synchronous transmission system is able to withstand a failure of any single component without collapsing. Equipment downtime, however, reduces transmission capacity and redundancy and thus makes the transmission system slightly more vulnerable to faults.

Work safety will be improved simply by reducing manual work at substations. Continuous online measurements of switchgear will replace some manual measurements which are conventionally performed when switchgear is test-operated. Current measurements inside switchgear control cabinets require physical connection of the measurement instrument. Online connections are a risk in general but especially an unintentionally opened secondary circuit of an online conventional current transformer exposes the service personnel to a real hazard [**36**]. Connections will be no longer necessary when test-operations are recorded online using permanently connected IoT sensor units.

4 Fingrid's Condition Monitoring Solutions

So far Fingrid has been using online condition monitoring for power transformers and SF_6 gas in circuit breakers and in Gas-Insulated Switchgear (GIS) substations. The new IoT concept widely extends monitoring to other characteristics of switchgear. Substation buildings will be equipped with IoT sensors and solutions for other primary equipment will be also developed. Conventional offline measurements and inspections have been producing condition data for decades.

This Chapter presents Fingrid's condition monitoring solutions including the new IoT sensor units, existing online monitoring and existing offline measurements.

4.1 Switchgear

Switchgear is Fingrid's largest group of primary assets consisting approximately of 8 500 operating 3-phase equipment [**10**]. In this Thesis, the term "switchgear" refers to circuit breakers, disconnectors and earthing switches. The term "switch" refers only to disconnectors and earthing switches. The ten-year average number of major faults in air-insulated switchgear is 17 in a year and correspondingly 236,8 in case of minor faults. 4,8 network disturbances in a year are caused by switchgear failures. [**37**]

Existing online condition monitoring

Most of Fingrid's 1200 air-insulated circuit breakers are SF_6 breakers. The remaining 140 minimum oil breakers will be replaced in 5 years. [**38**] SF_6 is a dielectric gas used for arc-quenching in circuit breakers and as an insulation medium in GIS. A circuit breaker is no longer able to operate if the gas pressure drops below a critical level. [**39**] SF_6 is also a greenhouse gas with high global warming potential [**40**]. Thus, it is important to repair leakages as soon as possible. Continuous online monitoring allows early detection of leakages.

All of Fingrid's SF_6 circuit breakers are equipped with a conventional gas density monitor with a pointer gauge. An example is presented in Figure 11.

Figure 11: SF_6 gas density monitor. [**41**]

A gas density monitor includes a built-in low-pressure alarm feature. When the gas density drops below an alarm level, contacts in the density monitor change the state to trigger an alarm to SCADA. The locking level is the minimum gas density required for a switching operation. At the locking level, in addition to triggering an alarm, the circuit breaker locks itself by cutting the control circuit in order to prevent operations. [**9**]

Fingrid's modern SF_6 circuit breakers are additionally equipped with gas density sensors. The gas density information is communicated in an analogue milliampere signal hard-wired to the substation LAN and further to the SCADA environment. Gas pressure is calculated from density at +20 C temperature. [**9**] Alarms are set to indicate a short-term drop of pressure and a long-term downtrend [**42**].

Otherwise, no more online monitoring exists for switchgear. Equipment performance in online operations is not monitored except in the online inspection routine which is explained later in this Section.

Offline inspections

At a time interval of 8-10 years, an outage is performed for on-site inspection and performance testing of switchgear. Measurement instruments are manually connected to primary and secondary circuits of switchgear. A current generator is connected to the primary contacts of a circuit breaker. [**9**] Operational values, such as motor operation time, motor current, circuit breaker operation time, circuit breaker coil current profiles and etc., are measured while the switchgear is test-operated in an offline state [**10**],[**9**]. Alignment and smooth operation of moving mechanical parts are visually inspected. As for static measurements, resistances of primary contacts are measured under a load of 300 A. The measurements are listed in detail in appendix A. The measured values are entered in an Enterprise Asset Management (EAM) database. Work orders for actual maintenance are created in the EAM if the measurements indicate degraded performance. [**9**]

Online inspection routine

Fingrid has created an online inspection routine which allows switchgear performance testing without an outage. It can be performed in Fingrid's typical substations where the busbar configuration allows closing another connection for the primary current in parallel with the circuit breaker under inspection. [**43**] Figures 12 and 13 present typical 400 kV and 110 kV busbar configurations in Fingrid's substations.

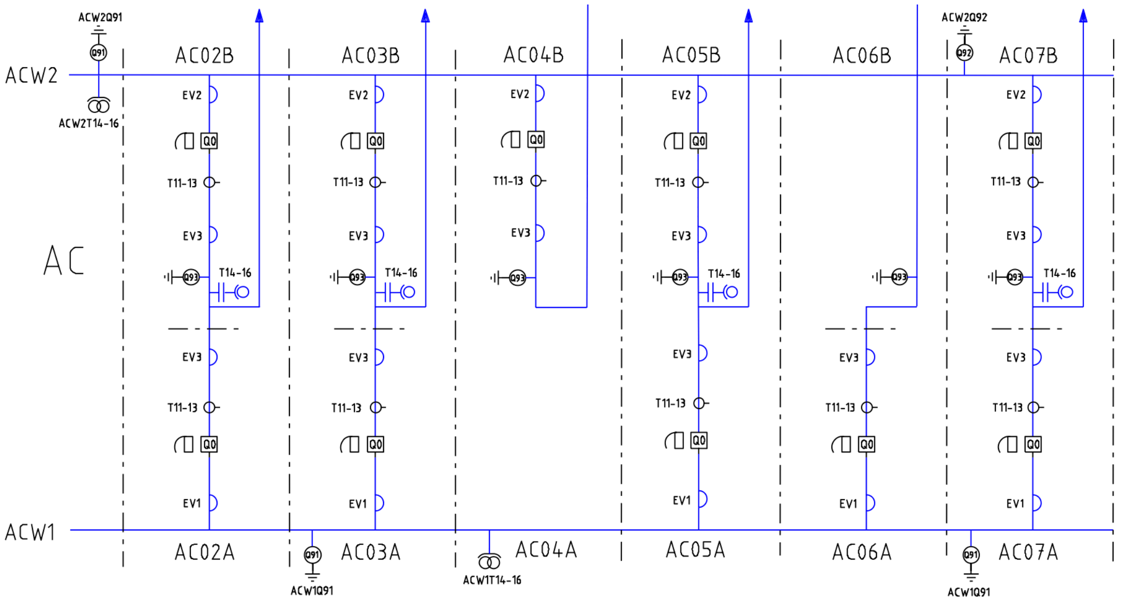


Figure 12: A typical Fingrid's 400 kV busbar configuration. [**44**]

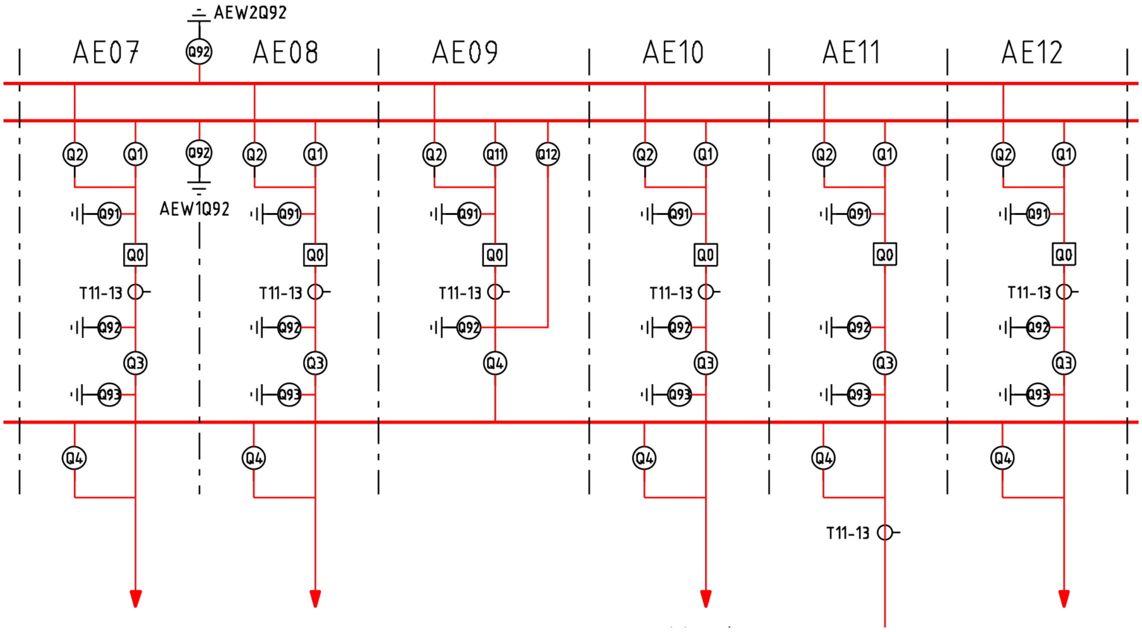


Figure 13: A typical Fingrid's 110 kV busbar configuration. [**44**]

One half of a 400 kV full duplex bay can be opened and test-operated once the other half is online and supplying the transmission line. In a 110 kV switchyard the by-pass circuit breaker AE09Q0 in Figure 13 can be closed in parallel with any other circuit breaker. When a breaker is opened, the load current keeps flowing through the by-pass breaker to supply the transmission line. In addition to the circuit breakers, most of the switches can be test-operated. Performance measurements are carried out for circuit breakers. In order to minimize the working time and the duration of an exceptional state of a switchyard, appropriate operation of switches is only visually verified by the service personnel. In case of some measurement quantities, like contact resistance, online measurements are not possible neither for circuit breakers nor switches. [**9**]

The online inspection routine is performed bay by bay. It saves a lot of working time compared to the conventional offline inspection and thus allows more frequent inspections for this asset group. It is scheduled to be performed at a time interval of 5 years. The offline inspections are accordingly reduced to be performed only once in the equipment lifespan, meaning 20 years from commissioning. The switchgear to which the online inspection routine cannot be applied is inspected as before. [**9**]

IoT solution

The IoT solution for online switchgear monitoring is based on microphones and current sensors connected to a sensor unit. The first version of the sensor unit was developed for 110 kV switchgear in collaboration with a Finnish company specialized in acoustic measurements. 68 units have been monitoring seven 110 kV bays of Kymi substation in Southern Finland since December 2017. Figure 14 shows the sensor unit and the sensors.

Figure 14: The first version of the IoT sensor unit for switchgear and sensors to be connected to the unit. [**45**]

The switchgear sensor unit has four acoustic inputs, a current input and an input for temperature and humidity. It is installed inside a switchgear control cabinet.

Figure 15 shows a disconnector control cabinet equipped with sensor units and sensors. Normally a control cabinet is equipped with one sensor unit but Figure 15 shows an additional unit that was installed for experimental purposes.

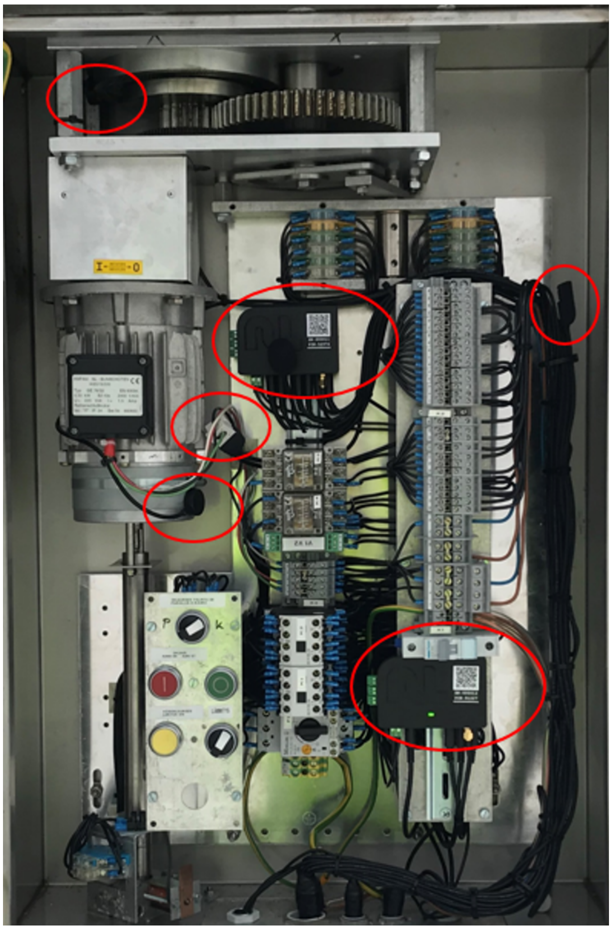


Figure 15: Sensor units and sensors installed in a disconnector control cabinet. [**46**]

A hall-effect clamp sensor measures the charging motor current of a circuit breaker or the motor drive current of a switch. Contact microphones are installed on the motor and near the gear train. An electret air microphone records any airborne sound. Motor rpm, gear sound and circuit breaker damper sound are obtained from sound recordings. Furthermore, all microphones can be used to detect deviations in the mechanical operation of switchgear. It seems that different microphones detect same sources of sound such as an arc in a switch. Thus, in the future development the number of microphones may be reduced. In addition, temperature and humidity are measured inside the control cabinet. In the future this information could be used to control heating resistors inside the cabinet instead of built-in thermostats. Heating is required to keep the control mechanics dry and to prevent them from freezing in wintertime. Currently without any feedback in the heating system, it is unclear how well the conditions inside the cabinets are maintained.

The second version of the sensor unit was developed by another Finnish company specialized in industrial IoT solutions. Units were installed in Naantalinsalmi 110 kV substation in Southwest Finland. The second version features additional current channels to measure circuit breaker control coil currents and auxiliary contacts such as position indicator. The most important development is an additional sensor unit installed in the bay marshalling cabinet. Six current sensors measure secondary currents of each current transformer phase and currents in the three control coils of circuit breaker. The sensor units are presented in Figure 16. The complete measurement setup is presented in Figure 17.

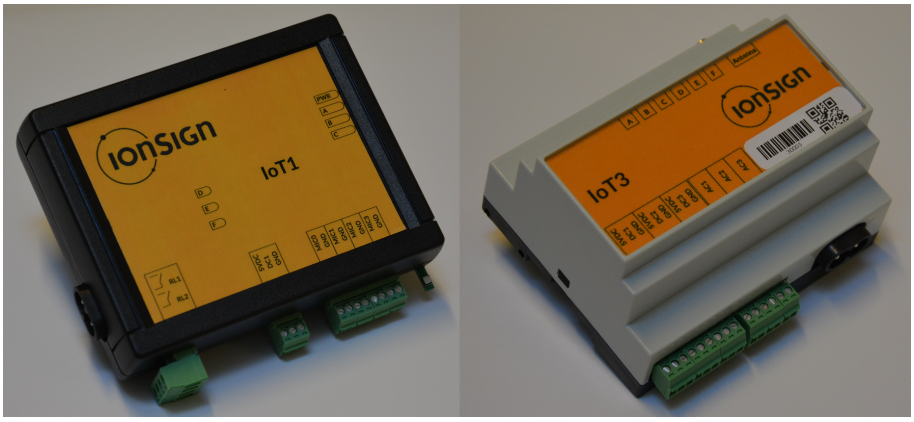


Figure 16: The second version of the switchgear sensor unit on the left and the additional sensor unit installed in a bay marshalling cabinet on the right. [**46**]

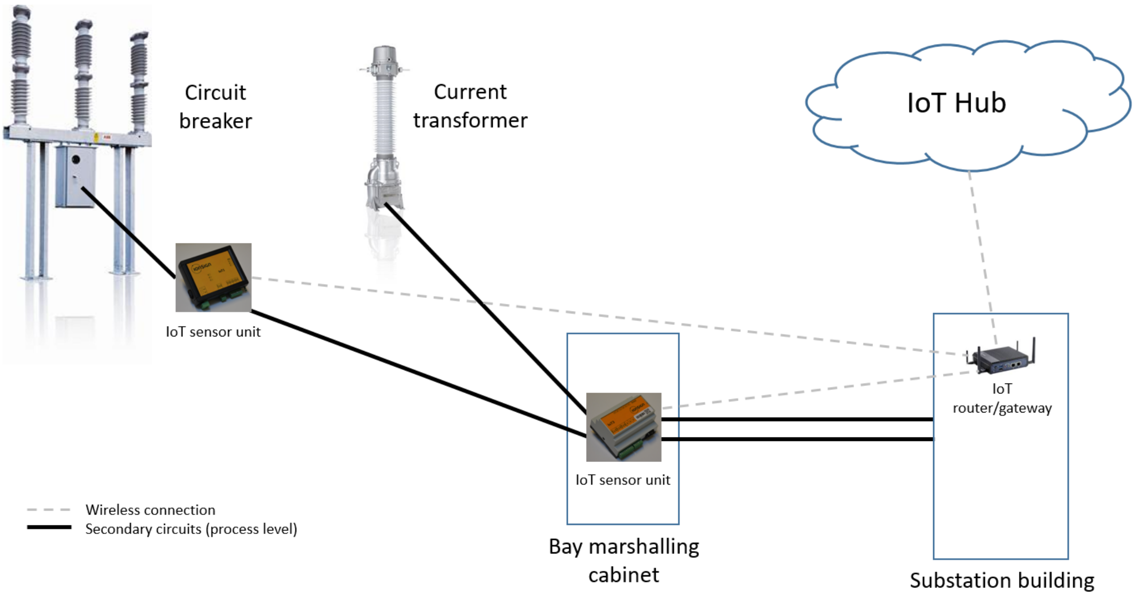


Figure 17: The IoT setup of switchgear at the sensor endpoint. Modified from [**45**], [**47**], [**48**], [**49**]

A control command to a circuit breaker energizes a control coil to mechanically release a spring that actuates the primary contacts [**9**]. Currents in the control coil circuits are measured in both sensor units, in the switchgear control cabinet and in the bay marshalling cabinet. The reason is that, when calculating a time duration between timestamps obtained from separate measurements, the measurements have to be time-synchronized. The timestamp of a circuit breaker control command is used as the start timestamp of several time-related performance quantities. This timestamp is the moment in time when a control coil current starts rising and thus it is obtained from the measurements of control coil currents. The end timestamp is obtained from a measurement taking place in the control cabinet or in the bay marshalling cabinet, depending on which time-related performance quantity is calculated. There is no time-synchronization between the sensor units installed in the control cabinet and in the bay marshalling cabinet. Duplicated measurements of control coil currents allows utilization of the control command timestamp for many purposes.

Time-synchronization between the two sensor units would eliminate the need for duplicated measurements of control coil currents. However, the duration of the physical phenomena of interest are only dozens of milliseconds which would demand high accuracy of time-syncronization between the sensor units. Thus, the approach with duplicated measurements is more simple and reliable.

The sensor units record each and every switchgear operation which is a major improvement in condition monitoring. However, excluding inspections high voltage switchgear is operated rarely [**50**]. Normally data acquisition for condition monitoring will be infrequent as switchgear may stay in an open or a closed position even for years [**50**]. Thus, the real benefit is gained by combining IoT online monitoring and the principle of the online inspection. The online inspection routine can be performed very efficiently when no external measurement instruments are required. Performance data flows automatically into the cloud while circuit breakers and switches are quickly test-operated one by one. An objective is a near real-time mobile access to the measurement data which will instantly allow the service personnel to further diagnose a piece of equipment with alarming measurement values. The IoT platform is being developed to allow fast data processing through the whole channel from sensor units to the cloud and finally to a visualization tool, all taking minutes in total.

In 2019, switchgear of eight 110 kV substations will be equipped with IoT sensor units. The current version of sensor unit is designed for switchgear with a common control cabinet for all the three phases which, in case of Fingrid's asset fleet, refers to 110 kV and lower voltage switchgear [**10**]. 400 kV switchgear are basically equipped with a separate control cabinet for each phase [**10**]. The difference is presented in Figure 18. A different design of IoT sensor unit is required for 400 kV switchgear because the sensor units in the three control cabinets have to be time-synchronized. Sensor units for 400 kV switchgear will be developed in the future.

Figure 18: Circuit breakers with a common control cabinet (left) and a separate control cabinet (right). [**47**]

4.2 Gas-Insulated Switchgear

In Air-Insulated Switchgear (AIS) SF_6 gas is only used for arc-quenching inside a circuit breaker whereas Gas-Insulated Switchgear (GIS) are high voltage equipment fully enclosed in SF_6 gas compartments [**51**]. In Nordic weather conditions GIS substations are built indoors [**9**]. The footprint of a GIS can be approximately 30 % of a corresponding AIS switchyard which makes GIS a good solution for urban areas and underground substations [**51**].

Existing online condition monitoring

A GIS consists of a number of separate gas compartments. Gas density of each compartment is measured with the same sensors as in AIS circuit breakers. Correspondingly to AIS circuit breakers, the GIS gas pressure data is wired in substation LAN. Figure 19 presents a part of a GIS circuit diagram for online monitoring. It shows there is a low pressure in one of the compartments which can be either due to a leakage or a sensor fault.

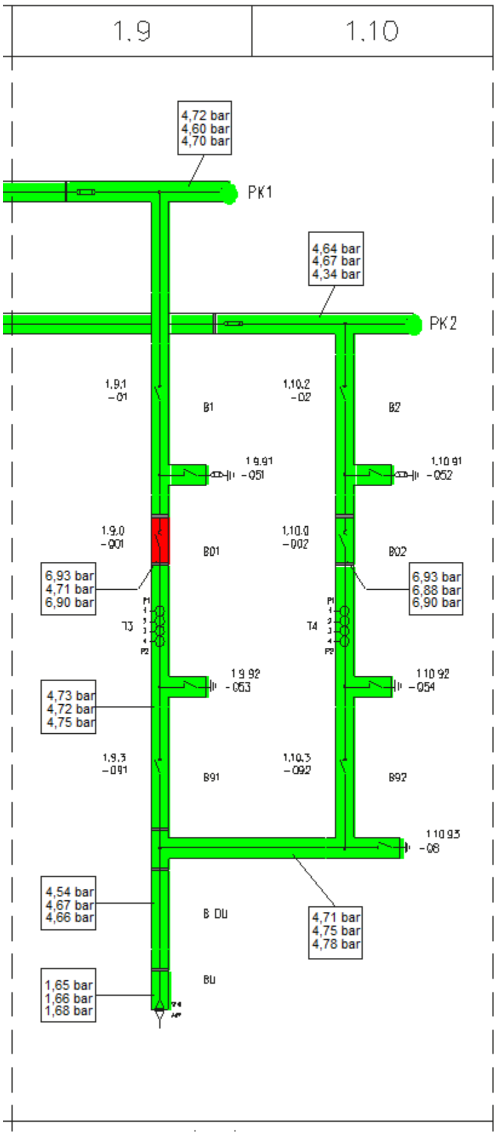


Figure 19: Gas compartment diagram of a GIS substation for online monitoring of SF_6 gas pressure. [**42**]

Modular Switchgear Monitoring

Fingrid ran a pilot project with ABB to experiment their new online condition monitoring system for GIS substations. The Modular Switchgear Monitoring (MSM) system measures currents and SF_6 gas densities at the moment. Microphones are not included. Otherwise the output is similar to the IoT solution for AIS circuit breakers described in Section 4.1. Operation times and charging motor currents of each circuit breaker operation are recorded. The SF_6 gas pressure of each GIS gas compartment is monitored.

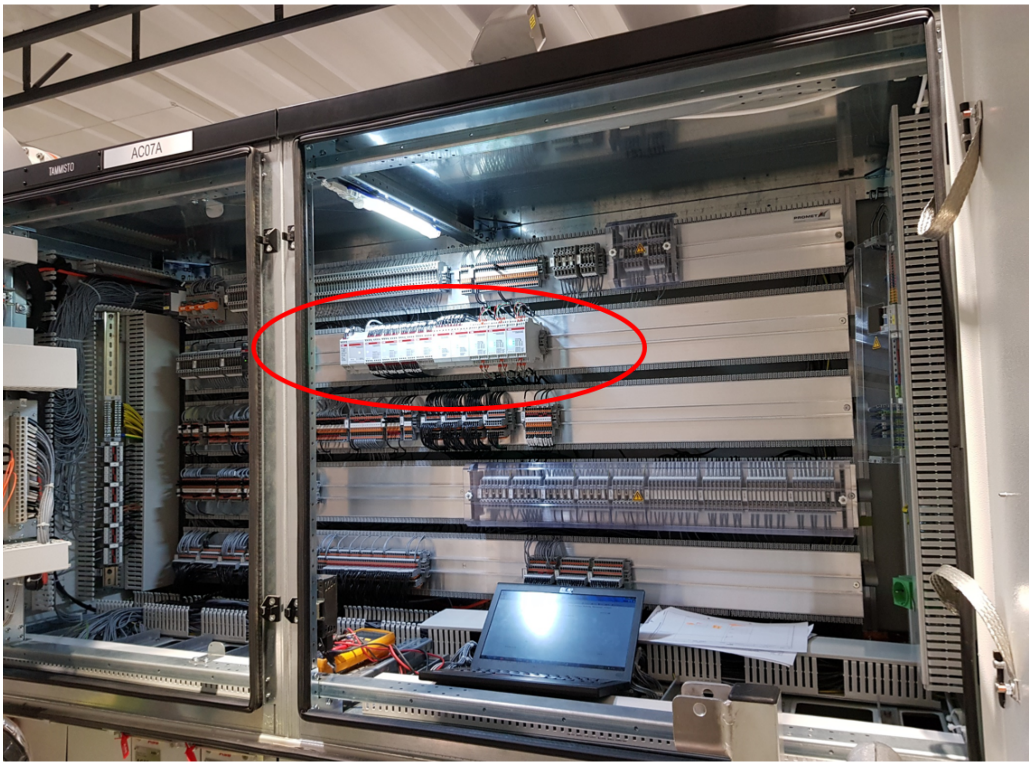


Figure 20: The MSM system installed in a Local Control Cabinet of Länsisalmi 400 kV GIS substation.

The MSM systems were installed in the Local Control Cabinets (LCC) of each bay in Länsisalmi 400 kV GIS substation. Circuit breaker control circuits, current transformer secondary circuits and SF_6 gas density sensors are hard-wired to the MSM modules. Current measurements are carried out by hall sensors inside the MSM modules. There is an edge gateway in the substation that communicates over a WiFi network with the MSM communication units. The gateway is connected to the MPLS (Multiprotocol Label Switching) switch of the substation for internet access. The data is transferred to "ABB Ability" cloud which is ABB's cloud platform built on Microsoft Azure.

The objective of this project is to experiment the MSM as a new solution for GIS online condition monitoring. There are no current plans to extend this solution to other Fingrid's existing GIS substations.

4.3 Power transformers

Being worth several millions of euros, a power transformer is the most expensive component in a substation. A power transformer failure would be a major incident for several reasons. There are only one or two power transformers in a substation connecting the voltage levels. Thus, a loss of one would significantly affect the transmission capacity of the transmission network. An outage could take a long time as the replacement of such a heavy unit is a major effort. Delivery times of power transformers are also long because they are custom-made and shipping is slow. In addition, a fire in a power transformer may lead to severe environmental damage. There are approximately 100 000 kilograms of oil inside that can ignite or spread to near surroundings [**10**].

Fingrid has 91 power transformers and in average they cause 4,1 network disturbances in a year [**10**], [**37**]. It is evident that condition monitoring of power transformers is necessary. It has been learnt in practice, too, as Fingrid has managed to prevent several power transformer failures during the past 10 years due to online condition monitoring [**52**]. There are well-established methods for condition monitoring of power transformers but IoT can bring something new to the table. This section presents Fingrid's condition monitoring practices for power transformers.

Dissolved Gas Analysis and Oil Analysis

Dissolved Gas Analysis (DGA) is a well-established condition monitoring method that can detect multiple transformer fault types. Degradation of oil and paper insulation inside a transformer produces different gases in the oil due to chemical breakdown of oil and cellulose molecules. [**53**], [**54**] Temperature at the fault location and materials in contact with the fault area determine which gases are formed and to what extent [**54**]. The fault type can be diagnosed by studying the ratios of different fault gases dissolved in the oil. The seven commonly considered fault gases are listed below: [**53**], [**54**]

- Acetylene (C2H2)
- Carbon Dioxide (CO2)
- Carbon Monoxide (CO)
- Ethane (C2H6)
- Ethylene (C2H4)
- Hydrogen (H2)
- Methane (CH4)

Conventional DGA is performed by sampling the oil in a syringe and dispatching it to a laboratory. A more advanced method to monitor gas formation is continuous online DGA. There are single gas and multiple gas online monitoring equipment available [**55**]. Single-gas equipment measure only hydrogen concentration while multiple-gas equipment can measure the three significant ones or even all the fault gases [**55**].

DGA is not exact science. In a laboratory analysis, the resulting gas concentration may vary even dozens of percent depending on the gas extraction procedure. [**54**] On the other hand, the continuous online DGA equipment is prone to faults and single-gas monitoring cannot detect all types of transformer faults [**52**], [**54**]. The advantage of continuous online DGA is the capability to monitor trends, meaning changes in fault gas formation [**53**]. Each power transformer is a custom-made individual unit with slightly different fault gas formation patterns. The absolute value of a fault gas concentration may not be informative when it is low whereas changes in a continuous trend most likely indicate an emerging fault. [**38**] Gas formation increases along with thermal stresses due to increasing load or temperature [**53**], [**54**]. Thus, short-term increase in gas formation may indicate an overloaded condition rather than deterioration of the transformer initiated by the transformer itself. Continuous online DGA data should be considered in correlation with temperature and loading. [**54**]

The insulation properties of the oil itself can also be measured in a laboratory analysis. Dielectric breakdown strength, dissipation factor, interfacial tension, and some other physical and chemical properties determine the condition of insulation oil [**56**].

Fingrid is using multi-gas analysers and single-gas analysers for continuous online DGA of power transformers [**10**]. Examples of the equipment is presented in Figure 21.

Figure 21: Equipment for continuous online DGA. [**10**]

Annual laboratory analyses produce trend data that is monitored continuously. There are different scopes of laboratory analysis covering only DGA, oil breakdown strength and DGA, or all the insulation properties of oil in addition to DGA. The annual analysis is of a narrow scope whereas wider scope analyses are performed less frequently. Additional analyses can be performed on demand and transformers with alarming fault gas formation behaviour are sampled more frequently. [**38**] An alternative for laboratory analysis is a transportable DGA instrument, presented in Figure 22. An oil sample is analysed on site in 30 minutes instead of dispatching it to a remote laboratory facility [**55**].

Figure 22: A transportable DGA instrument. [**55**]

Sweep Frequency Response Analysis

Sweep Frequency Response Analysis (SFRA) is a sensitive analysis technique for detecting mechanical faults in power transformer windings [**57**]. An impact in transport or a network fault close to the transformer may cause deformation or displacement of windings [**52**]. In order to detect these faults without opening the transformer cover, sinusoidal voltages at different frequencies are applied to a terminal of an offline transformer. Amplitude and phase of induced signals obtained from other terminals are recorded as a function of frequency. [**57**]

Frequency response of a power transformer is unique due to the fact that each power transformer is a custom-made unit. Local conditions and structures connected to a power transformer also affect the frequency response. Thus, an SFRA fingerprint of each new power transformer is recorded after installation on site. Further SFRA is not performed frequently but in case there are suspicions of a possible damage, for example after an external short circuit fault close to the transformer. A new fingerprint is always recorded after an overhaul. [**52**]

Analysis and interpretation of SFRA data are difficult. High expertise is required as highly developed tools and guidelines do not exist yet. [**57**]

Dissipation factor

Dissipation factor, also known as "Tan Delta", is the dielectric loss angle of insulation under an AC voltage. It is an efficient non-destructive method to measure condition of solid insulation. However, the dielectric loss angle should not be confused with the dielectric breakdown strength which cannot be measured without damaging insulation. [**58**] Dissipation factor is measured offline. It is performed at a time interval of 9 years for power transformer windings and bushings [**38**].

Online condition monitoring solutions of power transformer bushings are also available [**59**], [**60**]. Such equipment estimate the dissipation factor as a result of bushing leakage current measurements [**60**]. The equipment can also detect Partial Discharges (PD) inside the transformer tank [**59**], [**60**]. An experiment with online monitoring of power transformer bushings has been attempted in one of Fingrid's power transformers. The experiment was not successful due to problems with data transfer from the monitoring equipment to Fingrid's on-premise database. Further experiments will be probably carried out in the future. [**38**]

Temperatures and loading

Power transformer temperature and loading are basic parameters to be monitored. Overheating accelerates deterioration of insulation and consequently reduces the lifespan of a power transformer [**61**]. Loadability is determined by the temperature. A power transformer can be overloaded a bit until the temperature reach a critical level. Ambient temperature affects power transformer cooling and thus loadability, too. [**61**]

Power transformers are equipped with several temperature measurements. Temperature of each winding is measured separately and oil temperature is measured at one or two points [**42**]. Newer power transformers are equipped with fiber optic temperature measurements in addition to conventional Winding Temperature Indicators (WTI). Old transformers are only equipped with WTIs. [**52**] A conventional WTI determines a winding temperature by using oil temperature and winding current information. Oil temperature measurement is an indirect measurement system based on volume changes of a liquid. The secondary current of a bushing current transformer is fed to a resistor that heats proportionally to the winding which allows the winding temperature to be calculated. [**62**] For metering purposes the current and the voltages of a power transformer are measured by instrument transformers in the switchyard. Powers are calculated accordingly. All power transformer data is conventionally transferred to SCADA. [**52**]

IoT measurements

The expected lifespan of a power transformer is approximately 40 years. In order to extend the lifespan to 60 years, an overhaul can be performed 20-30 years after commissioning. Commonly the short circuit strength of a power transformer has degraded at that age due to loose windings. To restore the short circuit strength the cover of power transformer is opened and windings are tightened. Gaskets are replaced to ensure tightness of the oil tank, bushings are inspected in a laboratory, and the auxiliary equipment is replaced. Paper insulation can be dehydrated if necessary. [**63**]

An early IoT experiment project was run in Tammisto substation at the time of a power transformer overhaul in 2017. Four vibration sensors were attached on the transformer tank to measure winding vibration. [64] Loose turns of windings result in transformation of vibration on the transformer tank [65]. The objective was to experiment if vibration sensors can be used to detect loosening of power transformer windings. Thus, vibration was recorded before and after the overhaul. Regarding the experiment, it was unfortunate to find out in the overhaul that the windings of this particular power transformer were not loose. No transformation in the vibration after the overhaul was detected. Further experiments are needed to confirm if this kind of vibration measurement can be used to detect loose windings for scheduling of power transformer overhauls. [64]

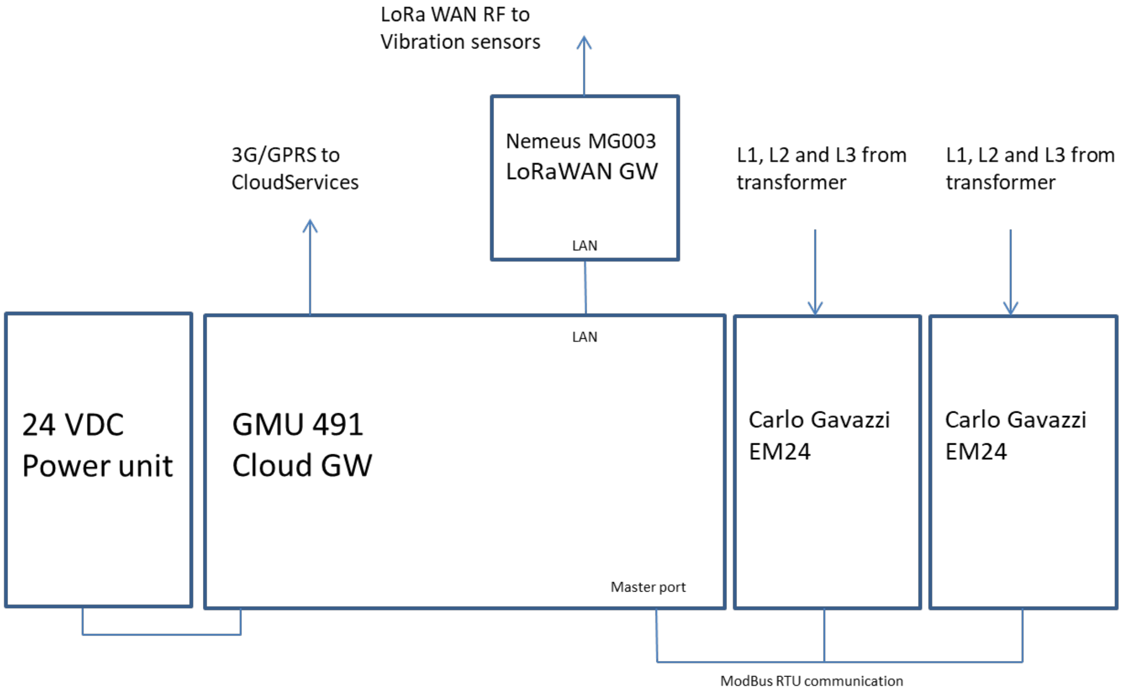


Figure 23: The architecture of Tammisto IoT system. [66]

Figure 23 presents the architecture of the IoT system in Tammisto. Vibration data is sent from the sensors to a gateway over a Long Range Wide Area Network (LoRaWAN). The LoRa gateway is wired to another gateway which sends the data in the Azure cloud by using 3G or General Packet Radio Service (GPRS). [66] The solution has turned out to be unreliable as significant amount of data is not received in the cloud. LoRaWAN signal strength is weak and there are suspicions that the power transformer and nearby reactors may interfere with the LoRaWAN data transfer. Further investigation will take place to find out the real cause of the problem. [64]

On-Load Tap Changer

On-Load Tap Changer (OLTC) is a piece of equipment in a power transformer to control network voltage on the low-voltage side. It changes the turn's ratio of transformer windings by switching the high-voltage side to a different turn of the primary winding. [**39**] Each of Fingrid's power transformers is equipped with an OLTC [**10**].

Being switching equipment, an OLTC has similar operational characteristics to switchgear. There is a motor drive for charging a spring that switches the primary contacts from a turn of winding to another. [**67**] Thus, the IoT sensor unit developed for switchgear could be possibly used for online condition monitoring of OLTCs, too. Normally an OLTC switches the step daily which would allow frequent data acquisition for condition monitoring [**68**]. Adaptation of the IoT sensor unit of switchgear to on-load tap changers will be experimented in the future.

4.4 Instrument transformers

The purpose of an instrument transformer is to transform a primary quantity to a smaller scale that can be measured in protection relays and energy meters [**69**]. The value of a primary quantity can be calculated by applying the transformer ratio to the secondary quantity of an instrument transformer. Voltage transformers can be either inductive or capacitive. An inductive voltage transformer is a conventional transformer with a primary winding and secondary windings on a common core. A capacitive voltage transformer contains a stack of capacitors as a capacitive voltage divider. [**70**] Current transformers are conventional transformers with several cores. The measurement range has to be a lot wider for current than for voltage because of high fault currents. Thus, different cores and windings are needed in current transformers for different purposes, referring to protection and load metering. [**69**]

Instrument transformers have slightly lower fault frequencies than switchgear [**37**]. Fingrid has approximately 2 100 voltage transformers and 4600 current transformers [**10**]. Instrument transformer failures can lead to severe damages. Pressure build-up in the sealed oil space may lead to an explosion which spreads the oil, and in case of ceramic insulation, heavy fragments of insulation on the switchyard [**38**]. In 2017 a few voltage transformers exploded and in 2018 a current transformer explosion had severe consequences as mentioned in Section 3.2. [**37**]

Existing condition monitoring

Currently, there is not much condition monitoring for instrument transformers. Oil leakages can be detected in substation inspections when the oil level indicators are inspected along with the overall appearance of the equipment. Dissipation factor measurement and dissolved gas analysis are performed on demand but not frequently. [**38**] Oil sampling is generally avoided as instrument transformers are hermetically sealed [**69**]. Radio-Frequency Interference (RFI) measurements are performed annually to detect possible partial discharges in insulation of instrument transformers and power transformers [**71**].

IoT measurements

A capacitive voltage transformer consists of a number of capacitors connected in series [**70**]. A short circuit of a capacitor would change the output voltage of the capacitive voltage divider. This kind of a fault could be possibly detected by monitoring the long-term trend of secondary voltages. In a short period of time, voltage fluctuations of a live network and imbalance between phases cause fluctuations of the secondary voltages. However, the difference between secondary voltages of different phases should not drift over time. If this happens, there is most likely a fault.

Secondary circuits of instrument transformers are connected to protection relays and to other automation systems. The data is transferred to the SCADA environment to allow operators in the control centre to monitor network voltages and currents in real-time. However, only line-to-line voltage data is available which means that phase voltages are not monitored [**72**].

Thus, in the first IoT experiment project in Tammisto, standard energy meters presented in Figure 24 were installed in the substation building to measure the secondary voltages of two 110 kV voltage transformers, meaning six pieces of primary equipment in total. [**64**] The IoT architecture in Tammisto was described in Section 4.3.

Figure 24: A regular energy meter used for measuring the secondary current of a current transformer. [**73**]

The voltages of three phases have remained stable in respect of each other and short-term fluctuations are visible. There were no suspicions of faults in advance in these particular voltage transformers and detecting a real fault was not a realistic objective of the project. The main objective was to build and test a first version of an IoT platform and have some reasonable data for monitoring [**64**]. The energy meters used in this experiment are expensive considering a large-scale extension of voltage transformer monitoring in dozens of substations. In addition, the meters are conventionally hard-wired and thus installation work is not minimized as it should be according to the main principles of Fingrid's IoT concept described in Section 3.2.

For possible extension of this kind of monitoring, it also has to be considered if it is better to install a separate meter for voltage measurement or make use of the phase voltages measured by existing substation automation.

For inductive voltage transformers and current transformers there are no such straightforward ways for continuous online condition monitoring. As explained in Section 4.3, online DGA and dissipation factor online measurements are a good condition monitoring methods for transformers. They would be useful for instrument transformers, too, but the monitoring equipment is too expensive in respect of the cost of an instrument transformer.

4.5 Substation buildings

Substation automation, telecommunication and auxiliary power systems accommodated in a substation building are essential systems for the operation of a substation. Protection, switchgear control, remote connection between a substation and the control centre, and the offline performance of substation automation are all taken care of by these systems. Appropriate conditions in the building ensure the systems performance. Risk of overheating applies to cabinets containing automation and telecommunication equipment whereas performance of batteries degrades at a cold temperature. The climate in Fingrid's regular substation building is kept somewhat constant, close to office conditions. HVDC (High Voltage Direct Current) converter stations include special rooms where maintaining constant conditions is critical for the operation of primary equipment [**74**]. However, there is currently no visibility to building conditions and thus it is not possible to know how they fluctuate in reality.

As stated in Chapter 2, an objective of the IoT project is to reduce time-based work on site. This will reduce visual inspections of the substation building. Thus, more real-time visibility to substation buildings is demanded to ensure the performance of critical secondary systems.

Indoor climate and water leakages

In 2018 the first substation buildings were equipped with Haltian Thingsee POD 2 sensor units presented in Figure 25.

Figure 25: The sensor unit for climate measurements. [**75**]

They are simple and low-cost sensor units measuring ambient temperature, humidity, air pressure, light level, movement and vibration [**75**]. The former three quantities are used in this case. The sensor units are placed in different rooms and in different spaces in the building structure. One sensor unit is measuring outdoors, too. In addition, separate sensors are used to detect water leakages on surfaces based on the electrical conductivity of water. Two copper contacts are galvanically connected by water to indicate moisture on a surface.

Data is transferred from the sensor units to a gateway and further to Haltian's Thingsee Operations Cloud which is built on AWS (Amazon Web Services) cloud platform. From Thingsee cloud the data is replicated to Fingrid's Azure cloud. In a future scenario, the data flow will be redirected to Fingrid's Azure cloud. However, it will be a considerable task to configure the Azure platform to communicate with the Thingsee hardware as they were originally developed for AWS platform.

Equipment monitoring

In addition to monitoring of the ambient conditions, specific equipment inside the buildings could be monitored. Current sensors and vibration sensors could possibly be used to measure the operation of air-source heat pumps and air ventilation fans. Thingsee POD 2 sensor units could be additionally placed inside relay racks or other automation cabinets in case overheating is suspected. Once the cloud platform has been established, new sensors can be easily added wherever it seems necessary, although provided that the costs of sensors are low.

4.6 Primary circuit temperature

Temperatures of structures in the primary circuit are measured with custom sensor units. They are attached with double-sided tape to the outer surfaces of primary equipment, to joints and close to contacts or switches. Figure 26 shows installed temperature sensors.

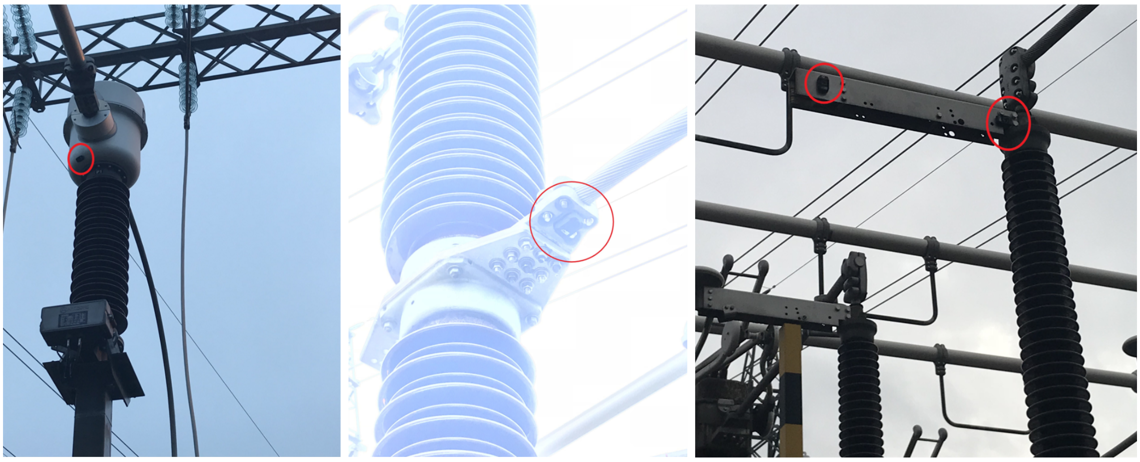


Figure 26: Custom temperature sensor units installed on primary circuits. [**46**]

Faults in conventional oil-insulated instrument transformers sometimes ignite a fire or even make them explode [**38**]. The idea of measuring surface temperature is to detect these faults early enough to prevent fire and explosions. However, there is no proof if surface temperature gives an early enough warning of such faults in reality. It will be discovered in the future.

Loose joints increase resistance which leads to energy losses and excess heating in structures carrying high currents. Temperature sensors attached to joints will probably make it possible to detect loose joints by analysis of temperature and current in similar joints. If the price of a sensor is low enough, all joints can be equipped with a sensor to have a full coverage of monitoring.

Overheating may occur also in primary contacts of disconnectors. Figure 27 is a real-life example of an overheating 20 kV disconnector.

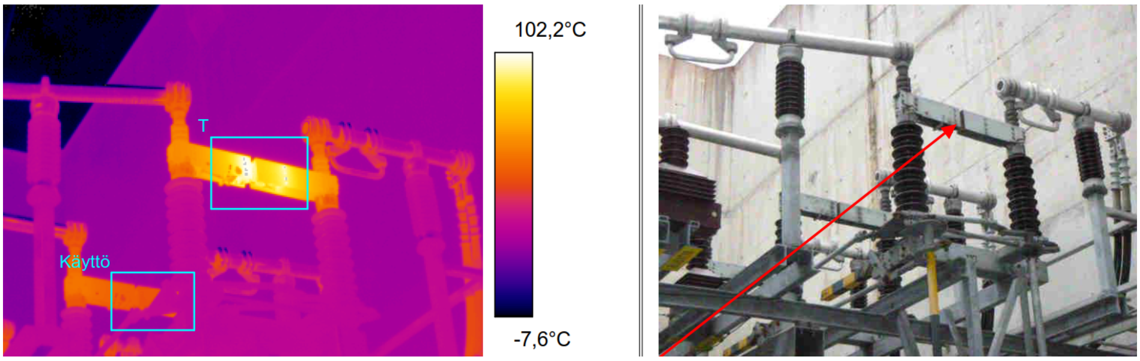


Figure 27: A 20 kV disconnector with excessively heating primary contacts. [**46**]

High contact resistance makes the temperature rise to more than 100 degrees Celsius whereas the temperature in a healthy phase is only 23 degrees Celsius. Thus, temperature sensors are attached close to the primary contacts.

A challenge with the temperature sensors is heat transfer from the primary structures to the sensor. In the first tests the sensors were strongly affected by wind and outside temperature. The internal design of the temperature sensor was changed accordingly. The adherence of the tape attachment is another uncertain aspect. The sensors have remained attached during several months of harsh winter weather conditions but there is not yet longer-time experience.

Usage of fixed low-resolution thermal cameras is also experimented in the IoT project. The advantage is that a few cameras can monitor the overall primary structures instead of specific measurement points.

4.7 Future development

There will be a lot of use cases for low-cost online measurements in the future. The already developed solutions can be adapted to new use cases and new solutions will be developed. Online condition monitoring will be deployed to other asset types and substation surveillance and work safety will be considered, too. Some future possibilities are listed below:

- Post insulator monitoring: Acoustic emission for detection of cracks
- Busbar vibration monitoring
- Reactor vibration monitoring
- SF_6 pressure monitoring: An IoT solution to replace conventional
- Surge arrester monitoring: Surge count and leakage current
- Instrument transformer monitoring: Cameras and image recognition for oil leakages and oil level indicators
- Auxiliary battery monitoring: Automatization of capacity testing, cell voltages and resistances
- Sliding gate monitoring: Motor drive and mechanics
- Substation area surveillance: Cameras and drones
- Working safety: Sensors in working clothes

5 Asset Performance Management application for Fingrid

According to Gartner, "Asset performance management (APM) encompasses the capabilities of data capture, integration, visualization and analytics tied together for the explicit purpose of improving the reliability and availability of physical assets." [**76**] An APM application is a software that provides the user with a visual interface to the process of asset performance management. Most importantly, an APM application is responsible for the third step of the condition-based maintenance technique, Data Visualization, presented in Figure 1. Condition data of assets is visualized and interpreted in an APM application to support decision-making of different user groups. This Chapter presents what kind of visualization of condition data is necessary in an APM application.

The functional requirements for an APM application depend on the available condition data and the end users of the application. To recognize Fingrid's needs, the condition monitoring solutions were explored in Chapter 4 and the user groups are classified in this Chapter. As one of the key ideas behind an APM application is to include all condition data under a single roof, it is important to understand where the data comes from. Several integrations of other applications, platforms and databases to an APM application are needed. Thus, this Chapter presents Fingrid's current situation regarding condition data sources.

5.1 User groups of asset condition information

Information on asset condition is useful for different purposes. On-site fault diagnostics, maintenance scheduling and investment planning are all dependent on asset condition. Accordingly, there are different user groups for an APM application. The needs of users are different, and thus it is important to understand the user groups to be able to specify Fingrid's requirements for condition data visualization in an APM application. In this Section, the main user groups are presented.

Equipment subject matter expert

Fingrid has equipment subject matter experts for all the primary equipment: switchgear, power transformers and instrument transformers, reactors, capacitors, surge arresters, GIS substations and HVDC converter substations. An equipment subject matter expert is responsible for the lifecycle policy of his asset group and defines maintenance practices and techniques.

An equipment subject matter expert needs to have real-time visibility to asset condition in order to identify assets in poor condition. He puts these particular assets under closer observation and defines what maintenance actions will be performed. He also does fleet analysis amidst the asset group under his responsibility. Common failure modes of a certain asset model may reveal a factory defect or indicate a demand for improvements in the maintenance policy.

Service provider

All of Fingrid's grid construction and maintenance work is outsourced. There are several service providers, and each of them is responsible for substations in a work area. A geographical region consists of several work areas. Service providers perform maintenance activities according to the work orders and they are also standby around the clock prepared to react to a failure in a substation.

New IoT solutions will provide vast amount of detailed data, especially on switchgear. Ideally, an imminent fault is detected and prevented in advance by condition data analysis. However, it is difficult to foresee all the patterns that have to be considered alarming as such solutions for condition monitoring haven't been experimented earlier. Nevertheless, faults will inevitably occur. Being the first personnel arriving on site to look for a fault, service providers need access to the detailed condition data of a single asset for further diagnostics. Studying the data would ideally speed up the diagnosis and repair, and thus reduce the equipment downtime.

As explained in Section 4.1, an important element of the IoT solution for switchgear is the online inspection routine. Despite the switchgear is test-operated remotely from the control centre, the service providers are on site to visually verify appropriate operation of the switchgear. The service providers need a mobile interface with an informative summary dashboard to display the measured performance values of each circuit breaker and switch in a substation and to pinpoint outliers in the fleet under inspection.

Regional maintenance coordinator and manager of service provider

Fingrid has divided Finland into several geographical regions in terms of maintenance responsibilities. Each region is managed by a regional maintenance coordinator. Correspondingly, a service provider has a manager for a region under its responsibility. Fingrid's regional maintenance coordinator and a manager of service provider are together responsible for scheduling maintenance actions following the maintenance policies. Regional maintenance coordinators manage the maintenance work orders for service providers that are responsible for the work on site.

Inside his region, a regional maintenance coordinator aims to group maintenance actions efficiently for each substation. Therefore he is interested in the condition of each asset in each asset group. Predictive analysis of future condition trends would enhance the decision-making of a regional maintenance coordinator when estimating whether maintenance of an asset can be postponed or not. Prioritization of maintenance activities is unavoidable because of limited work resources. Besides optimizing the order of substations to be maintained, a regional maintenance coordinator needs to stay aware of assets currently in poor condition to be able to react quickly to a sudden equipment failure.

Refurbishments manager

The planned lifespan of a switchyard is 40 years. In case a switchyard is still necessary as a part of the network after its lifespan, a refurbishment is performed. The scope of a refurbishment depends on equipment condition, suitability of the busbar configuration to future requirements, and other characteristics of each individual substation. The scope may include replacement of certain or all equipment and structures. Sometimes the whole substation is replaced with a new one placed in the near surroundings.

The refurbishments manager is responsible for planning refurbishment investments. Referring to Section 3.2 in Chapter 3, refurbishment projects have to be prioritized to avoid having too many overlapping ones. On the other hand, scheduled refurbishment projects could be postponed to extend the lifespan of old assets that are still in a decent condition at the end of their expected lifespan, which is sometimes the case as stated in Section 2.1 in Chapter 2. Thus, the refurbishments manager is interested in the condition of individual assets but also the overall health of a switchyard and a substation.

Grid operation expert

A grid operation expert is responsible for outage planning. He does not monitor asset condition but he needs to be aware of potentially unreliable switchgear that may fail to operate properly when switching is attempted. Automatic highlighting of such equipment would be useful when creating a switching schedule for a planned outage.

5.2 Data sources

Azure

Microsoft Azure is the cloud service platform of the IoT concept. All the data from IoT sensor units is stored in cloud databases. Switchgear performance values are calculated out of the raw data in the cloud and stored there as well. The Azure platform has to be integrated to an APM application for visualization of the IoT data.

PI

OSIsoft PI is a time series data historian application for recording, analysing and monitoring industrial processes. It allows looking back at real-time data from dozens of years ago. [77] Separate time series curves can be flexibly displayed in a single chart for comparison. A scalable infrastructure supports deployment of a large amount of assets and data from multiple sources [77].

Fingrid uses PI as a historian of SCADA data. Basically all the data transferred from substations to SCADA, including existing online monitoring data, can be monitored and analysed in PI. Custom displays have been built for each monitored asset group and email alarms are automatically sent in case of abnormal conditions such as a low SF_6 pressure in a circuit breaker. Assets can be accessed in a hierarchical drill down navigation panel where substations are classified under work areas and assets under substations.

As listed in Appendix A, DGA data, SF_6 pressure data and equipment loading data are available in PI. An integration from the PI database to an APM application is needed. A one-time offline data load has to be performed to include historical PI data in an APM application or it can alternatively query the data in real-time from the PI database.

Maximo

IBM Maximo is Fingrid's Enterprise Asset Management (EAM) application. It is the master database of transmission network assets where asset hierarchy and nameplate data are stored. A new asset is created in Maximo which makes it appear in other systems via interfaces. In addition, it is a tool for work management. Maintenance work orders, equipment fault defects and most of the offline measurement results are managed in Maximo.

A bi-directional integration between Maximo and an APM application is required. A new asset should appear in an APM application when it is created in Maximo. Some nameplate data would be useful in an APM application, for example alarm and locking levels of SF_6 pressure for a circuit breaker. In that way some alarms could be automatically initiated in an APM application instead of hard-coding or manual configuration. Asset hierarchy, which is further discussed in Section 5.3, should be available in an APM application. Measurement values from equipment inspections should also flow to an APM application when entered in Maximo. Some measurement results, such as dissipation factor data from power transformers, are documents attached to work orders. These measurement results should also be automatically transferred to an APM application which may however require standardization of measurement data formats used by service providers.

In the opposite direction, from an APM application to Maximo, there should be a possibility of an automatic trigger for creating fault defects and maintenance work orders in Maximo for equipment in an alarming condition in an APM application. Maintenance history and future maintenance schedules are also useful information to show in an APM application, which is discussed briefly in Section 5.4. Another possible interesting use case for condition data in Maximo is switching schedules. A planned outage is performed according to a switching schedule that is a sequence of switchgear operations planned for each outage. A circuit breaker or a switch in a poor condition could be automatically highlighted in a switching schedule to alert control centre operators about the risk of a failing operation.

Transformer Oil Analyst

Transformer Oil Analyst (TOA) is a tool for storing and interpreting data on insulating fluids [**78**]. Fingrid's oil samples from power transformers are analysed by a laboratory or a transportable DGA instrument. The results about dissolved gases and properties of oil are entered in the TOA4 database. The TOA4 Online application features visualization and interpretation of data and alarm functionalities [**78**]. The most important feature for Fingrid is Duval triangles that can be used for diagnosis of fault types in a transformer [**38**]. Duval triangles are explained in Section 5.7.

Laboratory or portable DGA covers always all the fault gases whereas only hydrogen or a few fault gases are usually traced in real-time online DGA. [**56**] Thus, further analysis such as study of Duval triangles or fault gas signature is proceeded by using the TOA4 data. The real-time online DGA serves as an early warning feature. When a deviation is detected, further investigation is done by applying a laboratory or a portable analysis.

The oil analysis data is needed in an APM application for power transformer health assessment. It can be replicated to an APM application via an interface from the TOA4 database or the oil analysis results can be directly entered in an APM application. In the latter case TOA4 database would be no longer needed. Both solutions would be technically feasible. However, the workload of manual data entry must be minimized so in case of dropping out the usage of TOA4 database the laboratories have to be given access to enter data in an APM application.

5.3 Asset hierarchy

Asset hierarchy is a framework for segmenting assets under logical subsystems in an EAM. As the word "hierarchy" points out, the levels of a hierarchy are of different magnitude. The highest level is the entire asset infrastructure while the lowest level is a single physical asset or parts of a physical asset. The general hierarchy of Fingrid's substation asset data model in Maximo is presented in Figure 28.

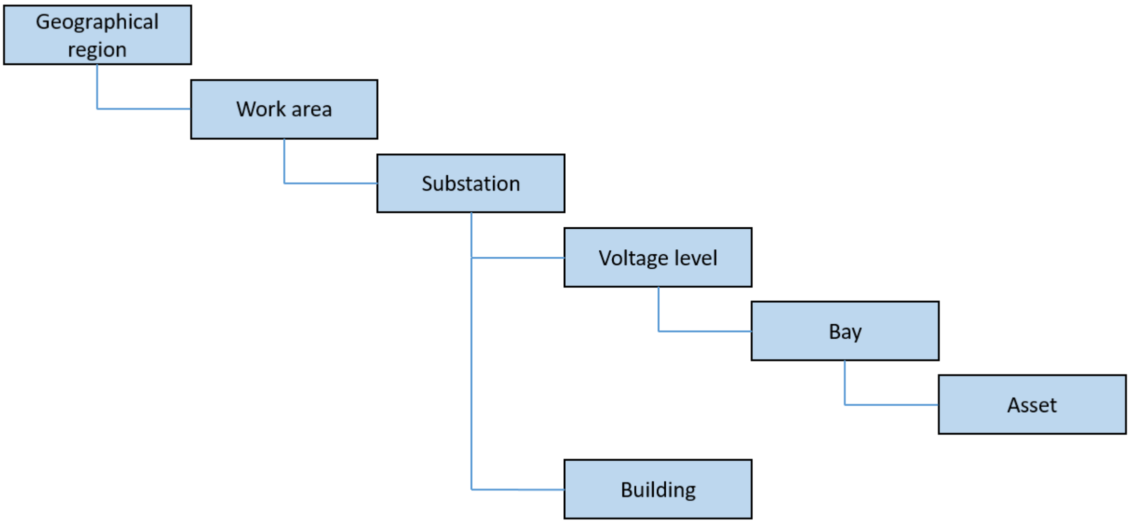


Figure 28: The substation asset hierarchy in Fingrid's EAM. Modified from [**10**]

Asset hierarchy is needed in an APM application for several reasons. An obvious use case for the end user is navigation in the APM application user interface. For efficient application usability, navigating between different assets has to be quick and intuitive. It can be obtained by different navigation panel designs. Three examples are presented in Figure 29.

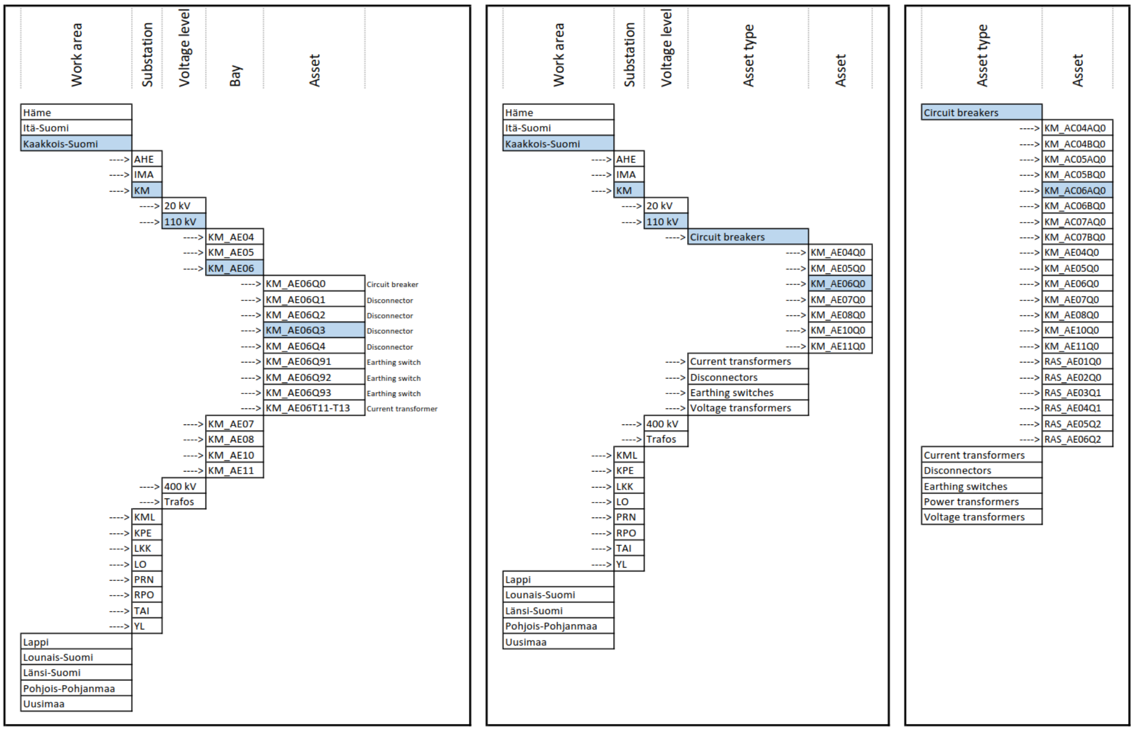


Figure 29: Alternative layouts of a navigation panel for an APM application.

The navigation panel layout on the left hand side consists of the asset hierarchy presented in Figure 28, from level "Work area" to level "Asset". An alternative layout making use of the hierarchy is presented in the middle. It lacks the level "Bay" as assets are classified under asset types. The asset type is a piece of data linked to each asset and it is not technically a part of the asset hierarchy. However, it is useful in this case. This alternative allows the user to move between assets of a certain type more easily which might be useful when studying a certain asset group in a substation. The idea of the layout on the right hand side is also easy navigation inside in an asset group. In this case all Fingrid's assets are visible in a single list instead of dividing them under work areas and substations. All of the alternatives are useful which means a great navigation solution would allow the user to choose between the different navigation panel designs.

In addition, asset hierarchy can be used for fetching data into dashboards displaying summaries about a group of assets. For example an average health score of circuit breakers in a certain substation can be calculated by fetching health scores from the circuit breakers that are under that specific substation in the hierarchy. Another example could be a real-time list aggregating all active condition alarms of assets in a substation by using the hierarchy.

Different measurement can be linked to different levels in the asset hierarchy. If the outside temperature is measured at one point in a substation, it is logical to link the measurement to the substation. Current is measured by a current transformer and the same current flows through all the equipment in the same bay. Thus, current measurements are linked to bays. The asset hierarchy makes it possible to bring data from higher levels down to lower levels such as a current in a bay to a piece of switchgear.

The asset hierarchy is structured in Maximo database. It can be either replicated in an APM application, or queried in real-time from Maximo. The end user of an APM application is not interested in the implementation. Technically both solutions are functional.

5.4 Dashboard levels

An APM application visualizes data for users that have different needs. Separate dashboards aggregate and visualize data in different ways to give users as much information as possible. Dashboards can be logically divided into a few separate levels. This section presents dashboard levels and their main elements.

Asset level

Asset level dashboards visualize condition monitoring data for one asset. In these dashboards the user should be able to study all the data related to an asset. Each asset type has different technical characteristics and related condition monitoring data. Thus, the asset level dashboards have to be designed separately for each asset type to visualize relevant data in an informative way. The focus in this Chapter is on switchgear and power transformers as they are the most important asset types in terms of condition monitoring.

In addition to the actual condition data, alarms and maintenance schedules are necessary in asset level dashboards. Alarms are discussed in more detail in Section 5.11. Briefly, they are notifications saying that there is a problem in the condition of an asset. Active alarms and alarm history of an asset should be visible in an asset level dashboard.

The objective of maintenance actions is to preserve assets in decent condition or restore faulty assets into operational condition. This means that maintenance changes performance characteristics of equipment. Such changes are visible in the measurement data. Maintenance history and future maintenance schedule should be visible in an asset level dashboard to allow the user to distinguish condition changes due to maintenance and deterioration or faults.

Summary level

A summary level dashboard shows a summary of an asset group. When viewing a substation, abnormal measurement values, alarms, past and upcoming maintenance activities, asset health indices and asset risk indices are presented. This information can be grouped to be visualized for each bay, each asset type or any other informative classification.

A work area view can show the same information from the assets in the work area but also aggregated health and risk indices for substations in the area. Similarly, an overall view can aggregate information to work area level. Comparison of work areas is interesting in terms of the efficiency of different service providers. Comparison of substations is necessary for example for scheduling refurbishment projects.

Fleet analysis

Monitoring a trend of a condition measure can reveal that something has changed in the condition of an asset. However, deterioration of equipment over time is unavoidable and normal. The question is what is normal deterioration and what is not. Online DGA of power transformers is such a well-established condition monitoring method that there is a lot of history data and experience. Condition models have been developed for diagnosis and prognosis. Patterns in gas formation trends are recognized and related to certain fault types. In case of switchgear, it will be difficult to evaluate new condition monitoring data. No condition models exist yet and there is not much experience about interpretation of measurement data in question.

Fleet analysis is comparing assets of an equal model to each other. The objective is to detect anomalies. Assets of an equal should all have remarkably similar technical characteristics in a normal operating condition. A dashboard is needed for fleet analysis because the asset level dashboards only display the data of one asset at a time. In a fleet analysis dashboard the user can choose the assets and the parameters to be compared. Data should be visible in graphical formats and also in a tabular format. Appropriate filters and selections should be available.

5.5 Performance quantities of switchgear

Raw data from the IoT sensor units in switchgear is mainly current profiles and sound recordings. Such data can be visually analysed but automated analysis is not as straightforward. Thus, a set of performance quantities have been defined to be calculated out of the data in order to characterize the performance of the equipment. The idea is to have one value of a performance quantity from one switchgear operation. A value does not necessarily need to be very informative as such. Instead, the idea is to look at the trend over time and analyse fleets. If values of a performance quantity stay nearly constant for a great number of operations and then start drifting, there is a reason to suspect an emerging fault. Naturally some performance quantities are informative as absolute values, too, such as motor current that is one of the main technical specifications of an electric motor.

Usability of some of the performance quantities is obvious, such as operation times. However, some of them, especially the ones related to sound spectra, remain rather speculative because there is no prior experience of such analysis for high voltage switchgear. It is not possible to foresee at this stage what a sound spectrum looks like in case of a faulty or deteriorating piece of equipment. Further experience will show how well the performance quantities indicate real-life changes in equipment condition. Evaluating the feasibility of performance quantities is not in the scope of this Thesis. Further study of data analytics will probably be conducted in the future once the IoT concept is up and running and producing an established flow of measurement data.

Some of the performance quantities of switchgear are explained below. All are listed in Appendix B. Some of them are the same as the ones measured in a conventional manual switchgear inspection, such as primary operation time of a circuit breaker. Performance values, meaning the values of performance quantities, are calculated in Azure cloud and the data is stored in the same database where the raw data is stored, too.

Operation time

Standard IEC 62271-100 defines characteristic quantities for circuit breakers. Many different time quantities can be measured. The performance quantities "primary operation time" and "mechanical operation time" used in this Thesis are not defined by the standard. Primary operation time corresponds to "make time" and "break time" in the standard with the exception that no arcing occurs in the online inspection routine. Mechanical operation time is close to "closing time" and "opening time". [**79**] Figure 30 shows how the primary operation time of a circuit breaker is calculated in case of a trip operation.

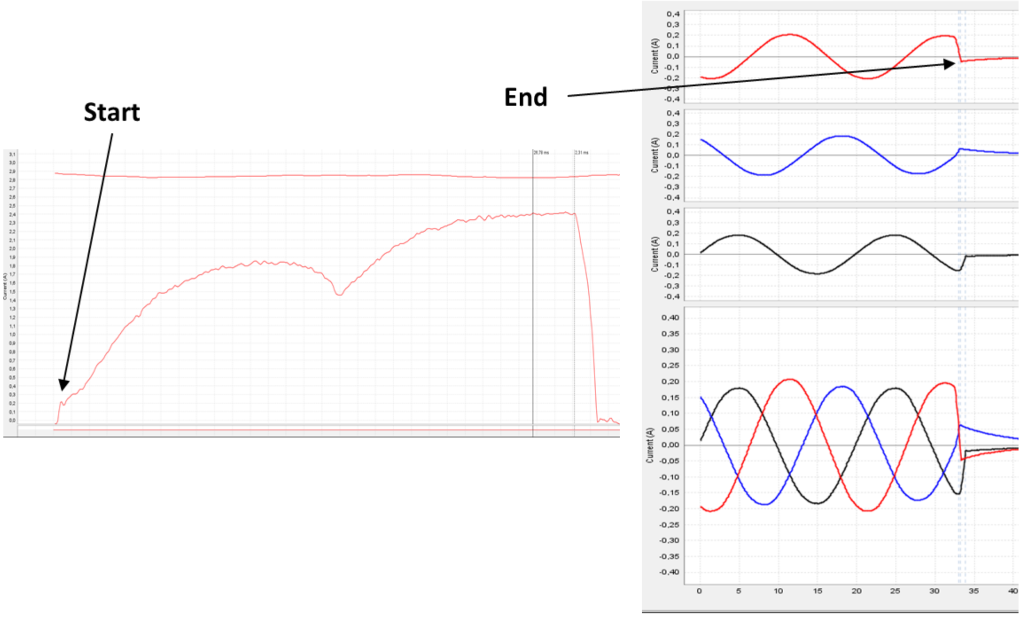


Figure 30: The primary operation time of a circuit breaker is calculated from a control coil current profile and current of a current transformer.

The graph on the left presents a current profile of a trip coil over time. The start timestamp is the instant when a trip command is activated and the trip coil current starts rising. The graphs on the right present secondary currents of a current transformer. The end timestamp is the instant when the secondary current breaks which equals the instant of primary circuit opening. The primary operation time of a circuit breaker is the time duration between these start and end timestamps. Respectively in case of a close operation, the start timestamp is obtained from a close coil current profile and the end timestamp is the make of primary circuit. Primary operation time is an important performance quantity that indicates how quickly a circuit breaker performs its primary function. It is measured manually in a conventional circuit breaker inspection.

Mechanical operation time is the time duration between the timestamp of a control command and the timestamp of a position indicator state change. The position of a circuit breaker is indicated by auxiliary contacts mechanically connected to the primary contacts. When the primary contacts move from the closed position to the open position or vice versa, the auxiliary contacts change the state indicating the current position of the circuit breaker. [**9**] Measuring the mechanical operation time indicates the condition of the mechanics related to auxiliary contacts. If the primary operation time is normal whereas the mechanical operation time is not, there is reason to doubt the condition of auxiliary contact mechanics. The position information is used in SCADA where false information would be a serious issue. In case of switches, the primary contacts are motor-driven. Thus, the only operation time to be monitored is the motor drive operation time.

Control coil current profile

Figure 31 shows the same trip coil current profile than in Figure 30.

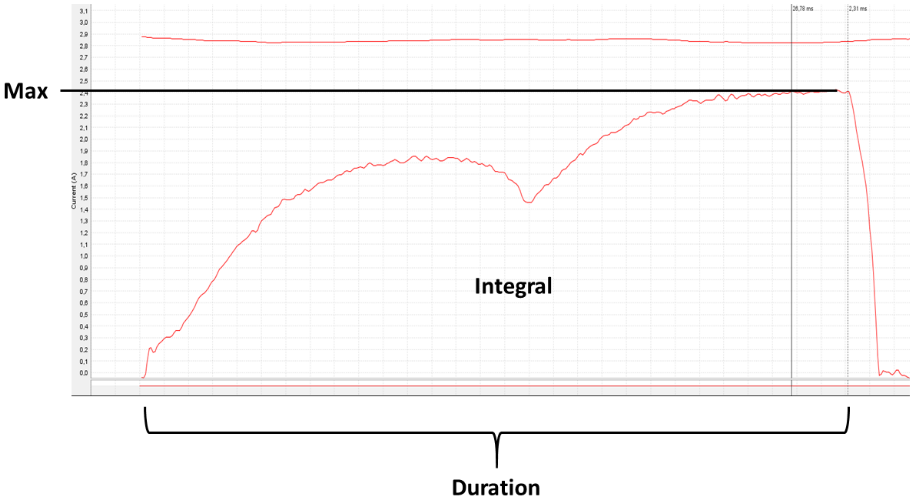


Figure 31: A current profile of a circuit breaker control coil. [**46**]

The condition of a control coil is assessed by analysing the current profile. Three performance quantities are calculated: maximum current, signal duration and integral of current over time. Maximum current and time integral are supposed to indicate an abnormal shape of the current profile. Signal duration is related to mechanics as the signal is switched off by a mechanical auxiliary contact which changes its state along with primary contacts.

Motor current profile

The charging motor of a circuit breaker charges the closing spring after a closing operation. The energy of the closing spring is used to close the primary contacts and to charge the opening spring that accordingly opens the contacts in a trip operation. [**80**] Figure 32 shows a current profile of a circuit breaker charging motor operation.

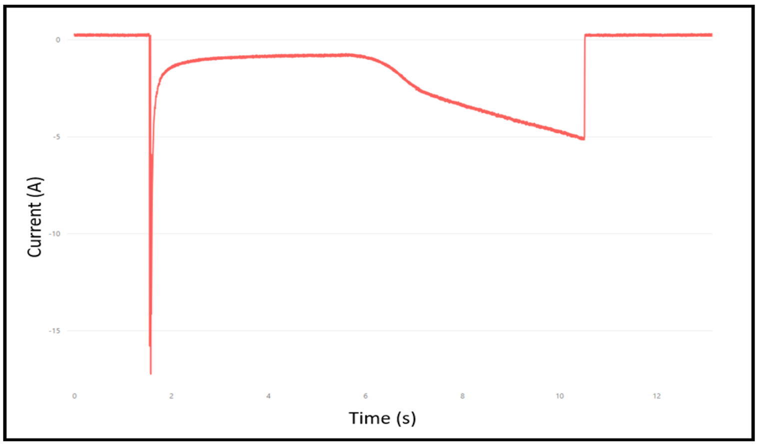


Figure 32: A current profile of a circuit breaker charging motor operation. The negative sign of the current is due to the orientation of the installed current sensor.

The motor current profile consists or three main periods. There is an inrush current peak at start, a flat period when there is not yet much torque applied and finally a period of increasing current during the actual spring charging. The performance quantities calculated are magnitude of the inrush peak, average magnitude of the flat period, time integral of the current profile and time duration of the motor operation. The same performance quantities are applied to motor drive current profiles of switches, too. The shape of current profile is different but basically the monitored component is similar, an electric motor.

5.6 Switchgear data visualization

Visualization of condition monitoring data of switchgear is sketched in this Section. Presentation forms of the data are discussed in the beginning.

Data presentation forms

Online condition monitoring of switchgear is mostly based on events, meaning switchgear operations. Time series presentation is simple and informative visualization for the performance quantities as there is basically one value of a quantity for one operation. A time series chart shows how the value of a performance quantity fluctuates over time. Data accumulates when a circuit breaker or a switch is operated and a data point is plotted according to the event timestamp. To limit the number of separate charts, several performance quantities can be plotted in a single chart.

In addition to event data, there are continuous online measurements: SF_6 pressure and related conditions, including control cabinet temperature and humidity, primary circuit temperature and current. Time series presentation is simple and informative in case of this data, too. For SF_6 pressure, the leak rates can be additionally calculated and visualized in a bar chart. However, time series presentation is necessary to allow viewing history data which is not possible in a bar chart.

Asset level dashboards for trends

There is no one right solution for the design of dashboards. A set of data can be divided in pages and tabs in several logical ways. Sketches of dashboards in this section are created by considering the physical components in switchgear and on the other hand the data presentation form. The dashboards are neither detailed nor finished as the idea is to simply present what content is to be shown and how. Some of the example charts are made in Excel with fictive data and some are charts with real data. The dashboard sketches in this section are created mainly for circuit breakers but the main elements and ideas are applicable for switches, too.

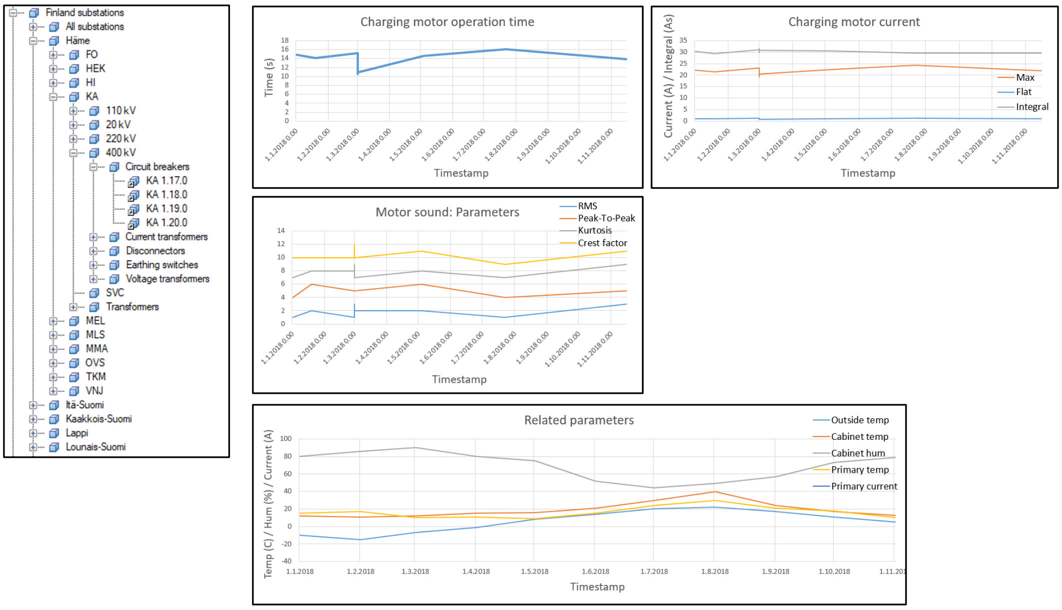


Figure 33: A dashboard for trends of circuit breaker motors. Modified from [**42**]

Figure 33 illustrates a dashboard for time series charts of performance quantities related to circuit breaker charging motor or switch motor drive. Motor operation time is an important quantity as such, especially for switches [9]. Thus it is plotted in a separate chart from the other quantities. The other three performance quantities explained in Section 5.5 are plotted in a single chart because they characterize the same current profile. The performance quantities of motor sound are plotted in one chart.

For switches, motor drive operations should be separated into close and open operations which should not be compared to each other [9]. Thus, for switch dashboards, a few more charts or additional curves in the same charts are needed for performance quantities related to motor drive operations.

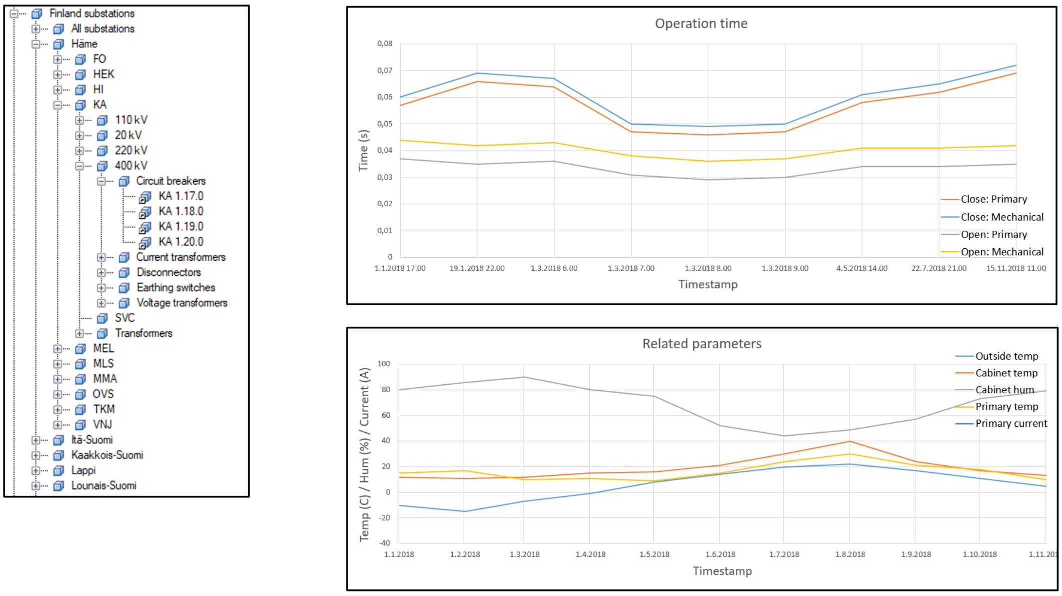


Figure 34: A dashboard for circuit breaker operation times. Modified from [**42**]

Figure 34 illustrates a dashboard for circuit breaker operation times. Primary and mechanical operation times have the same order of magnitude so it is convenient to plot them in a common time series chart. This dashboard is not needed for switches as the only operation time to be measured is the motor drive operation time.

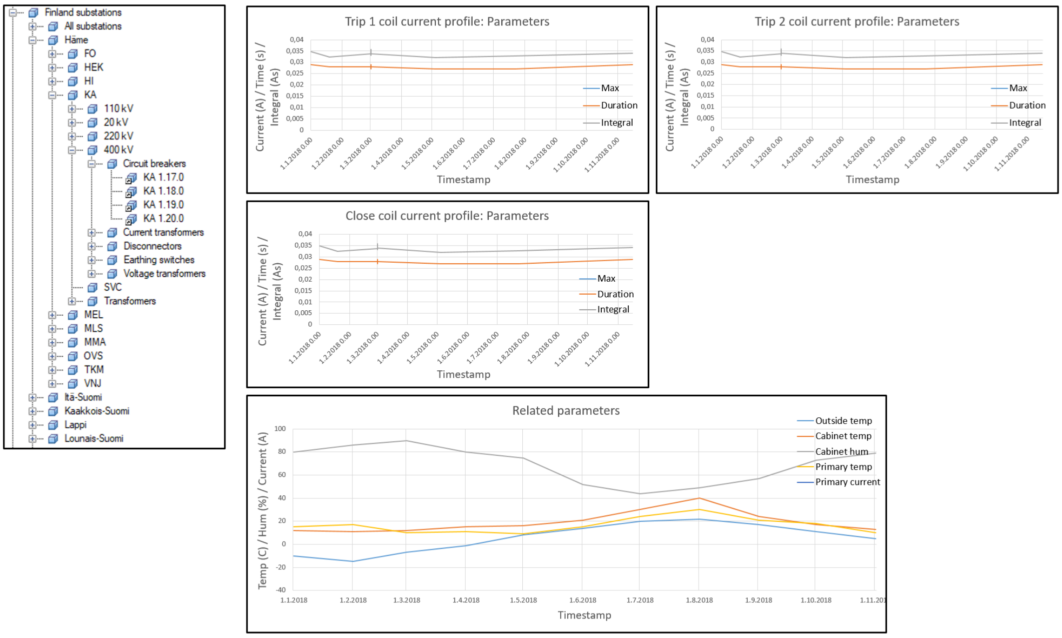


Figure 35: A dashboard for trends of circuit breaker control coils. Modified from [**42**]

Figure 35 illustrates a dashboard for performance quantities of circuit breaker control coil currents. A circuit breaker is equipped with two trip coils for redundancy in trip operation. Close operation is controlled by a single close coil. The three performance values explained in Section 5.5 are plotted in a single time series chart, separately for each coil. An opposite approach would be plotting the three performance quantities in separate charts so that there are data from all coils in each chart. However, the approach in Figure 35 is more intuitive considering the coils as separate physical components of a circuit breaker.

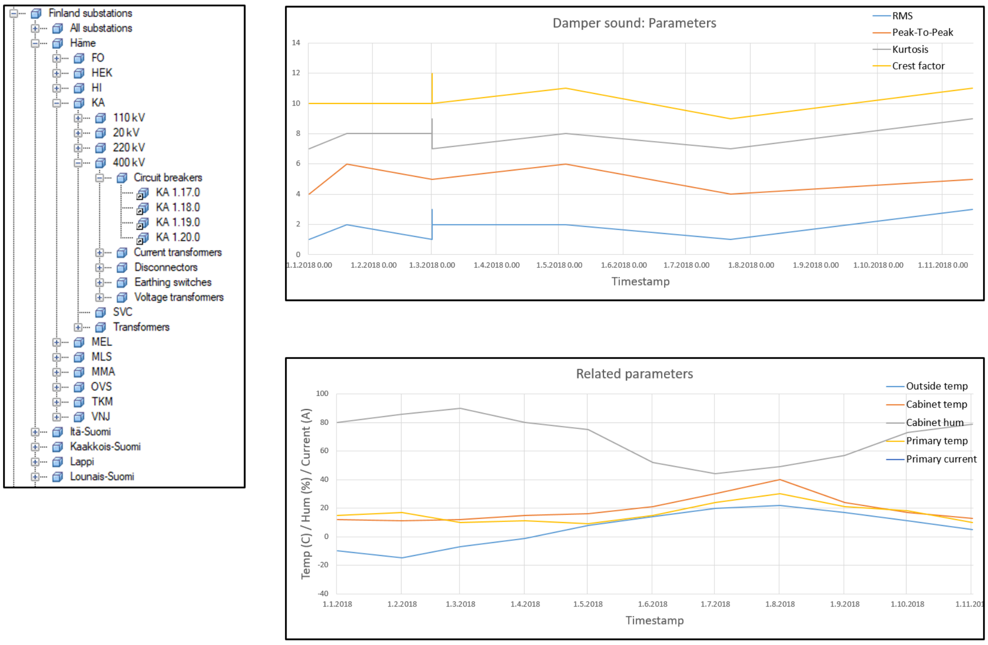
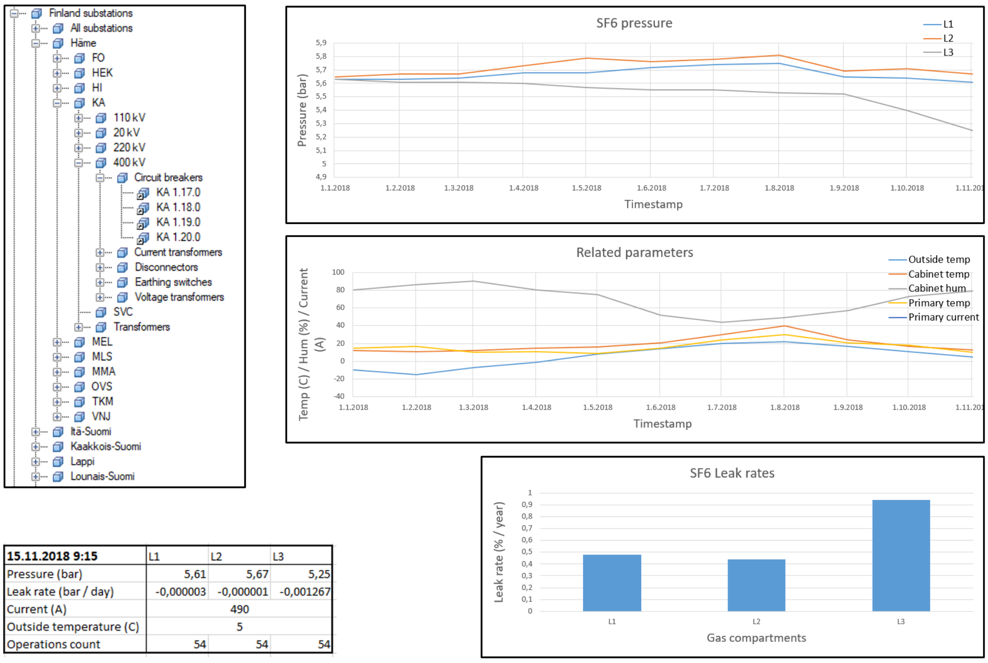


Figure 36: A dashboard for circuit breaker dampers. Modified from [42]

Figure 36 illustrates a dashboard for performance quantities of circuit breaker damper acoustics. In most circuit breakers a hydraulic damper attenuates bouncing of the primary contacts in a trip operation [9].



15.11.2018 9:15	L1	L2	L3
Pressure (bar)	5,61	5,67	5,25
Leak rate (bar / day)	-0,000003	-0,000001	-0,001267
Current (A)		490	
Outside temperature (C)		5	
Operations count	54	54	54

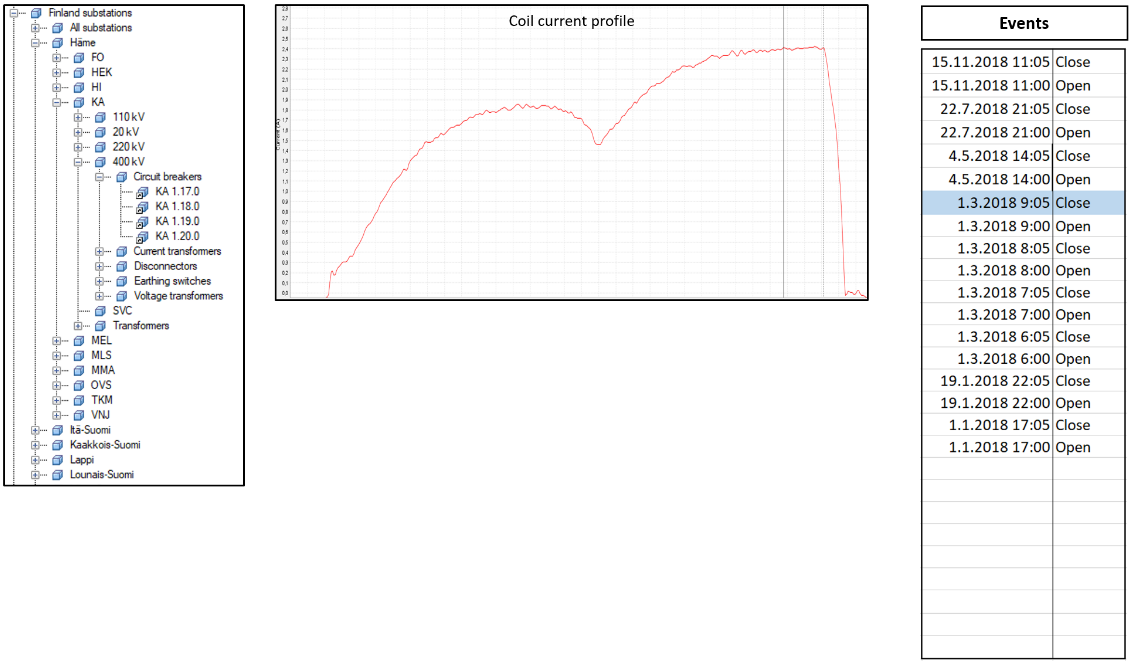
Figure 37: A dashboard for SF_6 gas pressure monitoring. Modified from [42]

Figure 37 illustrates a dashboard for SF_6 gas pressure of circuit breakers. SF_6 pressure data is not event-based data. Gas density in the gas compartment is measured continuously and it is not dependent on operations. A single time series chart displays the gas pressure that is calculated from the density. Despite the switchgear dashboards are designed for 110 kV switchgear in this Thesis, SF_6 pressure has to be visualized also for 400 kV switchgear with separate gas compartments. As the idea of an APM application is to centralize all condition monitoring data in a single application, the existing SF_6 pressure monitoring solutions have to be included.

Asset level dashboards for events

In case an abnormal operation occurs, the user wants to study more closely the event data related to that specific operation. Figure 38 shows a profile of circuit breaker coil current and Figure 39 shows a profile of circuit breaker charging motor current and revolutions per minute. The event selection list displayed on the right allows the user to navigate between events.

Figures 38 and 39 illustrate event views for circuit breakers whereas the previously presented dashboards in Figures 33-37 are designed for trend monitoring.



Events	
15.11.2018 11:05	Close
15.11.2018 11:00	Open
22.7.2018 21:05	Close
22.7.2018 21:00	Open
4.5.2018 14:05	Close
4.5.2018 14:00	Open
1.3.2018 9:05	Close
1.3.2018 9:00	Open
1.3.2018 8:05	Close
1.3.2018 8:00	Open
1.3.2018 7:05	Close
1.3.2018 7:00	Open
1.3.2018 6:05	Close
1.3.2018 6:00	Open
19.1.2018 22:05	Close
19.1.2018 22:00	Open
1.1.2018 17:05	Close
1.1.2018 17:00	Open

Figure 38: A dashboard for current profiles of circuit breaker control coils. Modified from [**42**]

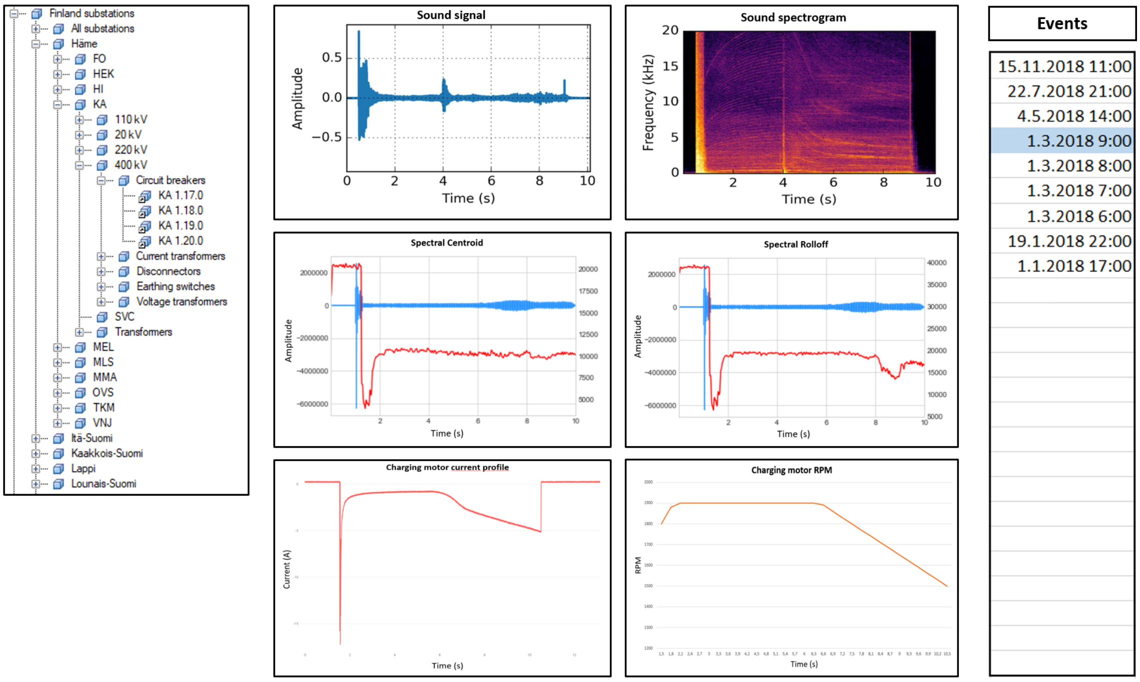


Figure 39: A dashboard for circuit breaker charging motor operations including revolutions per minute, a current profile, a sound signal, a spectrogram and some additional analysis. Modified from [**81**], [**82**], [**42**]

Operation direction and first operation are important attributes in the event list. The operation direction determines whether trip coil current profiles or a close coil current profile is displayed in the view. In case of a trip operation two coil current profiles are to be displayed as Fingrid's circuit breakers are mostly equipped with two redundant trip coils [**9**]. Operation directions have to be separated also for switch motor drives. In case of circuit breaker charging motors, there is only one operation direction. "First Trip" is a term which means the first trip operation of a circuit breaker after a significant standby time period [**50**]. Circuit breaker performance in a first trip operation is usually negatively affected by past environmental conditions [**50**]. Phenomena such as thickened lubricants and rust buildup in the mechanics yield a slow first operation [**50**]. The following operations in the same day tend to be quicker [**50**]. The same applies to switches although the operation time of switches is not as important measure as in case of circuit breakers [**9**]. First operations are denoted with an asterisk in the event list. An additional input field allows the user to define the length of the standby time period that classifies the events into first operations and normal operations.

An important feature to be included in the trend dashboards is drilldown to the event views that display the data of a single event. The user should be able to move easily to an event view for example by clicking a data point in a trend chart.

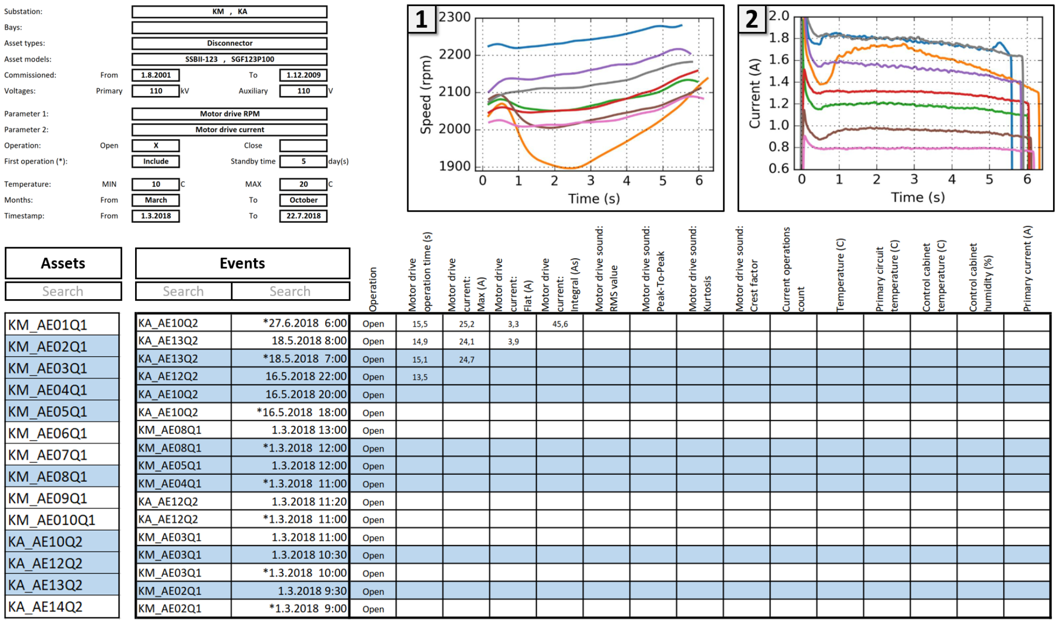
Related parameters

There is a chart for related parameters in each of the trend dashboards. The idea is to visualize data of ambient conditions that may affect the performance of switchgear and explain some trend patterns of performance quantities. Outside temperature data is already available in PI but an alternative solution is to use data from an IoT sensor unit. One of the units monitoring the substation building is installed outside. Conditions inside a switchgear control cabinet are measured by the IoT sensor units. Primary circuit temperatures are measured by the IoT sensors attached to surfaces and joints of primary equipment. There may be several sensors attached on one piece of primary equipment so the related parameters chart can include multiple curves for that data. Primary current is measured by a current transformer and the data is available for each bay in PI.

Implementation of such a related parameters chart requires data from multiple sources. Some of the data in the chart originates from individual pieces of primary equipment while other data is linked to the substation or to a bay. Asset hierarchy can be used for linking all the data correctly to one asset.

Fleet analysis dashboard

An illustration of a fleet analysis dashboard is presented in Figure 40. There are four main elements: A filter panel, an asset selection list, an event list with performance values, and charts with multiple curves. Unlike the previous examples, this one is for switches. However, the main elements are applicable for circuit breakers, too.



Substation: KM , KA
Bays:
Asset types: Disconnector
Asset models: SSBII-123 , SGF123P100
Commissioned: From 1.8.2001 To 1.12.2009
Voltages: Primary 110 kV Auxiliary 110 V

Parameter 1: Motor drive RPM
Parameter 2: Motor drive current
Operation: Open X Close
First operation (*): Include Standby time 5 day(s)

Temperature: MIN 10 C MAX 20 C
Months: From March To October
Timestamp: From 1.3.2018 To 22.7.2018

Assets

Search

- KM_AE01Q1
- KM_AE02Q1
- KM_AE03Q1
- KM_AE04Q1
- KM_AE05Q1
- KM_AE06Q1
- KM_AE07Q1
- KM_AE08Q1
- KM_AE09Q1
- KM_AE010Q1
- KA_AE10Q2
- KA_AE12Q2
- KA_AE13Q2
- KA_AE14Q2

Events

Search Search

		Operation	Motor drive operation time (s)	Motor drive current: Max (A)	Motor drive current: Flat (A)	Motor drive current: Integral (As)	Motor drive sound: RMS value	Motor drive sound: Peak-To-Peak	Motor drive sound: Kurtosis	Motor drive sound: Crest factor	Current operations count	Temperature (C)	Primary circuit temperature (C)	Control cabinet temperature (C)	Control cabinet humidity (%)	Primary current (A)
KA_AE10Q2	*27.6.2018 6:00	Open	15,5	25,2	3,3	45,6										
KA_AE13Q2	18.5.2018 8:00	Open	14,9	24,1	3,9											
KA_AE13Q2	*18.5.2018 7:00	Open	15,1	24,7												
KA_AE12Q2	16.5.2018 22:00	Open	13,5													
KA_AE10Q2	16.5.2018 20:00	Open														
KA_AE10Q2	*16.5.2018 18:00	Open														
KM_AE08Q1	1.3.2018 13:00	Open														
KM_AE08Q1	*1.3.2018 12:00	Open														
KM_AE05Q1	1.3.2018 12:00	Open														
KM_AE04Q1	*1.3.2018 11:00	Open														
KA_AE12Q2	1.3.2018 11:20	Open														
KA_AE12Q2	*1.3.2018 11:00	Open														
KM_AE03Q1	1.3.2018 11:00	Open														
KM_AE03Q1	1.3.2018 10:30	Open														
KM_AE03Q1	*1.3.2018 10:00	Open														
KM_AE02Q1	1.3.2018 9:30	Open														
KM_AE02Q1	*1.3.2018 9:00	Open														

Figure 40: A fleet analysis dashboard for comparing measurement results from different operations and different assets. Modified from [81]

Filter panel allows user to select which assets and which parameters are compared. Selection could be implemented in a different way, too, such as using an asset hierarchy tree combined with filters. The objective of this example is to show which attributes are necessary for the selection. The attributes of the filter panel are listed and explained in the following list. However, an agile system would allow selection and filtering by any attribute.

- Substation: To filter assets of certain substations to be displayed in the asset selection list.
- Bays: To filter assets of certain bays to be displayed in the asset selection list.
- Asset types: To filter assets of a certain type to be displayed in the asset selection list. A substation and a bay always include assets of different types.
- Asset models: To filter assets of a certain model to be displayed in the asset selection list. This is necessary especially for fleet analysis.
- Commissioned: To filter assets that have been commissioned in a certain period of time.
- Voltages: To filter assets of a certain primary and auxiliary voltage level to be displayed in the asset selection list. Same equipment is used at different primary voltage levels [**9**]. For example 110 kV rated switchgear are used in 20 kV tertiary systems that include shunt reactors [**9**]. Auxiliary voltage in Fingrid's substation is either 110 VDC or 220 VDC [**69**]. A filter for the auxiliary voltage is necessary because the auxiliary voltage affects the characteristics of switchgear control circuits and motor drives. Performance values at different auxiliary voltage levels are not comparable.
- Parameters: To select which parameters are shown for selected assets in the charts.
- Operation: To filter events as open or close operations to be displayed in the event list.
- First operation: To choose whether first operations are included or excluded in the event list. It should be also possible to choose only the first operations. An additional filter for the standby time allows the user to define which operations are classified as first operations.
- Temperature: To filter events on a range of ambient temperature to be displayed in the event list. Temperature affects the performance of switchgear mechanics. For example performance values from operations at -30 C are not comparable to an operation at +30 C.
- Months: To filter events on a range of months to be displayed in the event list.

- Timestamp: To filter events on a range of timestamps to be displayed in the event list.

Asset selection list displays assets according to applied filters. Blue color indicates a selected asset.

Event list displays operations of the switchgear selected in the asset selection list. Performance values from each operation are visible in the table.

Charts visualize the selected parameters of the selected assets. The selected events are plotted and events or trends can be visually compared. The example in Figure 40 lacks legends but the curves of different colors are supposed to correspond to the selected events. The approach is a bit different for event data and trend data. The case of event data is simple. The profiles from the selected events are plotted as in the example charts in Figure 40. Comparison of trend data is more demanding. The trends of the selected parameters, that are performance quantities, would be plotted for the selected assets. Events in the event list are data points in a trend profile. The data included in a trend profile could be restricted by the filters and manual selection in the event list. A challenge of trend data comparison is different time frames of trend patterns among a group of assets. Assets of an equal model may have been commissioned at different times in the first place and deterioration appears at different times during the lifespans. Thus, the user needs to have manual control of time frames of different curves separately. Similarity of trend patterns can be studied by aligning the curves over each other adequately.

Dashboard for online inspection routine

The online inspection routine of switchgear was presented in Section 4.1. The IoT concept allows performing the online inspection routine very efficiently as measurement data is instantly available after test-operations. The service provider in charge of the inspection will verify the measured data in a mobile device on site. Thus, an appropriate dashboard is needed to display the measured performance values in a simple format.

An example of a dashboard for switchgear online inspections is presented in Appendix C. It is a tool for service providers that contains an event list with a table including all the performance values similarly to what is shown in Figure 40. The table is filled with a few fictive values. The table in this dashboard includes performance values for both, circuit breakers and switches, unlike the one in Figure 40 that was designed only for switches as an example. The values in parenthesis could be averages of past years or averages of that particular equipment model in order to set a baseline for verification of the recent values. In addition, there would be probably some alarm limits set for the performance quantities in an APM application. These limits could be additionally displayed next to the recent values and values beyond the limits could be highlighted. There are numerous possibilities for a functional implementation of this dashboard. The main idea is to provide the user with all the appropriate information to allow efficient verification of recently received measurement data. In case deviations are detected, the service provider can further examine the piece of equipment in question.

Gas-Insulated Switchgear

Online condition monitoring of GIS substations is currently SF_6 pressure monitoring as stated in Section 4.2. One GIS substation is equipped with switchgear monitoring system as an experiment.

SF_6 pressure of a GIS substation can be visualized in the same way as circuit breaker SF_6 pressure. A GIS consists of dozens of gas compartments which means that all the pressure data may not fit conveniently in a single time series chart. Measurements can be divided into several charts for example according to bays.

Time series presentation is preferred as it shows the history data. However, additional bar charts for current pressures and leak rates can be implemented to allow the user to check the current situation at a glance. Current pressures and leak rates of all compartments can be fitted into two bar charts. Examples are presented in Figures 41 and 42.

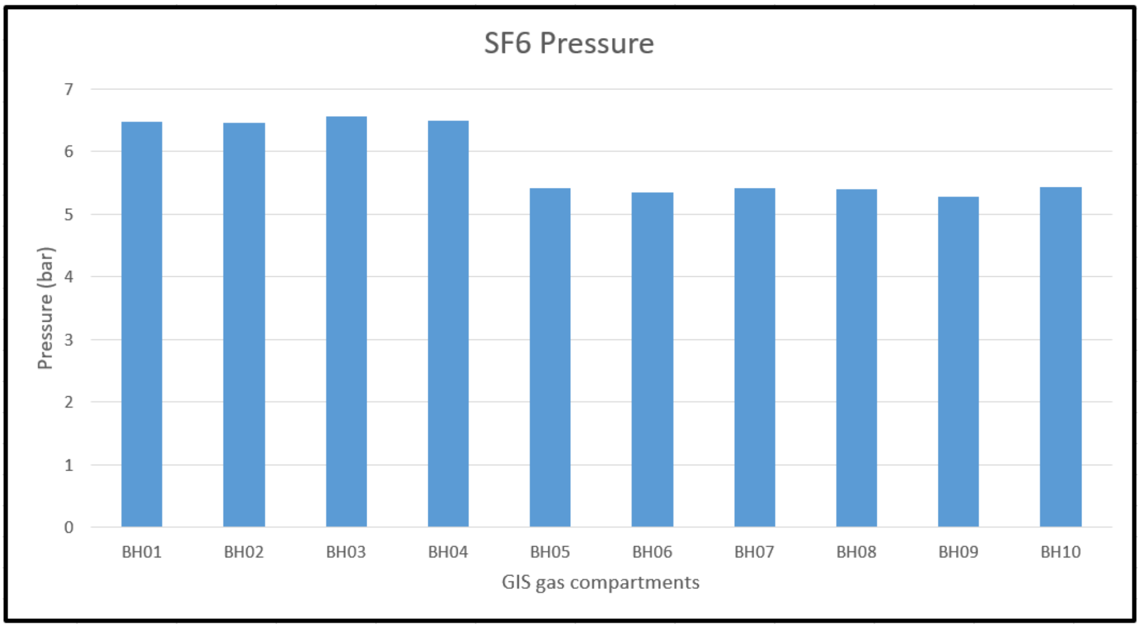


Figure 41: A bar chart presentation for the current SF_6 gas pressure in GIS gas compartments.

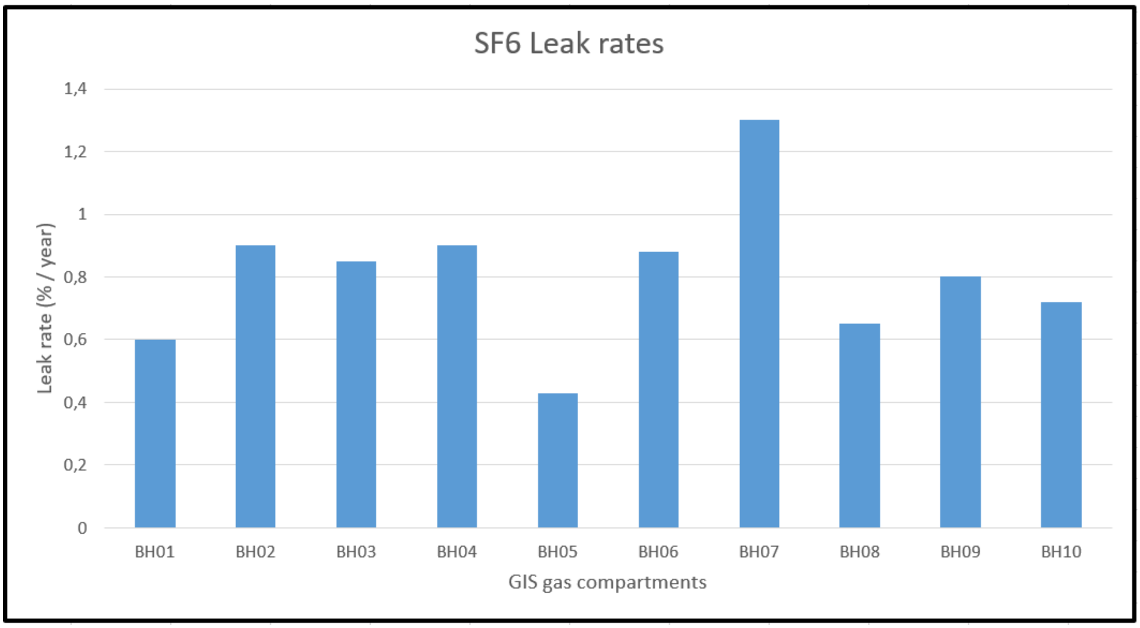


Figure 42: A bar chart presentation for the current leak rates of SF_6 gas in GIS gas compartments.

5.7 Power transformer data visualization

Condition monitoring methods for power transformers are well-established and a decent amount of data is available. The data is distributed in separate systems and databases and a limited set of basic views have been implemented. An APM application could enhance the usability of the available data and get more value out of it in form of more advanced analyses and visualization. The current situation regarding condition data management of power transformers is listed below.

- PI: Online DGA data and dashboards for monitoring.
- TOA4: Oil sample data and tools for analytics, e.g. Duval triangles.
- Cognos: A platform for custom reporting and data analytics. Analysis of TOA4 data and dissipation factor data. Visualization on custom dashboards.

In this Section, necessary elements of power transformer condition data visualization are reviewed. Most of the elements are already used in the existing systems so they are used as examples.

Fault gases

Formation of fault gases can be visualized in one time series trend chart or in separate charts for each fault gas. There is a lot of variation in orders of magnitude of different fault gases [**42**]. Thus, in case of a single chart implementation there has to be a possibility to manually exclude curves from a chart and control the axes. Fault gas data from online DGA and laboratory DGA can be visualized in an equal way but separately. Figures 43 and 44 present how the online DGA data is currently visualized in PI.

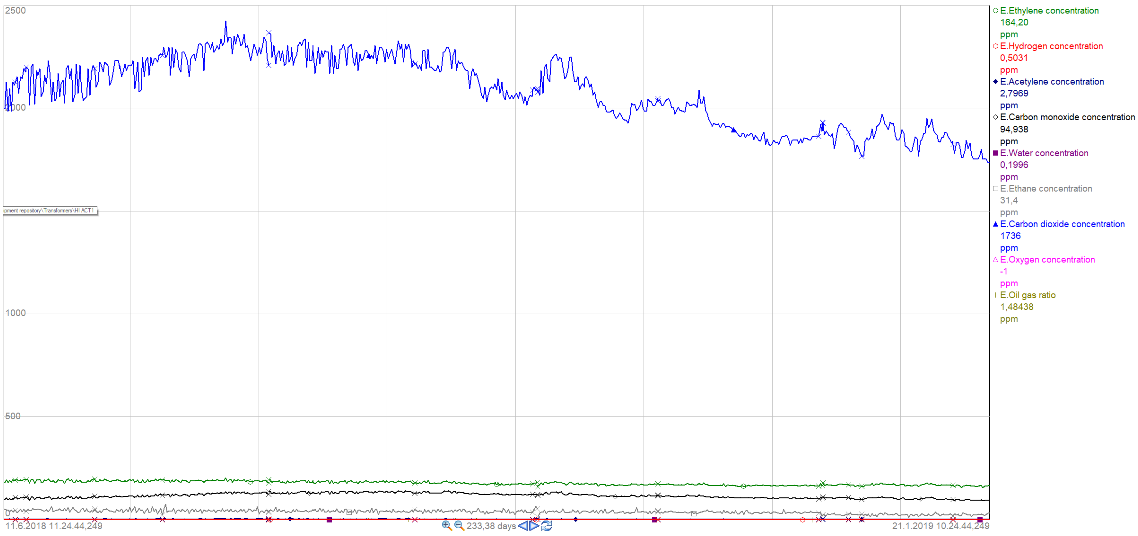


Figure 43: Fault gas concentrations in a power transformer in a time period of 233 days. [**42**]

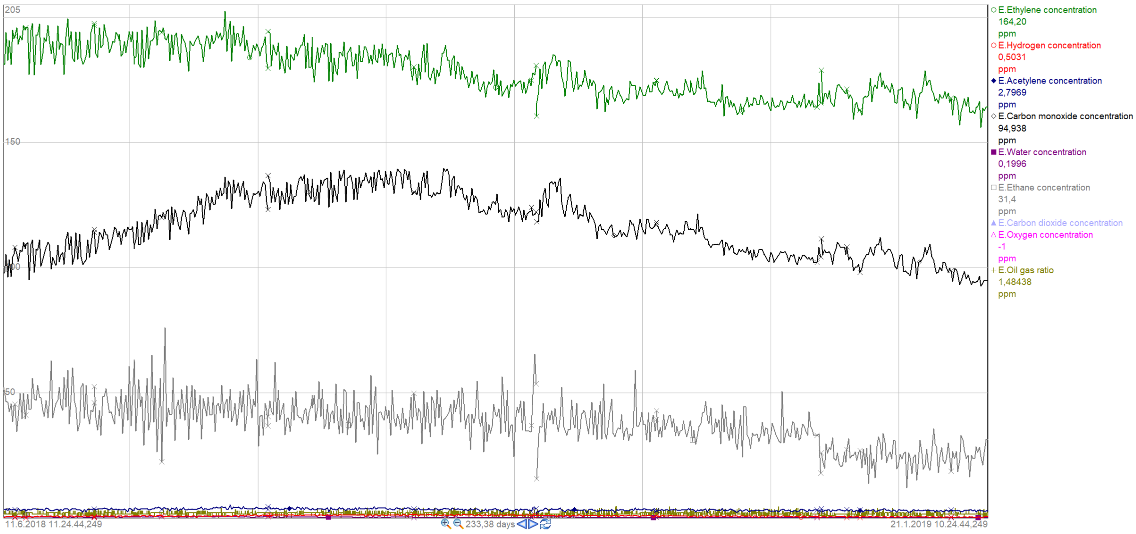


Figure 44: Fault gas concentrations in a power transformer in a time period of 233 days, excluding carbon dioxide. [**42**]

The PI implementation features all the previously mentioned functionalities and thus the usability is efficient. Figure 45, however, is a visualization of fault gas data from oil analysis.

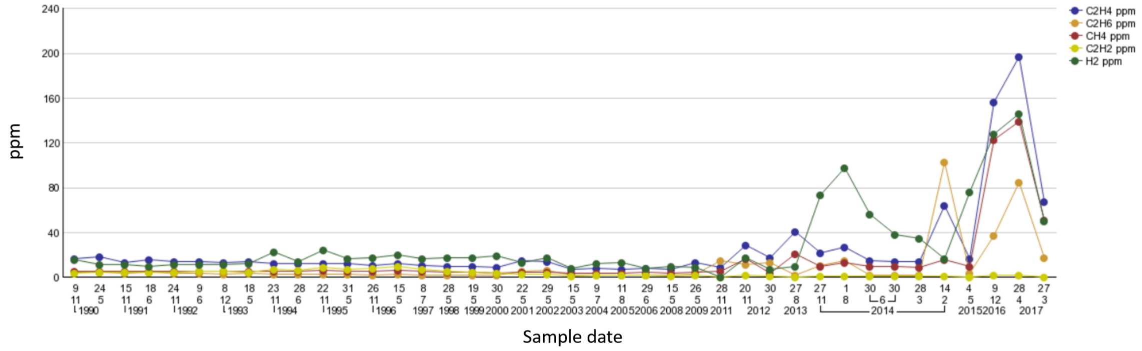


Figure 45: Trends of fault gas concentrations in oil samples extracted from a power transformer. [**83**]

Cognos implementation lacks functionalities for efficient usability. There is only a simple filter for selecting the displayed time period [**83**]. The chart is not as informative as the equivalent in PI. Moreover, as stated in the beginning of this Section, a challenge is distribution of data visualization. Two separate systems are used to visualize data related to the same physical phenomenon. Both, online DGA and laboratory DGA data, should be visualized in time series charts in an asset level dashboard of power transformers in an APM application.

Fault gas signature

Fault gas signature of a transformer is a visualization of fault gas percentages. The result of laboratory analyses are displayed in chronological order in a clustered bar chart. Fault gas signature does not show absolute concentrations of fault gases. [**83**] Instead, the idea is to early detect changes in fault gas formation behaviour of a transformer even before the absolute concentrations start increasing significantly. The fault gas signature of a 400 kV power transformer implemented in Cognos is presented in Figure 46.

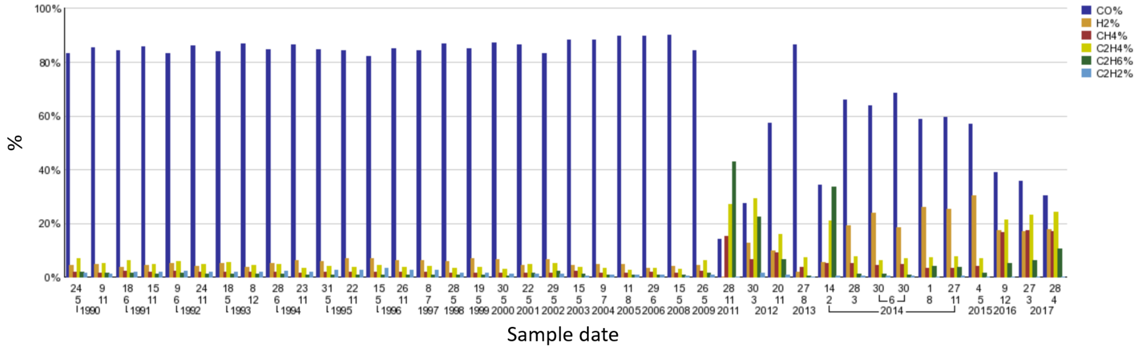


Figure 46: Fault gas signature of a power transformer presented in a bar chart. [**83**]

Such a chart clearly shows changes in the signature. In Figure 46 the signature remained unchanged for two decades. The dominant fault gas was carbon monoxide which is an indication of a healthy transformer [**38**]. The signature changed drastically in 2011 which indicates an alarming change in the condition of the transformer. Since then the oil has been sampled more frequently and the signature seems to keep changing. Thus this transformer is kept under closer monitoring.

Fault gas signature is currently visualized only for oil sample data. Most of Fingrid's transformers are equipped with online DGA instruments that measure only a few fault gases which makes it pointless to implement a signature chart for online data, too. It would not provide a lot of additional value. Nevertheless, fault gas signature is an important feature in an asset level dashboard of power transformers.

DGA score

DGA scoring is used for health assessment of power transformers. Asset health assessment is discussed in general in Section 5.9. Briefly, the worse the fault gas formation behaviour of a transformer is, the higher the DGA score is [**83**]. A score is calculated from each laboratory result and the scores are plotted in a time series trend chart. An example is presented in Figure 47.

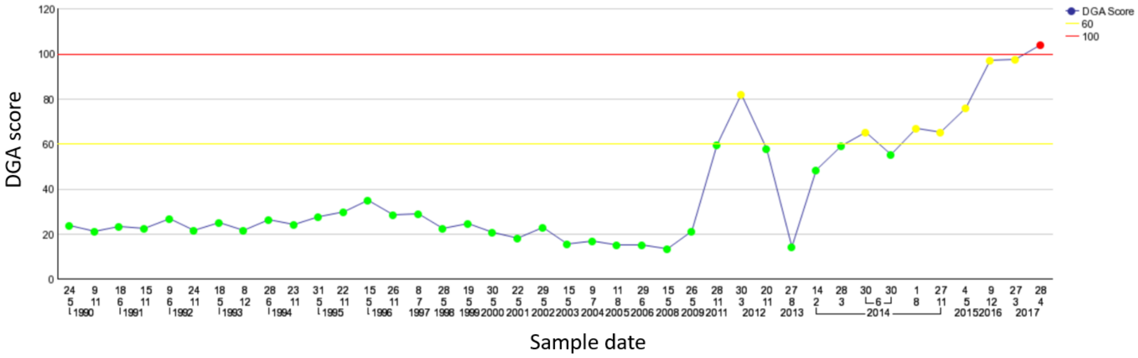


Figure 47: The trend of a power transformer DGA score. [**83**]

Dissipation factor and SFRA

Dissipation factors of power transformer bushings can be analysed with the same idea as the performance quantities of switchgear. Measurement results can be visualized in time series trend charts despite the number of performed measurements in a power transformer lifespan is not high. In general, graphical visualization is more informative than tabular.

SFRA of power transformers is performed so rarely that including the data in an APM application would not bring additional value. The data can be analysed by an equipment subject matter expert in a specific application if necessary.

Temperatures and loading

Temperatures of power transformer windings and oil along with loading are useful data to be monitored as such. In addition, fault gas formation in a power transformer correlates with transformer temperatures and loading, as explained in Section 4.3. Thus, study of temperatures and loading is essential when assessing fault gas trend patterns.

Power transformer temperature and loading data is available in PI. Figure 48 presents a PI dashboard for monitoring of power transformer temperatures and loading.

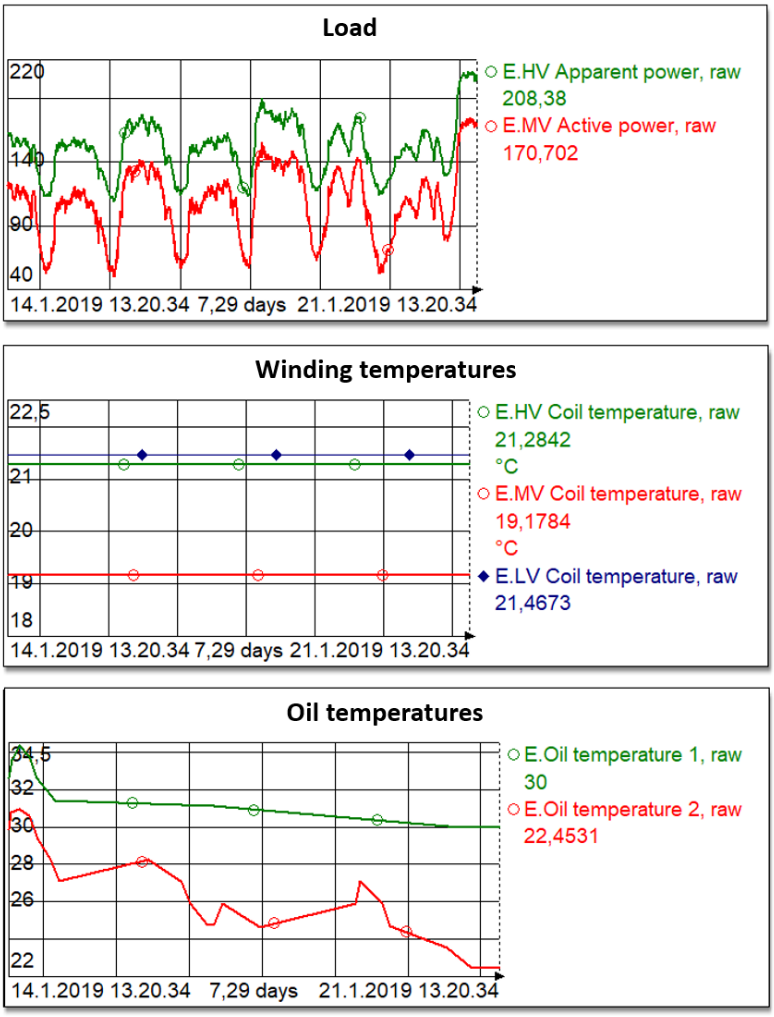


Figure 48: Loading data and temperature data from a power transformer. [**42**]

This is a simple and informative dashboard with appropriate usability. There are three time series charts for loadings, winding temperatures and oil temperatures. The charts can be maximized by a double-click and the user has control over the axes, which is a great basic feature in PI.

A commonly used presentation to describe transformer loading and capacity utilization is a load duration curve. It shows how much time a transformer has been under a certain load or higher. The curve is always descending. The load duration curve is similar to a chronological load curve but the data is ordered in descending order of magnitude instead of a chronological order. [**84**] Duration curves are useful also for winding and oil temperatures. The duration curves of a power transformer are presented in Figure 49. The stars indicate the present condition.

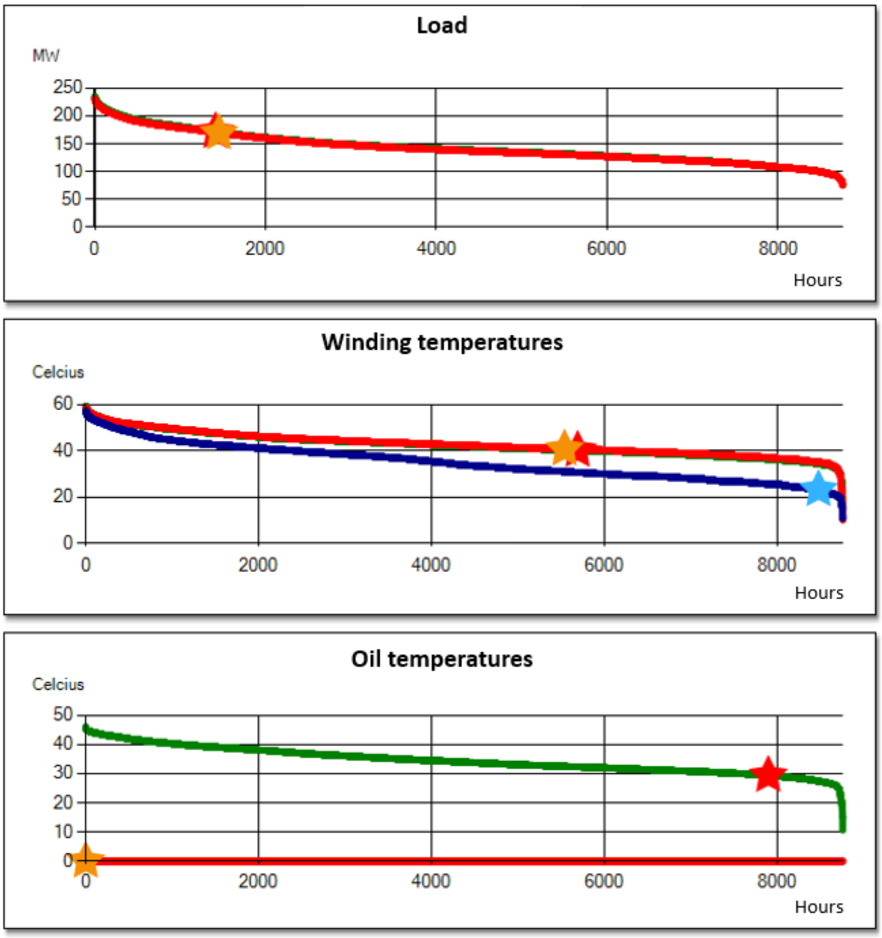


Figure 49: Duration curves of power transformer loading and temperatures. [**42**]

The duration curves in Figure 49 are built for the past year meaning the past 8760 hours, which is a common practice. However, an enhanced implementation would include the whole history of the transformer and a manual selection of time period. It could be useful to study load duration for example only in summertime or in wintertime. As for temperatures, the validity of the operation of transformer cooling systems can be estimated. Cooling systems of power transformers are supposed to maintain appropriate temperatures under high loading. Comparing the correlation of load and temperature duration curves of a transformer to another transformer could reveal inappropriate control settings of a cooling system.

Duval triangles

Duval triangles are tools for transformer diagnostics developed by Michel Duval in 1974 [**85**]. Fault type can be diagnosed by applying DGA data to the triangles [**86**]. An example is presented in Figure 50.

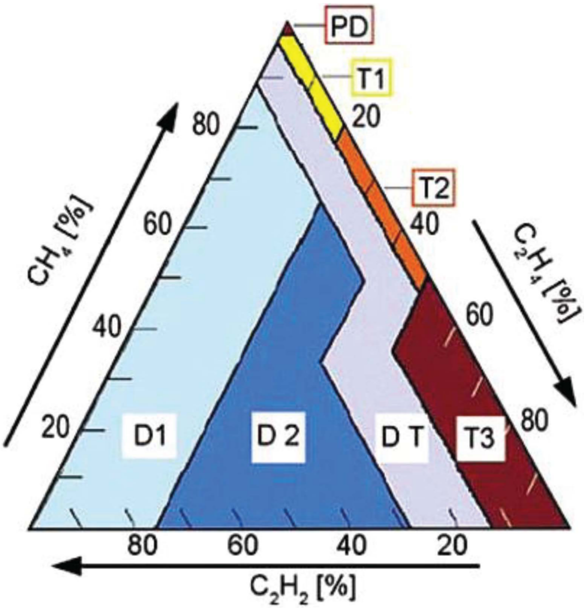


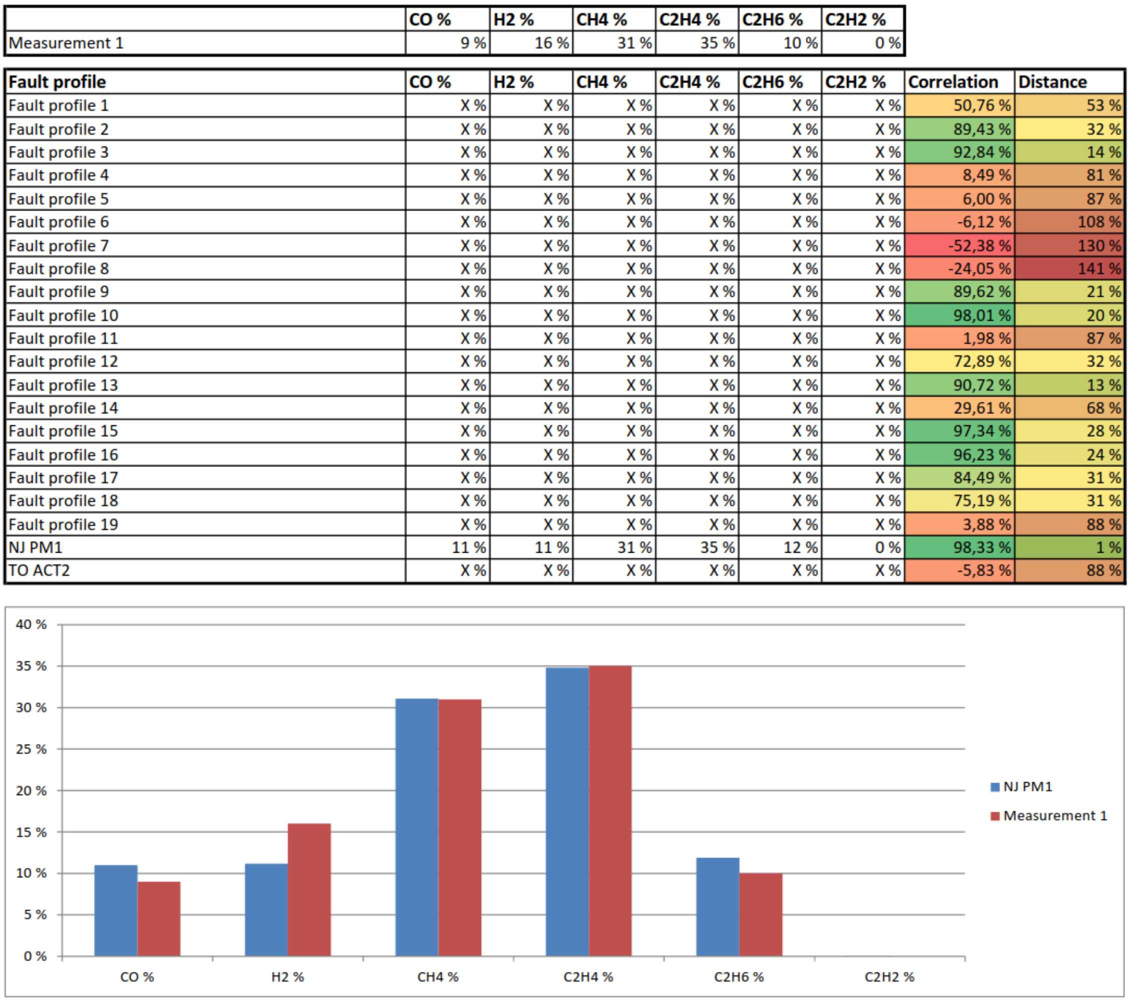
Figure 50: A Duval triangle for power transformer diagnostics. [**87**]

A Duval triangle includes different zones, each referring to a certain fault type. The edges of the triangle are axes for percentage ratios of three different fault gases. A point is plotted on the triangle according to the measured ratios. The zone in which the point is located indicates the likely fault type of the transformer. There are slightly different versions of Duval triangles for different oil types and fault types. However, Duval triangles cannot be used as the only tool for diagnostics as they do not consider the absolute concentrations of fault gases. A fault is always indicated because only ratios are involved. Duval triangles can only be used after having an indication of a fault from another analysis, for example simply a high absolute concentration of a fault gas. [**86**]

The dimensions of Duval triangle zones are openly available which allows easy implementation of this diagnosis method [**85**]. Duval triangles are necessary in an asset level dashboard for power transformers.

Fault profiles

The ratios of fault gases, in other words the fault gas signature, indicate fault type and fault location in a transformer as stated in Section 4.3. A fault profile is a reference signature of a fault type, for example "Shorted turns in windings". The fault gas signature of a transformer is compared to different fault profiles in order to find out the most likely fault type. Thus, tabular and graphical presentations of fault profile correlations are necessary features in an asset level dashboard of power transformers. An example is presented in Figure 51.



	CO %	H2 %	CH4 %	C2H4 %	C2H6 %	C2H2 %
Measurement 1	9 %	16 %	31 %	35 %	10 %	0 %

Fault profile	CO %	H2 %	CH4 %	C2H4 %	C2H6 %	C2H2 %	Correlation	Distance
Fault profile 1	X %	X %	X %	X %	X %	X %	50,76 %	53 %
Fault profile 2	X %	X %	X %	X %	X %	X %	89,43 %	32 %
Fault profile 3	X %	X %	X %	X %	X %	X %	92,84 %	14 %
Fault profile 4	X %	X %	X %	X %	X %	X %	8,49 %	81 %
Fault profile 5	X %	X %	X %	X %	X %	X %	6,00 %	87 %
Fault profile 6	X %	X %	X %	X %	X %	X %	-6,12 %	108 %
Fault profile 7	X %	X %	X %	X %	X %	X %	-52,38 %	130 %
Fault profile 8	X %	X %	X %	X %	X %	X %	-24,05 %	141 %
Fault profile 9	X %	X %	X %	X %	X %	X %	89,62 %	21 %
Fault profile 10	X %	X %	X %	X %	X %	X %	98,01 %	20 %
Fault profile 11	X %	X %	X %	X %	X %	X %	1,98 %	87 %
Fault profile 12	X %	X %	X %	X %	X %	X %	72,89 %	32 %
Fault profile 13	X %	X %	X %	X %	X %	X %	90,72 %	13 %
Fault profile 14	X %	X %	X %	X %	X %	X %	29,61 %	68 %
Fault profile 15	X %	X %	X %	X %	X %	X %	97,34 %	28 %
Fault profile 16	X %	X %	X %	X %	X %	X %	96,23 %	24 %
Fault profile 17	X %	X %	X %	X %	X %	X %	84,49 %	31 %
Fault profile 18	X %	X %	X %	X %	X %	X %	75,19 %	31 %
Fault profile 19	X %	X %	X %	X %	X %	X %	3,88 %	88 %
NJ PM1	11 %	11 %	31 %	35 %	12 %	0 %	98,33 %	1 %
TO ACT2	X %	X %	X %	X %	X %	X %	-5,83 %	88 %

Figure 51: Fault profile correlations of a set of DGA results. Modified from [83]

In addition to the actual fault profiles it is useful to store data from known real faults as references. The fault profiles "NJ PM1" and "TO ACT2" are the fault gas signatures of Fingrid’s two failed power transformers. In Figure 51 the sample signature "Measurement 1" correlates strongly with the fault of the power transformer in substation NJ.

Fleet analysis

Fleet analysis regarding fault gas formation behaviour is useful, especially for power transformers of the same production batch, but for all power transformers in general, too. An agile APM application would allow selecting any fault gas trend curves into a time series chart for analysis. Flexible usability of time series is necessary as time frames of curves has to be adjusted to match the curves in a chart for analysis of certain patterns. Both online DGA and laboratory DGA data should be available for analysis. In addition, fault gas signatures of any transformers should be available for comparison in a similar way as the fault profile correlations in Figure 51.

Fleet analysis is useful also for bushings. Comparing dissipation factor measurement results of bushings from the same production batch provides useful information.

Dashboards for power transformers

This section presented the main elements to be included in the asset level dashboards for power transformers. They allow efficient condition monitoring. However, the available data is rich enough for more advanced analytics. The scope of this Thesis did not allow further development.

In general, continuous measurement data such as online DGA data can be visualized only in a time series format. Event data, meaning manual measurement results such as laboratory DGA of an oil sample, should be additionally presented in a tabular format to allow the user to study closely all the measurement results of an event. An additional table with present conditions in a numeral format would be useful. As a conclusion, the necessary elements of the dashboards for power transformer are listed below:

- Online DGA: Time series trends.
- Laboratory DGA: Time series trends, table.
- DGA score: Time series trends, table.
- Fault gas signature chart.
- Fault profiles: correlation table and bar chart.
- Oil analysis: Time series trends and table.
- Dissipation factor results: Time series trends and table.
- Loading: Time series and duration curves for apparent powers of all windings.
- Temperatures: Time series and duration curves for windings and oil.
- Table for present conditions: Temperatures, currents, powers, OLTC step, fault gas concentrations.

5.8 Substation building data visualization

Temperature, air pressure, air humidity and water leakages are measured in substation buildings. The former three are continuous measurements that produce a constant data flow like SF_6 density and fault gas monitoring. Similarly, time series presentation is simple and informative. For water leakage measurements, there are two states in practice. A measured value is a resistance between the contacts and it is very high when there is no water. The resistance falls low when water connects the contacts. Thus, no visual presentation is necessary for this data. Automatic alarms and a list of water leakage events are sufficient.

Figure 52 presents real temperature data from a substation building.

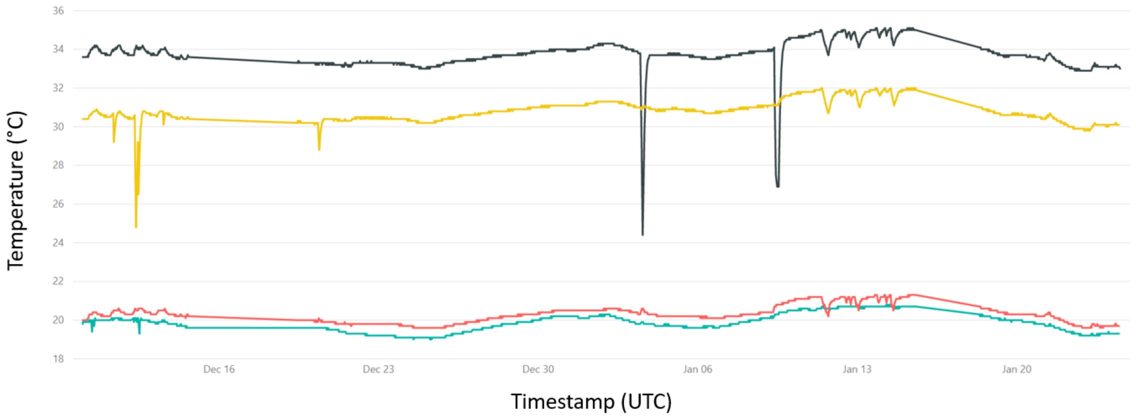


Figure 52: Temperatures in a substation building.

The lower two curves are temperatures inside a GIS hall and a local control centre of a substation. The top curves are temperatures inside cabinets that enclose telecommunications and remote control equipment. The downward peaks and sharp fluctuations are due to opening of doors during work on site.

Time series charts for temperatures, air pressures and air humidities are needed in an APM application. All measurements of a quantity in a substation building can be plotted in one chart as in Figure 52. Outside conditions should be included.

5.9 Asset health and risk assessment

Asset health assessment is quantitative scoring of the condition of an asset. [88] Asset specific health indices are essential for asset condition visualization. Health indices express the absolute condition of an asset to some extent, depending on the validity of the condition model. However, more importantly, a health index expresses the differences in the condition of assets which is useful for comprehensive asset fleet management. There is always a limited budget for asset maintenance so the available resources must be allocated in a way that produces most value. A value is for example the transmission system reliability and the transmission capacity. Thus, it is important to realize the differences of asset condition in an asset fleet to be able to invest efficiently.

Health indices alone do not lead to the most efficient decisions. Some assets are more important than others for transmission network operation. An asset causing significant consequences in case of a failure should be prioritized in maintenance decision-making over assets of lower importance, even though similar scopes of maintenance activities were technically necessary. Thus, an importance classification is needed.

A high value of maintenance investments is obtained by investing in assets that are in high risk. Risk index is a combination of health index and importance [**89**]. Health and risk indices are aggregated from down to top in the asset hierarchy which allows calculating an index for a bay and for a switchyard, too.

Health and risk indices enable informative asset condition visualization and are thus important features in an APM application. Basic principles are presented in this Section. This subject is not yet topical as the current focus is on implementing an APM application to give real-time visibility to the measurement data. Thus, further study on asset health and risk assessment will be carried out in the future and it is not in the scope of this Thesis.

Condition models and health index

A condition model is a set of measurable quantities with gradual scales. A score is assigned to a measurement value to indicate how "good" the value is. [**88**] For example a rapidly operating circuit breaker gets a better score of operation time than a slowly operating one.

Condition models can be specific to asset types or asset models. The former case is simple as only a few models are required and a small number of scales are to be defined. The latter case allows more accurate modeling. However, as equipment models have different technical characteristics, a great number of models with individually configured scales are necessary. This is the case for switchgear whereas all transformers can be scored with a single model considering fault gases.

Measured quantities are weighted according to their importance in the operational condition of the equipment. [**88**] Other measures such as age and operations count can be included in the scoring. Finally a total health index is accomplished by counting the weighted scores. Appropriate weighting is important because deviations of measurement values are of different severity and urgency. For example a power transformer with a bad bushing has to be disconnected quickly which is more urgent than increased fault gas formation in a transformer [**52**]. Usually the latter case can be momentarily stabilized by reducing the load of the transformer which gives some time for further analysis of the situation [**52**]. Thus, sometimes it may be reasonable to study the subscores separately and assess the situation with specialist expertise.

Health index of power transformers and switchgear

Fingrid is using health indices for power transformers and switchgear. The condition model of power transformers consists of the following three elements: [**83**]

- DGA
- Dissipation factors
- Oil analysis

The DGA subscore is calculated by making the amount of fault gases proportional to the Total Dissolved Combustible Gas (TDCG) value [**71**]. Thus, the DGA score is strongly linked to the fault gas signature instead of absolute amounts of fault gases. The score of dissipation factor includes bushings and the transformer itself. The score of oil analysis is determined by four measured quantities that are interfacial tension, inhibitor content, dielectric breakdown strength and moisture. Weighted subscores are summed to produce the total value of the health index. [**83**]

As for switchgear, a more appropriate definition for the health index would be "fault health index" because the condition model is based on fault history. The factors of the condition model are listed below: [**89**]

- Age
- Operations count
- Fault history of the asset
- Fault frequency of the asset model with respect to age

Thus, the index is purely statistical and does not reflect the real physical condition of an individual asset. Instead, condition models based on measurement data from individual assets should be implemented. A model should consist of quantities that are measured frequently. Quantities that are measured only one or a few times in the 40 year lifespan of an asset are useless and even distort the health indices.

For power transformers Fingrid is using a custom scoring system. The health index includes alternatively the subscore of DGA, dissipation factor, oil analysis, a combination of two or even all the three. DGA and dissipation factor measurements are established practices so condition models based on measurement data have been developed for power transformers. However in case of switchgear, appropriate models for Fingrid's needs do not exist because the IoT sensor units collect such new data that conventional measurements haven't provided before.

Health index serves rather well in condition management of asset fleets when new data is received frequently and the health score is kept up to date. This is the case for example for power transformers. Laboratory DGA is performed annually and online DGA is continuous. Switchgear is more challenging as measurement data is received infrequently, only after operations. The online inspection routine is performed at time intervals of a few years and other operations are not necessarily performed in the meantime. Thus, the health index of a circuit breaker or a switch may remain unchanged for years. If its condition has degraded during that time period, the health index suddenly changes dramatically when the online inspection routine is performed for the next time. Then maintenance is performed urgently and the health score recovers back to normal. Thus, it is questionable how much additional value can be gained by applying a health index to switchgear as it actually may not affect maintenance decision-making significantly. However, if frequent enough data is received, in other words if the online inspection routine is performed often, for example annually, the health index could be useful.

Importance

Importance classification of assets is a challenge of multidimensional nature. It can be partly based on the location of an asset in the network topology but there are other defining aspects, too, for example practices in network operation. In addition, the real importance of an asset is variable because of planned outages, contingencies and changes in the power system.

Fingrid is using an importance classification of switchgear on bay level. An importance is assigned to each bay and the switchgear in a bay have the same importance due to the fact that the equipment is mostly connected in series. For 110 kV bays importance is calculated according to power of the customer connection point, Customer Interruption Costs (CIC), the type of busbar configuration and the market price of electricity. For 400 kV and 220 kV bays the importance is defined according to their role in the power system. The difference is due to the fact that all of Fingrid's 400 kV and 220 kV transmission networks are meshed and customers, excluding the nuclear power plants, are connected only to the 110 kV level. Importance of power transformer bays are determined according to power data of the transformers. Importance is assigned also to busbars. [**89**]

Importance is not likely to be determined in an APM application. Calculations making use of the network topology would be performed in systems where the topology is available and an EAM is a logical master storage of importance data. Thus, this data would be fetched from other systems to an APM application over an interface and no specific functionalities for importance classification are required in an APM application.

Risk index

Risk is a combination of health and importance. Health index and importance are set on the axes of a two-dimensional graph and the values are normalized into a common scale. A line crossing the origin determines how the axes are weighted as the risk index is the perpendicular distance of a point from the line. The weight of health and importance are equal when the angle of the line is 45 degrees. The weighting can be adjusted by changing the angle. An example is presented in Figure 53. [**89**]

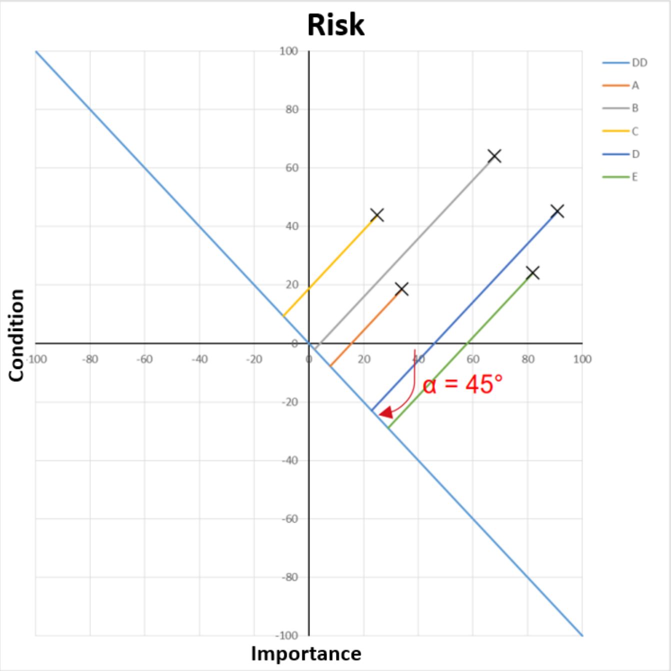


Figure 53: An importance-condition chart where risk is the distance of a point from the line crossing the origin. [89]

Figure 54 shows another presentation form. It is an importance-condition graph with zones indicating the risk level. The edges of the zones are inclined and correspond to the line in the previous example.

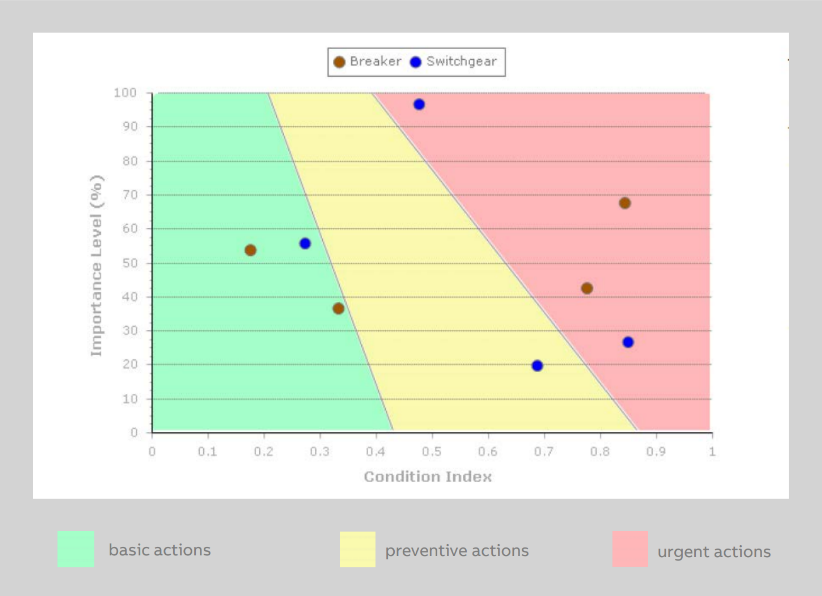


Figure 54: An importance-condition chart showing risk as coloured zones. [90]

5.10 Summary dashboards

Dashboards for the substation level and higher are summary dashboards for asset fleet management. Visualization of condition data should give the user a comprehensive overview of the asset condition in a substation, a work area, a geographical region or the whole power system. More precisely, the substation level means switchyards. Different voltage levels are managed separately and many of Fingrid's substations include both 400 kV and 110 kV switchyards.

Data presentation forms

A summary chart can visualize different quantities: health index, risk index, a subscore of a health index or the current change rate of any of the three. Data presentation form here depends on the number of assets to be shown. Dozens of assets, roughly up to one hundred, can be fitted into a single bar chart showing any of the previously listed quantities. An example is the DGA score chart of all of Fingrid's 91 power transformers presented in Figure 55.

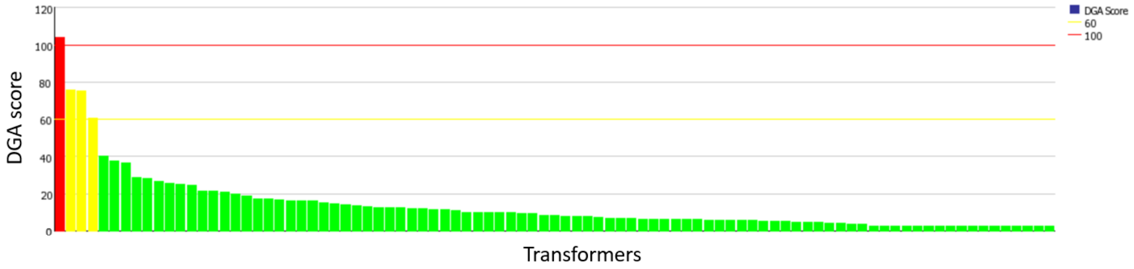


Figure 55: A bar chart for DGA scores of Fingrid's power transformers. The higher the score is, the worse the condition of a transformer is. [**83**]

The color of a bar indicates the severity of a DGA score according to the limits that are also visible in the chart. In this chart the assets are sorted in order of magnitude but other sorting methods should be available in an APM application, preferably selectable by the user. Assets in a switchyard can be sorted for example according to bays. Fingrid's power transformer fleet is small enough to be fitted into a single bar chart, unlike the switchgear fleet. However the number of switchgear in a switchyard is in a scale of dozens which allows this kind of presentation in a substation level dashboard but not in the work area level or higher.

A high number of assets has to be presented in another way. A two-dimensional scatter chart is suitable for risk index as presented in Figures 53 and 54 in Section 5.9. Health index or a subscore of a health index can be plotted similarly together with age. However, overlapping of points is likely to occur as many assets are always in similar condition. Thus, additional charts are necessary to show the number of assets of different health or risk as it is difficult to see in a scatter chart. Figures 56 and 57 are examples of different summary charts indicating asset health or risk. There are numerous ways to implement this.

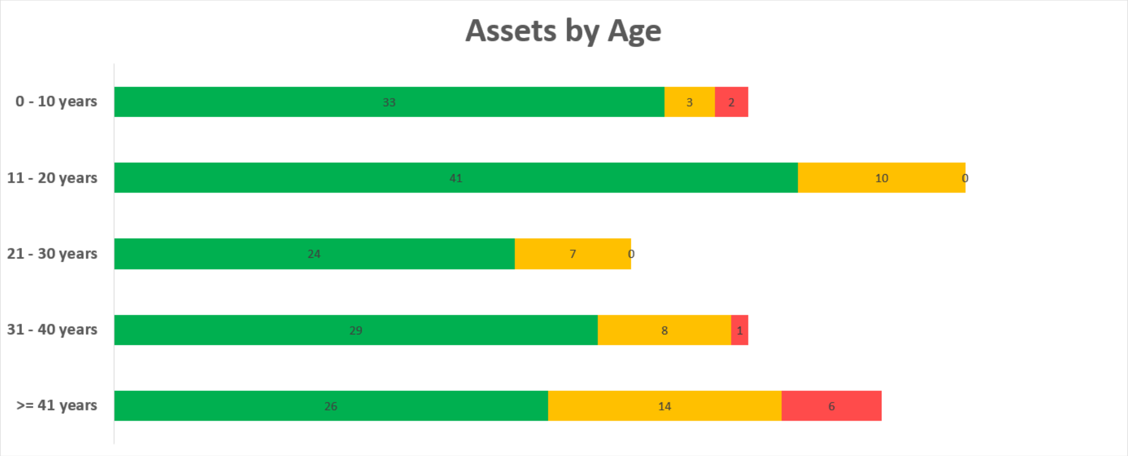


Figure 56: A summary chart showing risk of assets of different age.

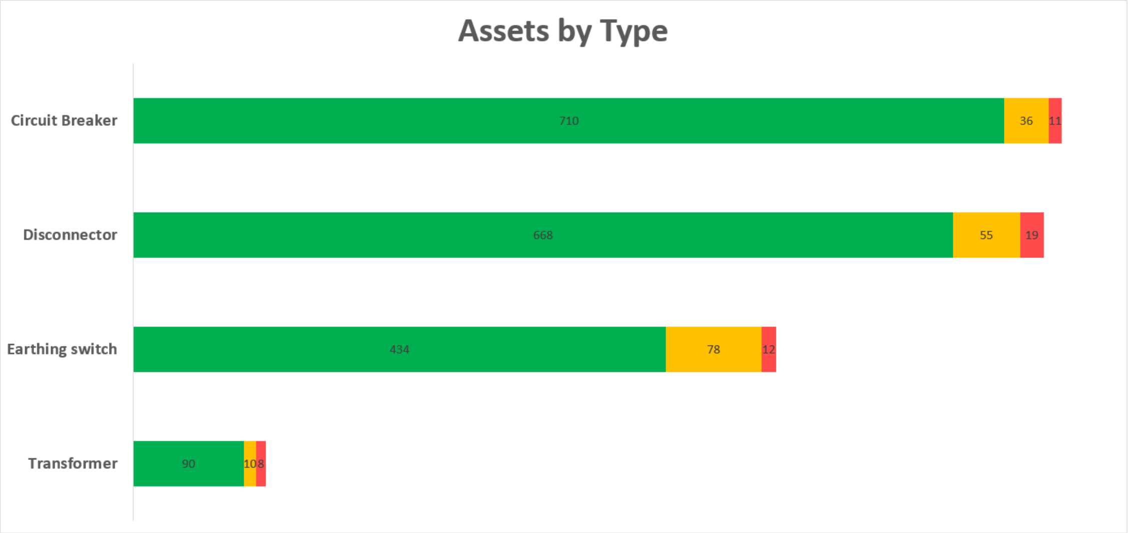


Figure 57: A summary chart showing risk of assets of different type.

Another interesting approach would be study of the evolution of asset health or risk. A scatter chart can be turned into an animation where the points drift in the chart over time. An alternative could be a stacked area chart showing the absolute number of assets or percentages at each health or risk level. An example is presented in Figure 58.

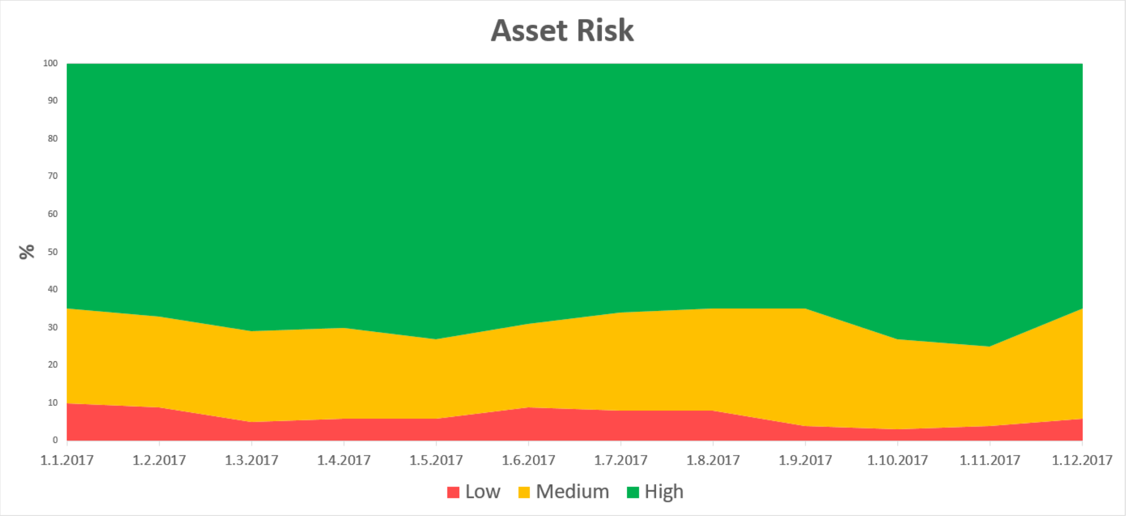


Figure 58: A stacked area chart showing the evolution of the risk distribution in an asset fleet.

Other features

Summary dashboards present an overview of asset condition. Some additional features related to asset condition management and work management are necessary, too. As discussed in Section 5.4, alarm list and maintenance schedules are useful in asset level dashboards and they can be aggregated to higher level summary dashboards. For example a service provider who is working at a substation needs to see all the alarms of that substation in a substation level dashboard. A regional maintenance coordinator needs to see all the alarms in the geographical region under his responsibility.

Visually an informative feature is a spatial view. Summary dashboards should include a map showing geographical region, work areas and substations. Drill down to an area or a substation should be possible in a spatial view. Previously presented summary charts, alarms and scheduled maintenance activities could be also integrated to a spatial view to provide easily understandable overall information of the current situation. Even though condition monitoring of transmission lines in an APM application is not considered at this stage, the network model could be integrated from another system to a spatial view in an APM application. Fingrid is using ArcGIS for spatial asset data modeling of transmission lines and substations.

Useful features in summary dashboards in addition to the actual condition data visualization are listed below.

- Alarm list including alarm history
- Maintenance schedules and history
- Spatial view with drill down, summary charts and network model

5.11 Alarm functionalities

Alarms notify the user about abnormal asset conditions as condition data is not supposed to be manually monitored. The purpose of alarm functionalities overlap with anomaly detection to some extent as the objective of both is to pinpoint deviations in a data set. However, alarms are more related to the technical implementation of an APM application whereas anomaly detection is purely processing and analysis of data. This section concentrates on what kind of alarm functionalities are necessary in an APM application. The idea of the trend alarms was learned by studying the current implementation of SF_6 gas alarms in PI.

Alarm limits

For some quantities it is possible to unambiguously define limits within which a measured value has to be. For example the conventional low-pressure alarms in a SF_6 circuit breaker are a built-in feature configured by the manufacturer, as stated in Section 4.1. The alarms in an APM application can be set accordingly. Another example is circuit breaker operation time. The manufacturer of a circuit breaker gives limits for the operation time of a healthy circuit breaker. Simple alarm limits can be used in an APM application for this kind of quantities. The user has to be able to manually set multiple low limits and high limits for measured quantities of individual assets and an asset group such as assets of an equal model. Alarm limits of SF_6 pressure can be automatically fetched via an interface from nameplate data in an EAM.

There are no obvious limits for many performance quantities because they haven't been studied so far. In this case the limits should rely on fleet analysis and should thus be self-adjusting. The idea is that performance values of all assets of an equal model are considered. The majority of the assets are healthy, and thus the alarm limits should adjust to trigger when a value differing from the majority is detected.

Trend alarms

Previous sections showed that most condition monitoring data is presented in form of time series. In addition to continuous online monitoring like SF_6 pressure monitoring, performance quantities calculated from more complex data like sound spectra and current profiles allow simple time series presentation. Thus, it is essential to have appropriate alarms for time series trends. The changes in a trend can be rapid or slow. For example SF_6 gas in a circuit breaker may leak at different leak rates. Separate algorithms are needed to detect different slopes of trends.

The idea of a simple algorithm for detecting rapid changes is to calculate the change of the measured quantity in respect of a past average for example from 30 days or a number of switchgear operations [**42**]. No time frame has to be defined for the change. Slow changes do not trigger the alarm as the 30 days average changes along with a slow change and the differences between the average and the measured values remain small. The change can be a drop or an increase of a certain percentage or an absolute quantity. The magnitude of change has to be configured for each asset type. In addition, the direction of change has to be considered for the reasons that are explained in the following list.

- SF_6 pressure: Drop and increase has to be considered. Typically the pressure drops due to a leakage but an increase is also possible in abnormal conditions. In 2018, an increased pressure was discovered in a gas compartment of a GIS prior to a breakdown. Temperature affects the operation of a gas density sensor so it is unclear if the increased pressure was due to a real increase or false measurement results. However, it was an indication of an abnormal condition that should have triggered an alarm.
- Fault gases: Fault gas formation increases in a power transformer due to deterioration of insulation. An increase can be caused by an actual fault or increased loading. However, a sharp increase of fault gas formation is alarming regardless of the reason and should thus trigger an alarm. A decrease of fault gas formation can be caused by a decrease of transformer loading. An alarm is not necessary for a decrease.
- Building temperature: A sharp increase of a temperature is alarming. Faulty equipment may overheat which has to be detected. A sharp decrease however should not be set to trigger an alarm because opening of doors would be followed by false alarms. A decrease caused by a fault in heating equipment will not be sharp because of slow heat transfer in building structures. Such an alarming decrease is to be detected by an algorithm made for slow changes.
- Performance quantities: There is no real-life experience yet how changes in condition of switchgear reflect to most of the performance values. Thus, configuring parameters for alarms is challenging. Both directions of change should trigger an alarm until a reason to change the implementation appears.

An algorithm for detecting slow changes is based on slopes of trend curves [**42**]. The objective is to detect a change that will lead to a failure if the change continues. A great example is SF_6 pressure. A minor leakage decreases the pressure and one day it will reach a critical level. The idea is to detect the leakage right after it has begun. Sharp bounces should be ignored. For example bright sunshine in a hot day can heat a gas density sensor to indicate an increased pressure compared to the previous day that was cloudy and cold [**9**]. This is not a changing long-term trend and therefore it should not trigger a long-time trend alarm.

A linear regression is applied to data in a period of time, for example in 30 or 60 days. The slope of the regression line is calculated. If the magnitude of the slope exceed a defined limit, an alarm is triggered. [**42**] The challenge here is setting the limit of the slope. Currently Fingrid has a circuit breaker which is leaking SF_6 gas but it does not trigger the slow alarm because the leak rate, the slope, is minimal. However, the circuit breaker had to be refilled with gas in the past years which means the leakage is not negligible either. The leakage will be repaired as soon as the state of the network allows an outage. Too low a limit of the slow alarm would cause false alarms which is not too serious, though, because the condition monitoring system is not integrated to switchgear control. Alarming data can be manually analysed and ignored if the alarm is proved false.

Notifications

Notifications are email or SMS messages that are automatically sent to a group of users to inform them about an activated alarm. An APM application should allow enabling notifications for user groups at different levels of asset hierarchy and alternatively according to asset type. Basically a user wants to receive notifications about assets under his responsibility. For example notifications from assets in a work area should be sent to the service provider that is responsible for the concerned work area. The allocation of the main user groups for notifications is as follows:

- Geographical region: Regional maintenance coordinator
- Work area: Service provider
- Asset type: Equipment subject matter expert, Control centre

5.12 Mobile application

A mobile application of an APM application is necessary for on-site work as condition data is useful for inspections and fault diagnostics. Equipment with suspicious measurement results can be inspected with extra care and faulty equipment can be diagnosed with help of the measurement data. A mobile application must be simple and easy to use because it is used outdoors in variable weather conditions. Only necessary content has to be shown. When working on-site, only the data related to that substation is interesting.

The most necessary element in a mobile application is the dashboard for online switchgear inspections. A service provider works in an outdoor switchyard executing the test-operations in remote collaboration with the control centre. The service provider needs access to the measurement data in a mobile device shortly after an operation to verify whether the operation was appropriate or not.

Raw data from switchgear like coil and motor current profiles may be useful for more detailed diagnosis of equipment. In addition, substation level dashboards can give an overall picture of the situation in a substation. Thus, this content would be useful for work on site. However, efficiency in usability is not as important as in case of the online switchgear inspection because the need to access this data is occasional.

6 Conclusions and further work

6.1 Conclusions

This Thesis documented Fingrid's current situation with online condition monitoring solutions. The outcome of the study points out that online condition monitoring is currently concentrated on switchgear, power transformers and substation buildings. However, the IoT solutions are under intensive development and thus new solutions will come up in the near future for other asset types, too.

The IoT solutions for switchgear and buildings will produce a lot of new data some of which have however been available before to a small extent. Thus, visualization of that data was sketched from scratch for Fingrid's needs. Necessary condition data from power transformers is already available whereas the visualization turned out to be limited. The most important basic charts and analyses are available but more value can be obtained by enhancing the visualization and the usability of the data. The useful elements of the current implementation were reviewed in this Thesis. The scope did not allow further development of analyses.

There are two types of condition data that determine Fingrid's requirements for data visualization in an APM application: time series data and event data. Measurements of continuous processes, like SF_6 pressure, produce continuous time series data. Switchgear operations and oil samples and electrical measurements of power transformers produce event data. A significant difference is the amount of data as events occur only a few times in a year. In terms of visualization techniques, the needs are correspondingly divided into two categories: Time series presentation and reporting formats.

The most important data presentation form is time series. A time series trend indicates how the value of a monitored quantity changes along with aging of equipment which is useful information for preventive maintenance decision-making. Visualization of time series trend is informative for both, continuous time series data and event data. In case of event data, specific performance quantities have to be calculated out of the raw data to allow time series presentation. Similarities in technical performance of assets and relations between measured quantities can be analysed by comparing trend patterns. Thus, it is important to have efficient time series functionalities in an APM application. Analysis of multiple curves in a time series chart requires scalable axes, cursors and separately adjustable time frames of curves.

In addition to time series presentation, a lot of data can be visualized in other types of charts and in tabular formats. This kind of visualization is closer to reporting than monitoring of a continuous industrial process. Fault gas signatures of power transformers are visualized in bar charts and fault profile correlations are calculated in a table. Current measurements from switchgear are in form of profiles and a summary table is needed for performance values of online inspection routines. In general, all event data should be available in a tabular format in addition to the actual visualization.

An APM application can bring additional value by combining data of different measurements. Data from an asset can be useful when combined with data from other assets in the same bay or in the substation. For example primary current data is stored at bay level, primary circuit temperature is measured on an asset in a bay and outside temperature is measured at the substation building. Linking all the data together allows analysis of primary circuit heating behaviour. Combining data is possible by means of asset hierarchy which should be fetched from an EAM.

It is questionable if any single APM application will fulfill the requirements. Time series data management is different business than data reporting. An APM application loses its purpose as an all-encompassing system for asset condition management if it cannot respond to the requirements as other supporting applications are needed. In case a decent APM application is not available, a considerable alternative for Fingrid could be implementing a custom platform that combines separate specific tools for time series data presentation and reporting. Fingrid needs agile tools that allow efficient usability of data as the IoT development will create new data to be analysed in the near future. The deficiency of such a custom solution is that implementation of asset level dashboards is probably not possible as illustrated in Section 5.6. Data will divide into the two separate applications according to the form of visualization instead of logical division by the context regarding the physical structure of the monitored equipment. A value of an APM application would be integration of all condition monitoring data to a single application.

6.2 Further work

The IoT solutions will dramatically increase the amount of available condition data in a few upcoming years. The current challenge is finding an APM application or implementing a custom platform that features efficient usability of data to access the information that the data can reveal. In case of switchgear, the interest is finding out what kind of faults the data will reveal in reality and how.

Once some experience has accumulated, switchgear condition modeling by means of measurement data needs to be studied. Asset health and risk assessment is relevant only with appropriate condition models that do not exist yet for switchgear.

Data analytics is another subject to be studied in the future. The performance quantities introduced in this Thesis are the starting point. It is certain that anomaly detection needs to be developed. Applying artificial intelligence in form of machine learning requires a lot of data that is not yet available.

At the sensor endpoint, possibilities for development are wide. IoT sensor units have to be developed to fit in 400 kV switchgear with separate control cabinets. There are also many asset types to be monitored in addition to switchgear and power transformers. Studies can be carried out to find efficient methods of data acquisition for online condition monitoring.

Digital substation is another interesting trend that will probably take over the design of substations. Online condition monitoring solutions need to be studied from greenfield implementation point of view, too. A limiting constraint in the current development of IoT solutions is the demand for retrofitting. More sophisticated solutions can be implemented to substations in the design phase and factory-fitted in new equipment.

7 Summary

Fingrid is making the transition from time-based maintenance to condition-based maintenance in order to increase the cost-efficiency of substation asset condition management and to prevent equipment failures. Digitalization improves real-time visibility to asset condition as Fingrid is developing an Internet of Things concept for online asset condition monitoring.

The objective of this Thesis was to specify Fingrid's requirements for asset condition data visualization in an Asset Performance Management application. A secondary objective was to document Fingrid's IoT concept and existing condition monitoring practices. Asset maintenance strategies, digitalization and Internet of Things were discussed in order to understand the background of this study and the driving forces behind Fingrid's IoT concept. The IoT concept was introduced and Fingrid's condition monitoring solutions including the new IoT solutions and the existing solutions were explained. For the IoT data of switchgear, simple illustrations of dashboards were drawn to show how the data could be visualized in an APM application. Regarding power transformers, the necessary basic elements for condition data visualization were reviewed. All the available condition data was listed in Appendix B and specifications for condition data visualization were listed in Appendix C. Asset health and risk assessment and a few other important features of an APM application were also discussed.

Online condition monitoring is currently concentrated on switchgear, power transformers and substation buildings. The IoT solution for switchgear consists of low-cost sensor units installed in switchgear control cabinets and bay marshalling cabinets. Currents in control circuits and current transformer secondary circuits are measured and microphones record sound phenomena. The main benefit of the switchgear IoT solution is gained by combining it with the online inspection routine that allows switchgear to be frequently test-operated without causing an outage. Power transformers are equipped with online DGA instruments which is a well-established practice. In substation buildings, the climate and water leakages are monitored with low-cost IoT sensors.

The conclusion of the study was that there are two types of condition data that determine Fingrid's requirements for data visualization in an APM application: time series data and event data. Monitoring of continuous processes, like SF_6 gas pressure monitoring, produces a large amount of continuous time series data. A tool with efficient functionalities for time series data presentation and analysis is needed. Switchgear operations and oil sampling produce event data. It is visualized in forms of data reporting and special analyses in addition to time series trend presentation. The amount of event data is small even though it will increase due to IoT.

It is questionable if any single application will fulfill the requirements. Time series data management is different business than data reporting. In case a decent APM application is not available, a considerable alternative for Fingrid could be implementing a custom platform to combine separate tools for time series data presentation and reporting. Fingrid needs agile tools that allow efficient usability of data as the IoT development will create new data to be analysed in the near future.

References

[1] Ahmad, R., Kamaruddin, S. An overview of time-based and condition-based maintenance in industrial application. *Computer & Industrial Engineering*, online journal, 2012, vol. 63, issue 1, p. 135-149. Accessed on 5.11.2018.

[2] Hinchberger, B. Substations in the digital age. *The Magazine, Energy*, Siemens online magazine, 9.8.2018. Accessed on 15.10.2018. Available: `https://www.siemens.com/customer-magazine/en/home/energy/power-transmission-and-distribution/digital-electrical-substation.html`.

[3] Kuosa, D. Vika- ja kunnossapitotietojen hyödyntäminen suurjännitekytkinlaitteiden kunnonhallinnassa. Master's Thesis, University of Technology, Electrical engineering and communications, Espoo, 2007.

[4] Fingrid Oyj. S52104 Maintenance of circuit breakers. Internal specification. 2018.

[5] Fingrid Oyj. S52105 Maintenance of disconnectors. Internal specification. 2018.

[6] Jardine, A., Lin, D., Banjevic, D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, online journal, 2006, vol. 20, issue 7, p. 1483-1510. Accessed on 5.11.2018.

[7] Kone Oyj. Intelligent KONE 24/7 Connected Services. Product information. Accessed on 5.12.2018. Available: `https://www.kone.com/en/products-and-services/solutions-for-existing-buildings/24-7-connected-services.aspx`

[8] Kivilinna-Korhola, T. Fleet management ohjelmistot – Ponsse, Komatsu ja John Deere. Thesis, University of Applied Sciences, Forestry, Mikkeli, 2016.

[9] Tammi, J. Specialist. Switchgear. Fingrid Oyj. Helsinki. Interviews [10/2018-2/2019]

[10] Fingrid Oyj. Maximo. Fingrid's Enterprise Asset Management application and database. 2018.

[11] Fingrid Oyj. Digital substation. Online material. Accessed on 5.11.2018. Available: `https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/toimikunnat/neuvottelukunta/digitaalinen-sahkoasema-9-2018.pdf`.

[12] Koivula, P. Digitaalisen sähköaseman toteutus projektitoimittajan näkökulmasta. Master's Thesis, University of Vaasa, Faculty of Technology, Vaasa, 2015.

[13] Valkola, A. Expert. Communications, power system monitoring and control. Fingrid Oyj. Helsinki. Interviews [10/2018-2/2019]

[14] ABB. Substation evolution from conventional to digital. Accessed on 5.11.2018. Available: `https://new.abb.com/substation-automation/systems/digital-substation/bridging-the-gap`.

[15] Kunsman, S. IEC 61850 in Digital Substation and Cyber security. *72nd Annual Georgia Tech Protective Relaying Conference*, Conference presentation. 2.-4.5.2018. Atlanta, Georgia Tech Hotel and Conference Center. Accessed on 5.11.2018. Available: `https://new.abb.com/substation-automation/systems/digital-substation/bridging-the-gap`.

[16] Fingrid Oyj. Digital substation. Project plan, internal document, 2017.

[17] Fingrid Oyj. Pernoonkoski Digitalization. Project plan, internal document, 2018.

[18] Arteche. Optical Current Transformer. Product information, manufacturer website. Accessed on 5.11.2018. Available: `https://www.arteche.com/en/products/optical-current-transformer`.

[19] Trachte. Substation relay protection buildings. Product information. Accessed on 5.2.2019. Available: `http://www.trachteusa.com/trachte_building_photos.html`

[20] VTT. Productivity Leap with IoT. Visions of the Internet of Things with a special focus on Global Asset Management and Smart Lighting. Online publication. Espoo. 2013. Accessed on 6.11.2018. Available: `https://www.vtt.fi/inf/pdf/visions/2013/V3.pdf`.

[21] ABB. Feeder protection and control REF615 IEC. Product information. Accessed on 20.2.2019. Available: `https://new.abb.com/medium-voltage/distribution-automation/numerical-relays/feeder-protection-and-control/relion-for-medium-voltage/feeder-protection-and-control-ref615-iec`

[22] ABB. Free Standing Fiber Optic Current Sensor FOCS-FS for digital substations. Product information. Accessed on 5.2.2019. Available: `https://new.abb.com/high-voltage/instrument-transformers/current/FOCS-FS`

[23] ABB. Capacitor Voltage Transformer CPB (72-800 kV). Product information. Accessed on 1.2.2019. Available: `https://new.abb.com/high-voltage/instrument-transformers/voltage/cpb`

[24] Ross, R.G. Can You Differentiate ‘Knowledge Workers’ by How Much Improvising or Innovating is Desired? Online article. Accessed on 5.2.2019. Available: `http://www.brsolutions.com/`

`can-you-differentiate-knowledge-workers-by-how-much-improvising-innovating-is-desired`

[25] Saravana Switchgears. Bay Marshalling Kiosk. Product information. Accessed on 5.2.2019. Available: `https://www.indiamart.com/saravana-switchgears/products.html`

[26] Wikipedia. Internet of Things. Online encyclopedia. Accessed on 6.11.2018. Available: `https://en.wikipedia.org/wiki/Internet_of_things`

[27] Kone Oyj. Taking services to the next level. Online article. Accessed on 5.12.2018. Available: `https://www.kone.com/en/news-and-insights/stories/taking-elevator-services-to-the-next-level.aspx`

[28] Microsoft. Azure. Product information. Accessed on 19.2.2019. Available: `https://azure.microsoft.com/en-us/`

[29] Databricks. Apache Spark. Product information. Accessed on 19.2.2019. Available: `https://databricks.com/spark/about`

[30] General Electric. What is Edge Computing? Online article. Accessed on 6.11.2018. Available: `https://www.ge.com/digital/blog/what-edge-computing`

[31] Herlihy, M. Blockchains and the Future of Distributed Computing. *ACM Symposium on Principles of Distributed Computing.* 25.-27.7.2017, Washington DC, USA. DOI: 10.1145/3087801.3087873.

[32] DeBeasi, P. A Guidance Framework for Architecting the Internet of Things Edge. Gartner research note. 2017. Available: `https://www.gartner.com/doc/3783144/guidance-framework-architecting-internet-things`

[33] Microsoft. Azure IoT Edge. Product information. Accessed on 5.12.2018. Available: `https://docs.microsoft.com/en-us/azure/iot-edge/`

[34] Canonical. Landscape. Product information. Accessed on 5.12.2018. Available: `https://landscape.canonical.com/`

[35] Lindholm, K. Regional Manager. Hämeenlinna. Interviews [10/2018-2/2019]

[36] Mörsky, J. Relesuojaustekniikka. Hämeenlinna, Otatieto, 1992.

[37] Fingrid Oyj. Equipment failure statistics. 2017.

[38] Mertanen, J. Specialist. Asset condition management. Fingrid Oyj. Helsinki. Interviews [10/2018-2/2019]

[39] Elovaara, J., Haarla, L. Sähköverkot II. Helsinki, Otatieto, 2011.

[40] Rabie, M., Frank, C. M. Assessment of Eco-friendly Gases for Electrical Insulation to Replace the Most Potent Industrial Greenhouse Gas SF6. *Environmental Science & Technology*, online journal, 2018, vol. 52, issue 2, p. 369-380. Accessed on 4.3.2019.

[41] Trafag. SF6 Gas Density Monitors. Product information. Accessed on 4.3.2019. Available: `https://www.trafag.com/en/products/sf6-gas-density-monitors-and-sensors/sf6-gas-density-monitors/`

[42] Fingrid Oyj. PI. SCADA historian application and database.

[43] Fingrid Oyj. S52104-E11 Online inspection of 110 kV circuit breakers. Internal specification. 2018.

[44] Fingrid Oyj. Substation diagrams. Internal documentation. 2018.

[45] Noiseless Acoustics. Product information. Accessed on 5.12.2018. Available: `https://nlacoustics.com/wp-content/uploads/2018/03/Noiseless_NL_Sense_A4_compressed.pdf`

[46] Laitinen, T. Expert. Switchgear. Fingrid Oyj. Helsinki. Interviews and emails [10/2018-2/2019]

[47] ABB. Air-insulated switchgear. Product information. Accessed on 5.12.2018. Available: `https://new.abb.com/high-voltage/AIS`

[48] ABB. High Voltage Instrument Transformers. Product information. Accessed on 19.2.2019. Available: `https://new.abb.com/high-voltage/instrument-transformers`

[49] Fingrid Oyj. IoT solutions for asset condition management. Project plan, internal document, 2018.

[50] Ylitalo, J. Katkaisijoiden kunnossapito CBA 3000 -katkaisija-analysaattorilla. Thesis, University of Applied Sciences, Electrical Engineering, Satakunta, 2017.

[51] ABB. GIS substations. Product information. Accessed on 5.12.2018. Available: `https://new.abb.com/substations/gis-substations`

[52] Ojanen, T. Expert. Power transformers. Fingrid Oyj. Helsinki. Interviews [10/2018-2/2019]

[53] Duval, M. Dissolved gas analysis: It can save your transformer. *IEEE Electrical Insulation Magazine*, online journal, 1989, vol. 5, issue 6, p. 22-27. Accessed on 4.12.2018.

[54] Leivo, S. Online DGA-monitoring of power transformers. Vaisala online webinar material. 2018. Available: `https://www.vaisala.com/sites/default/files/documents/Vaisala%20DGA%20webinar_Apr%202018.pdf`

[55] General Electric. Multiple Gas and Single Gas Transformer DGA. Product information. Accessed on 5.12.2018. Available: `https://www.gegridsolutions.com/md.htm`

[56] Fingrid Oyj. TOA4 database. Internal database for results from laboratory analysis of transformer oil. 2018.

[57] Secue, J.R., Mombello, E. Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers. *Electric Power Systems Research*, Elsevier online journal, 2008, vol. 78, issue 6, p. 1119-1128. Accessed on 5.12.2018.

[58] Malpure, B.D., Baburao, K. Failure analysis & diagnostics of power transformer using dielectric dissipation factor. *2008 International Conference on Condition Monitoring and Diagnosis.* 21.-24.4.2008, Beijing, China. DOI: 10.1109/CMD.2008.4580334.

[59] General Electric. Intellix BMT 330. Product information. Accessed on 5.12.2018. Available: `https://www.gegridsolutions.com/md/catalog/BMT330.htm`

[60] Camlin Ltd. Intego TM. Product information. Accessed on 5.12.2018. Available: `https://www.camlingroup.com/product/intego-tm`

[61] Rashid, N. Short-time Overloading of Power Transformers. Master's Thesis, Royal Institute of Technology, Department of Electrical Engineering, Västerås, 2011.

[62] Electrical Baba. Transformer Winding Temperature Indicator. Online article. Accessed on 10.1.2018. Available: `https://electricalbaba.com/transformer-winding-temperature-indicator/`

[63] Ojanen, T. Muuntajien ikääntyminen ja kunnonhallinta. Article in Fingrid's internal Wiki on Transmission Network. 2011.

[64] Lyly, T. Loppuraportti: IoT & edistyneen analytiikan hyödyntämisen pilotti. Internal project report. 2018.

[65] Garcia, B., Burgos, J.C., Alonso, A.M. Transformer tank vibration modeling as a method of detecting winding deformations-part I: theoretical foundation. *IEEE Transactions on Power Delivery*, online journal, 2006, vol. 21, issue 1, p. 157-163. Accessed on 4.12.2018.

[66] CGI Group. IoT for Condition Monitoring. Technical Documentation. Internal project documentation. 2018.

[67] Fingrid Oyj. Kantaverkon käsikirja. 2011. Internal opus.

[68] Itäpää, A., Lindblad, P. Käämikytkimien käyttö jännitteensäätöön. Article in Fingrid's internal Wiki on Transmission Network. 2011.

[69] Fingrid Oyj. Kantaverkon peruskoulutus. Internal opus.

[70] Arteche. An approach to instrument transformers. Online article. Accessed on 5.12.2018. Available: `https://www.arteche.com/en/products/capacitive-voltage-transformers`

[71] Nepola, K. Specialist. FACTS. Interviews [10/2018-2/2019]

[72] Laatikainen, M. Planning engineer. Grid operation. Helsinki. Interviews [10/2018-2/2019]

[73] STK-Tietopalvelu Oy. Sähkönumerot. Carlo Gavazzi - EM24. Number 66 040 04. Equipment specifications. Available: `https://www.sahkonumerot.fi/6604004/`

[74] Nästi, J. Specialist. HVDC. Fingrid Oyj. Helsinki. Interviews [10/2018-2/2019]

[75] Haltian Oy. Thingsee POD 2. Product information. Accessed on 5.12.2018. Available: `https://haltian.com/news/thingsee-pod-2-is-ready-for-sales/`

[76] Gartner. Asset Performance Management (APM). Online IT glossary. Accessed on 10.1.2019. Available: `https://www.gartner.com/it-glossary/asset-performance-management-APMapplication`

[77] OSIsoft. PI System. Product information. Accessed on 20.12.2018. Available: `https://www.osisoft.com/pi-system/`

[78] Delta-X Research. TOA4 Online. Product information. Accessed on 20.12.2018. Available: `http://www.deltaxresearch.com/solutions-online-dga/`

[79] IEC 62271-100. High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers. International standard. Version 2.0. 2008.

[80] Flurscheim, C. H. Power circuit breaker theory and design. London, Peter Peregrinus Ltd, 1982. P. 341-343.

[81] Laitinen, T., Lyly, T., Stenstrand, M., Tammi, J. Wireless sensor units for acoustic monitoring of switching devices. CIGRE Session papers & proceedings. Study Committee B3. 2018, Paris, France.

[82] Roima, A. Sähköaseman kytkinlaitteista kerätyn anturidatan hyödyntäminen ennustavassa kunnossapidossa. Master's Thesis, Tampere University of Technology, Information and Knowledge Management, Tampere, 2018.

[83] Fingrid Oyj. Cognos. Internal reporting platform. 2019.

[84] Wikipedia. Load duration curve. Online encyclopedia. Accessed on 10.1.2018. Available: `https://en.wikipedia.org/wiki/Load_duration_curve`

[85] Akbari, A., Setayeshmehr, A., Borsi, H., Gockenbach, E. A Software Implementation of the Duval Triangle Method. *2008 IEEE International Symposium on Electrical Insulation.* 9.-12.6.2008, Vancouver, Canada. DOI: 10.1109/ELINSL.2008.4570294.

[86] Duval M. The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers. *IEEE Electrical Insulation Magazine*, online journal, 2008, vol. 24, issue 6, p. 22-29. Accessed on 10.1.2019. DOI: 10.1109/MEI.2008.4665347.

[87] Srinivasan, V., Subathra, B., Srinivasan, S., Kannan, S. Asset Management in Smart Grids Using Improved Dissolved Gas Analysis. *International Conference on Power and Advanced Control Engineering.* 12.-14.8.2015, Bangalore, India. DOI: 10.1109/ICPACE.2015.7274968.

[88] Brown, R.E., Frimpong, G., Willis, H.L. Failure Rate Modeling Using Equipment Inspection Data. *IEEE Transactions on Power Systems*, online journal, 2004, vol. 19, issue 2, p. 782-787. Accessed on 10.1.2019. DOI: 10.1109/TPWRS.2004.825824.

[89] Tammi, J. Sähköasemien tärkeysluokitukset ja kokonaisindeksit. Internal specification. 2019.

[90] ABB. Asset condition and risk assessment. Product information. Accessed on 1.2.2019. Available: `https://new.abb.com/medium-voltage/service/advanced-services/asset-condition-and-risk-assessment`

[91] Fingrid Vuosikertomus 2017 Available: `https://www.fingrid.fi/globalassets/dokumentit/fi/sijoittajat/taloudelliset-julkaisut/vuoskareita/fingrid_vuosikertomus_2017.pdf`

[92] ABB. Ellipse APM application. Product information. Accessed on 5.12.2018. Available: `https://new.abb.com/enterprise-software/asset-optimization-management/asset-health-center`

[93] Pieniazek, P.E. Condition On-Line Monitoring. Presentation material, VI Engineering. 19.10.2011. Accessed on 12.2.2019. Available: `https://www.slideshare.net/vwedelich/electrical-condition-monitoring-part-2`

A Fingrid's substation condition data

This Appendix lists Fingrid's condition data in Table 1, including the new IoT data and the existing data. The table includes the quantities for each asset type, the data sources and information whether the monitored equipment is online or offline at the time of a measurement.

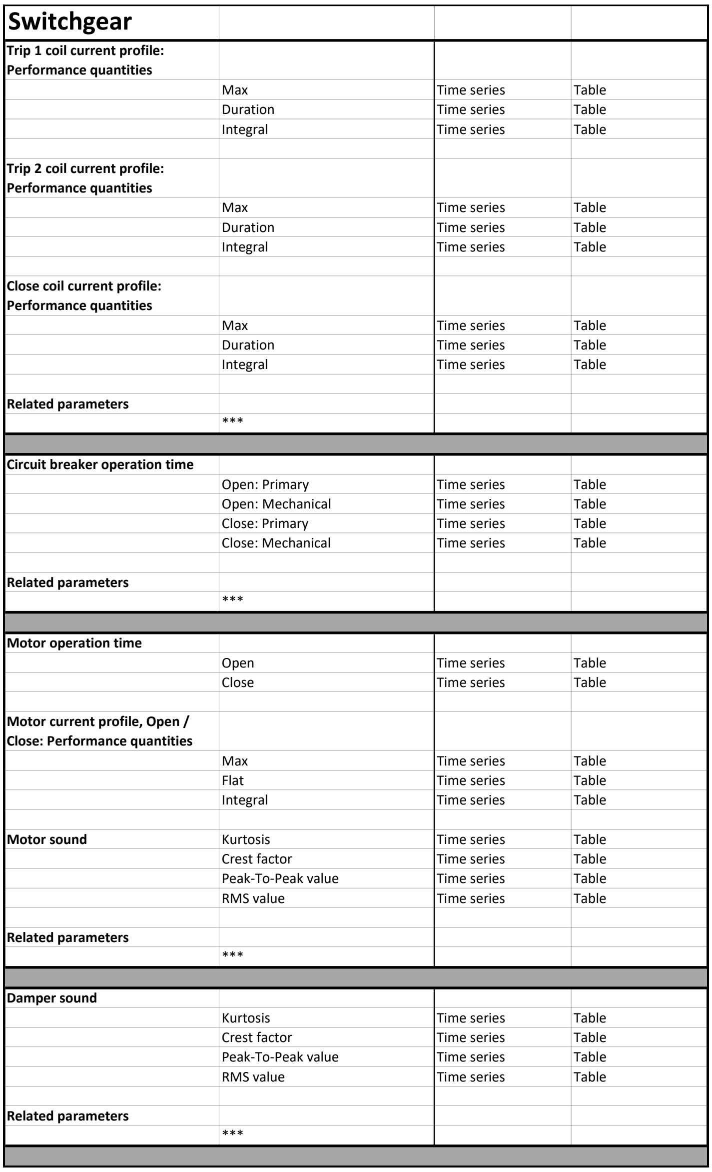
Table 1: Fingrid's condition data.

Circuit breaker	Online	Offline	Data source	Replaced by IoT / New IoT
Charging motor operation time	X		Maximo	Replace
Charging motor current, open	X		Maximo	Replace
Charging motor current, close	X		Maximo	Replace
Charging motor RPM				New
Primary operation time, open	X		Maximo	Replace
Primary operation time, close	X		Maximo	Replace
Operation time, open				New
Operation time, close				New
Trip coil 1 current profile	X		Local disk	Replace
Trip coil 2 current profile	X		Local disk	Replace
Close coil current profile	X		Local disk	Replace
Operations count		X	Maximo	Replace
Gear noise				New
Damper noise				New
Control cabinet temperature				New
Control cabinet humidity				New
Primary circuit temperature				New
Contact resistance with connectors		X	Maximo	
Contact resistance without connectors		X	Maximo	
Trip 1 coil minimum voltage		X	Maximo	
Trip 2 coil minimum voltage		X	Maximo	
Close coil minimum voltage		X	Maximo	
Gas moisture		X	Maximo	
Gas filled		X	Maximo	
Gas SF6 density	X		PI	
Disconnector / Earthing switch				
Motor operation time, open		X	Maximo	Replace
Motor operation time, close		X	Maximo	Replace
Motor current, open		X	Maximo	Replace
Motor current, close		X	Maximo	Replace
Motor RPM, open				New
Motor RPM, close				New
Operations count	X		Maximo	Replace
Gear noise				New
Control cabinet temperature				New
Control cabinet humidity				New
Primary circuit temperature				New
Contact resistance with connectors		X	Maximo	
Contact resistance without connectors		X	Maximo	
Power transformer				
Winding temperatures	X		PI	
Oil temperatures	X		PI	
Power	X		PI	
Current	X		PI	
Vibration				New
Online DGA	X		PI	
Laboratory DGA	X		TOA4	
Laboratory oil analysis	X		TOA4	
SFRA		X	Local disk	
Dissipation factor		X	Maximo	
Substation building				
Outdoor temperature	X		PI	Replace
Temperatures				New
Humidities				New
Water leakages				New
Instrument transformers				
Primary circuit temperature				New
VT secondary voltage				New

B Specifications for condition data visualization

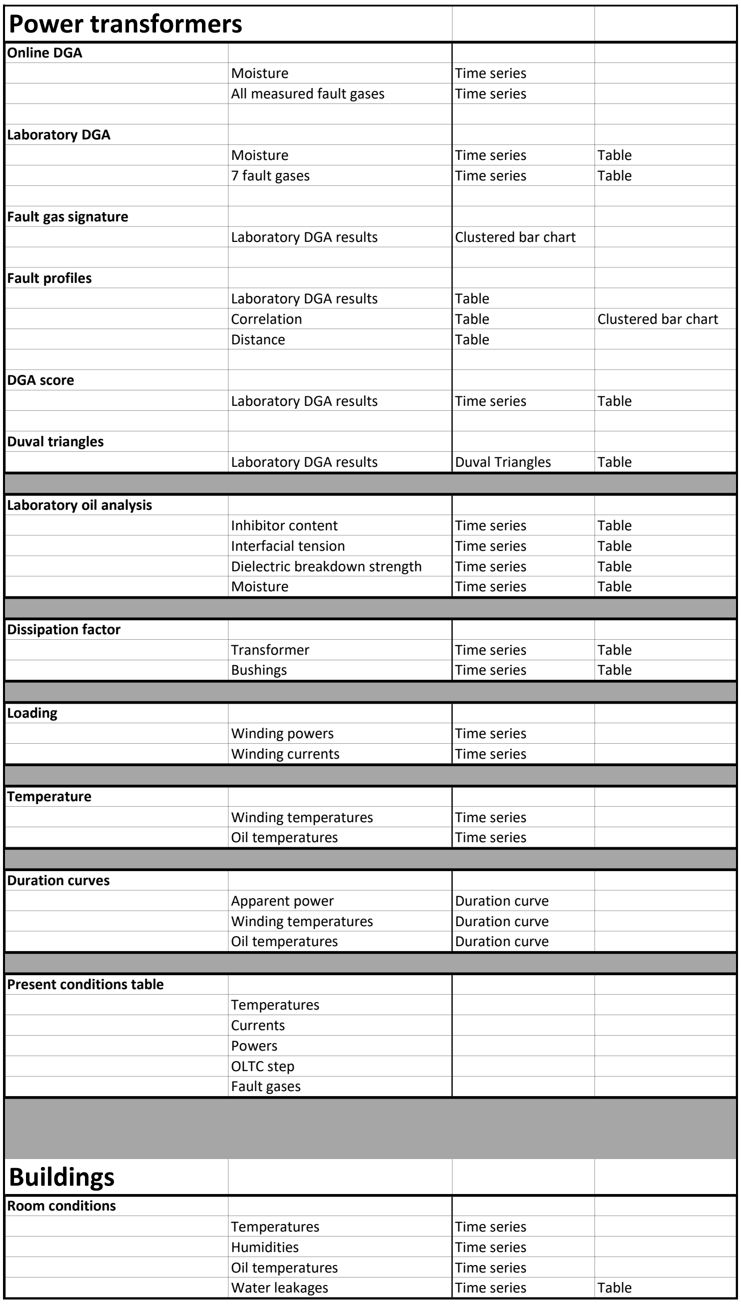
This Appendix lists the visualized data for switchgear, power transformers and substation buildings in Table 2. The table includes quantities and data presentation forms. Switchgear data is segmented in accordance with the skecthes of dashboards presented in Section 5.6. For power transformers and buildings, the necessary elements of asset level dashboards are listed. They are explained in Sections 5.7 and 5.8.

Table 2: Specifications of visualized quantities and data presentation forms.



Switchgear			
Trip 1 coil current profile: Performance quantities			
	Max	Time series	Table
	Duration	Time series	Table
	Integral	Time series	Table
Trip 2 coil current profile: Performance quantities			
	Max	Time series	Table
	Duration	Time series	Table
	Integral	Time series	Table
Close coil current profile: Performance quantities			
	Max	Time series	Table
	Duration	Time series	Table
	Integral	Time series	Table
Related parameters			
	***		
Circuit breaker operation time			
	Open: Primary	Time series	Table
	Open: Mechanical	Time series	Table
	Close: Primary	Time series	Table
	Close: Mechanical	Time series	Table
Related parameters			
	***		
Motor operation time			
	Open	Time series	Table
	Close	Time series	Table
Motor current profile, Open / Close: Performance quantities			
	Max	Time series	Table
	Flat	Time series	Table
	Integral	Time series	Table
Motor sound	Kurtosis	Time series	Table
	Crest factor	Time series	Table
	Peak-To-Peak value	Time series	Table
	RMS value	Time series	Table
Related parameters			
	***		
Damper sound			
	Kurtosis	Time series	Table
	Crest factor	Time series	Table
	Peak-To-Peak value	Time series	Table
	RMS value	Time series	Table
Related parameters			
	***		

SF6 pressure			
	L1, L2, L3	Time series	
Related parameters			
	***		
Related parameters	***		
	Outside temperature	Time series	
	Control cabinet temperature	Time series	
	Control cabinet humidity	Time series	
	Primary circuit temperature(s)	Time series	
	Primary circuit current	Time series	
Motor RPM profile			
Motor current profile			
Motor sound			
	Sound signal		
	Sound spectrogram		
	Spectral rolloff		
	Spectral centroid		
Event list			
	****		
Damper sound			
	Sound signal		
	Sound spectrogram		
	Spectral rolloff		
	Spectral centroid		
Event list			
	****		
Coil current profile			
Event list			
	****		
Event list	****		
	Timestamp		
	Operation direction		
	First operation		
	(Related parameters)		
Fleet analysis			
Charts for events and trends			
Event list			
	Asset		
	Timestamp		
	Operation direction		
	First operation		
	Performance values		
	(Related parameters)		
Filters / Selections			
	Substation		
	Bays		
	Asset types		
	Asset models		
	Voltages		
	Parameter to be displayed		
	Operation direction		
	First operation		
	Temperature		
	Months		
	Timestamp		



Power transformers			
Online DGA			
	Moisture	Time series	
	All measured fault gases	Time series	
Laboratory DGA			
	Moisture	Time series	Table
	7 fault gases	Time series	Table
Fault gas signature			
	Laboratory DGA results	Clustered bar chart	
Fault profiles			
	Laboratory DGA results	Table	
	Correlation	Table	Clustered bar chart
	Distance	Table	
DGA score			
	Laboratory DGA results	Time series	Table
Duval triangles			
	Laboratory DGA results	Duval Triangles	Table
Laboratory oil analysis			
	Inhibitor content	Time series	Table
	Interfacial tension	Time series	Table
	Dielectric breakdown strength	Time series	Table
	Moisture	Time series	Table
Dissipation factor			
	Transformer	Time series	Table
	Bushings	Time series	Table
Loading			
	Winding powers	Time series	
	Winding currents	Time series	
Temperature			
	Winding temperatures	Time series	
	Oil temperatures	Time series	
Duration curves			
	Apparent power	Duration curve	
	Winding temperatures	Duration curve	
	Oil temperatures	Duration curve	
Present conditions table			
	Temperatures		
	Currents		
	Powers		
	OLTC step		
	Fault gases		
Buildings			
Room conditions			
	Temperatures	Time series	
	Humidities	Time series	
	Oil temperatures	Time series	
	Water leakages	Time series	Table

C Table for performance values from online switchgear inspection

Table 3 in this Appendix is a part of the asset level dashboards of switchgear. It is a tool for a service provider who performs an online switchgear inspection routine. The performance values appear in the table after each test-operation of a circuit breaker or a switch.

Table 3: A dashboard for online switchgear inspection routine.

		Operation	Operation time, Primary (ms)	Operation time, Mechanical (ms)	Motor operation time (s)	Motor current: Max (A)	Motor current: Flat (A)	Motor current: Integral (As)	Trip 1 coil current: Max (A)	Trip 1 coil current: Flat (A)	Trip 1 coil current: Integral (As)	Trip 2 coil current: Max (A)	Trip 2 coil current: Flat (A)	Trip 2 coil current: Integral (As)	Close coil current: Max (A)	Close coil current: Flat (A)	Close coil current: Integral (As)	Motor sound: RMS value	Motor sound: Peak-To-Peak	Motor sound: Kurtosis	Motor sound: Crest factor	Damper sound: RMS value	Damper sound: Peak-To-Peak	Damper sound: Kurtosis	Damper sound: Crest factor	Current operations count
KM_AE02Q4	1.3.2018 10:35	Close	61 (55)	67 (60)	15,5 (15,2)	25,9 (24,2)																				
KM_AE02Q4	1.3.2018 10:30	Open	58 (54)	65 (61)	14,9 (15,1)																					
KM_AE02Q3	1.3.2018 10:25	Close	59 (60)	65 (63)																						
KM_AE02Q3	1.3.2018 10:20	Open	55 (56)																							
KM_AE02Q2	1.3.2018 10:15	Close																								
KM_AE02Q2	1.3.2018 10:10	Open																								
KM_AE02Q1	1.3.2018 10:05	Close																								
KM_AE02Q1	1.3.2018 10:00	Open																								
KM_AE02Q0	1.3.2018 9:55	Close																								
KM_AE02Q0	1.3.2018 9:50	Open																								
KM_AE01Q4	1.3.2018 9:45	Close																								
KM_AE01Q4	1.3.2018 9:40	Open																								
KM_AE01Q3	1.3.2018 9:35	Close																								
KM_AE01Q3	1.3.2018 9:30	Open																								
KM_AE01Q2	1.3.2018 9:25	Close																								
KM_AE01Q2	1.3.2018 9:20	Open																								
KM_AE01Q1	1.3.2018 9:15	Close																								
KM_AE01Q1	1.3.2018 9:10	Open																								
KM_AE01Q0	1.3.2018 9:05	Close																								
KM_AE01Q0	1.3.2018 9:00	Open																								