TAMPERE UNIVERSITY OF TECHNOLOGY

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DEVELOPMENT OF PROCESS DATA UTILIZATION IN PROACTIVE NETWORK MANAGEMENT

Master of Science Thesis

Examiner: Professor Pekka Verho
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ABSTRACT

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A continuously increasing amount of data is gathered from the distribution network. The increased amount of data offers new possibilities to be utilized but requires more sophisticated processing to be applied as well. This data consists mainly of different alarms, status indications and measurements. The target of this thesis was to study the process data and its possibilities for proactive network management.

The study for the present state of process data utilization was carried out from two different perspectives. At first, an exploration was made to the available process data and the processes exploiting it. The studied data sources were substations, automated disconnector stations, remote reclosers and smart meters. The study was complemented by including the user perspective with interviewing the personnel of Elenia. From the interviews, several visions for the improved process data utilization were encountered. These were refined to the functionalities of a novel Proactive Network Management System (PNMS) concept by studying the required initial data and some other boundaries. The functionalities will form a guideline for the system-driven development of proactive network management in Elenia.

More thorough analysis of the new functionalities revealed that it would not be reasonable to implement all of these into a single system; a novel nor an existing one. Some of the functions could be implemented into existing systems with little effort. Some of the functionalities instead require data from multiple locations and may not fit in any of the existing systems. Thus a need for a novel system was verified. Each of the functions requires still more careful evaluation before implementing them into practice. The features of this novel system were also discussed in general.

Finally, two of the discovered functionalities, repetitive reclosing analysis and the handling of disturbance records, were studied in more detail. The former represents a functionality which could be implemented in the Distribution Management System (DMS) in use at present. Next, a more detailed specification should be made with the software vendor. The latter would enable the multiple functionalities of which the improved fault analysis was studied the most. To have these functionalities implemented in practice, further research is needed with actual records to verify the potential of each function before rushing into system development.

TIIVISTELMÄ

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Jakeluverkon älykkyyden lisääntyessä muun muassa automaation suhteen, verkosta saatava tietomäärä kasvaa alati. Kasvava tietomäärä tarjoaa uusia mahdollisuuksia toimintojen kehittämiselle, mutta vaatii samalla yhä edistyksellisempiä tapoja prosessoidakseen sitä. Prosessitieto koostuu pääasiassa erilaisista hälytyksistä, tilatiedoista ja mittauksista. Tämän diplomityön tarkoituksena oli tutkia prosessitiedon hyödyntämisen mahdollisuuksia ennakoivassa verkonhallinnassa.

Prosessitiedon hyödyntämisen nykytilaa on tutkittu työssä kahdella eri tavalla. Nykyisin käytössä olevaan tietoon perehdyttiin tutkimalla sähköasemilta, kauko-ohjattavilta erotinasemilta, verkkokatkaisijoilta sekä älymittareilta kerättävää tietoa. Käsitystä täydennettiin haastattelemalla Elenian henkilökuntaa. Haastatteluissa tuli ilmi useita näkemyksiä kehittyneemmästä prosessitiedon hyödyntämisestä. Näistä jalostettiin edelleen toiminnallisuuksia uudelle verkonhallintajärjestelmäkonseptille. Toiminnallisuuksien osalta pohdittiin niiden vaatimia lähtötietoja ja tietojen sijaintia nykyisessä järjestelmäkentässä yhdessä muiden reunaehtojen kanssa. Nämä toiminnallisuudet muodostavat suuntaviivat järjestelmäkeskeisen ennakoivan verkonhallinnan kehittämiselle Eleniassa.

Uusien toiminnallisuuksien tarkempi analyysi osoitti, että kaikkia niistä ei ole mielekästä sisällyttää samaan järjestelmään, olisi kyseessä sitten uusi järjestelmä tai jokin nykyisistä. Osa olisi mahdollista sisällyttää osaksi nykyisiä järjestelmiä, mutta osa vaatii käyttöönsä tietoja useammasta järjestelmästä, eivätkä ne tyypiltään sovi nykyisiin järjestelmiin. Näiltä osin tarve uudentyyppiselle järjestelmälle vahvistui. Uuden järjestelmän ominaisuuksia pohdittiin työssä myös yleisellä tasolla.

Lopuksi työssä kuvattiin tarkemmin kaksi hahmotelluista toiminnallisuuksista. Analyysi toistuvien jälleenkytkentöjen havaitsemiseksi olisi mahdollista toteuttaa nykyiseen käytöntukijärjestelmään. Seuraavaksi tulisikin tehdä toiminnallisuudelle yksityiskohtainen määrittely yhdessä järjestelmätoimittajan kanssa. Automaattinen häiriötallenteiden analysointi mahdollistaisi useita hyödyllisiä toiminnallisuuksia, joista eniten tutkittiin vianhallinnan kehittämistä. Näiden toiminnallisuuksien vieminen käytäntöön vaatii kuitenkin tarkempaa tutkimusta todellisten tallenteiden avulla.

PREFACE

The topic of this Master of Science thesis was provided by Elenia Oy and it is related to the national research program Smart Grids and Energy Markets. The work was carried out during the time between June 2012 and January 2013. The idea was originally presented by M.Sc. Ville Maksimainen, currently in Netcontrol Oy. The supervisor from Elenia was M.Sc. Heikki Paananen who I would like to thank for guidance during the work. The examiner of this thesis was Professor Pekka Verho from the Department of Electrical Engineering in Tampere University of Technology whom which I would like to express my gratitude not only for examining my thesis but the guidance and encouragement throughout my studies and previous undertakings.

I was privileged to have an opportunity to interview a great number of experts in their field. I would like to express my gratitude to all the interviewees listed at the end of this thesis. The interest they showed towards my topic gave me a lot of belief to the work I am doing. I would also like to thank all the other colleagues whom with I have had interesting conversations related to my thesis but also enjoyable breaks during the passed months.

Many thanks to all of my friends who provided me with an escape from studies whenever I needed to do so. Especially I would like to thank my brother in arms, Sami Vehmasvaara, lastly for valuable comments to my thesis but also for numerous challenges we defeated together during studies and in life as well.

Finally, I would like to thank my parents, Raili and Reima for encouragement and support in all what I have ever been into. My father has been the greatest mentor for me during my studies. Without him being the example of a great engineering mind I would not have been made it this far.

Tampere, January 15th, 2013.

Vesa Hälvä

CONTENTS

ABBREVIATIONS

AM/FM/GIS	Automated Mapping/Facilites Management/Geographical Information System
AMR	Automatic Meter Reading
API	Application Programming Interface
CBM	Condition Based Maintenance
CBR	Case-Based Reasoning
CIM	Common Information Model
CIS	Customer Information System
CRM	Customer Relationship Management
DA	Distribution Automation
DBMS	Database Management System
DMS	Distribution Management System
DSO	Distribution System Operator
DSS	Decision Support System
EMS	Energy Management System
ESB	Enterprise Service Bus
ERP	Enterprise Resource Planning
FLIR	Fault Location, Isolation and Restoration
FMI	Finnish Meteorological Institute
FTP	File Transfer Protocol
GEO	Geosynchronous Earth-Orbiting
GPRS	General Packet Radio Service
HEMS	Home Energy Management System
HV	High Voltage
IaaS	Infrastructure as a Service
IEC	International Electrotechnical Comission
IED	Intelligent Electronic Device
ISDN	Integrated Services Digital Network
LAN	Local Area Network
LV	Low Voltage
MDMS	Meter Data Management System
MOM	Message-Oriented Middleware
MRS	Meter Reading System
MV	Medium Voltage
NCC	Network Control Centre
NIS	Network Information System

OHL	Overhead Line
OLTC	On-load Tap Changer
OPGW	Optical Fiber Composite Overhead Ground Wire
PaaS	Platform as a Service
PLC	Power Line Communication
PNMS	Proactive Network Management System
RBM	Risk Based Maintenance
RCM	Reliability-Centered Maintenance
RPC	Remote Procedure Call
RRA	Repetitive Reclosing Analysis
RTU	Remote Terminal Unit
SaaS	Software as a Service
SCADA	Supervisory Control And Data Acquisition
SQL	Structured Query Language
TBM	Time Based Maintenance
UPS	Uninterruptible Power Supply
XML	Extensible Markup Language

1. INTRODUCTION

The quality of service in electricity distribution has attracted a lot of attention recently. This is a consequence from society's increased dependency on the electricity together with the major disturbances occurred in the past few years. These are the main reasons which have driven the distribution system operators to find different options to reduce interruptions in their network.

Elenia serves approximately 408 000 customers in Ostrobothnia, Central Finland, Häme and Pirkanmaa in Finland. The market share is 12 % being the second largest distribution network utility in Finland. The area of 50 000 km^2 including about 100 municipalities is covered with 140 primary substations, 22 000 km of medium voltage lines, 21 600 secondary substations and 39 000 km of low voltage lines.

The distribution network of Elenia is operated by 180 employees which leads to relatively large amount of network per employee. The strategic approach is to exploit network automation and information systems as much as possible to maintain and improve the quality of service. Additionally, according to the strategic choice made in 2009, Elenia installs the new and renovated network only as underground cables. Partnerships are also a crucial part of Elenia's strategy, meaning in practice that all the field work is outsourced to contractors.

The fault management is continuously improved by FLIR (Fault Location, Isolation and power Restoration) functionalities, for example, but a relevant question remains: Could we prevent the faults from happening in the first place? The main target for this thesis is to define a concept for a Proactive Network Management System (PNMS). This could include development of a new system or improving the existing ones. The intention of the system is to contribute to preventive maintenance and by these means improve the quality of service. However, this novel system is designated to answer the needs not only for the maintenance but also other levels of the electric utility. These levels and some motivating factors are discussed in more detail in chapter 2. The distribution automation entity has a focal role in the system development of this kind and therefore it is presented in general level in chapter 3.

Chapter 4 describes the process data available via the distribution automation system of Elenia. The present state and visions for improved process data utilization are presented as well. The present state is studied by exploring the data available from different parts of the network of Elenia. The different visions and requirements were gathered mainly via interviews of the personnel of Elenia. The data gathered via visual inspections provide valuable information for the condition management but the analysis of this data has been consciously cropped out from this thesis. The concept of PNMS can be considered a relatively large entity and therefore the description has been divided into smaller entities. The concept can be seen formed by functions processing the initial data gathered from the network. The functions discovered are evaluated briefly including their requirements for initial data, its location and the execution time requirements.

The general requirements for the novel proactive condition management system are discussed in chapter 5. The chapter 6 concretises this concept with two examples and some development suggestions. The business model is discussed in brief as well.

This thesis is part of a five-year research program Smart Grids and Energy Markets (SGEM) during 2009-2014 coordinated by Cleen Ltd (Cluster for Energy and Environment). The program is divided into seven work packages which are further divided into smaller tasks. This thesis is part of the task 6.12 Proactive Network Monitoring in work package six: Intelligent Management and Operation. The project is financed by the Finnish Funding Agency for Technology and Innovation and the industrial partners such as Elenia.

Vuorinen (2012) has studied the utilization of the process data mainly for the primary transformers and circuit breakers. In that work it was discovered that the process data has potential for various purposes if it is exploited efficiently. This thesis concentrates finding as much potential targets for development around the process data utilization. There is a research in progress in the SGEM program concerning the condition monitoring of primary transformers. This study is carried out by University of Vaasa. This is one of the reasons why the condition monitoring of primary transformer is left out from this thesis. On-going process data related activities exist also in the vendor industry. Kostiainen et al. (2012), for example, are developing improved fault location analysis which could be exploited around the topics discussed in this thesis as well. These activities are also carried out within the SGEM project.

2. DISTRIBUTION NETWORK MANAGEMENT

Distribution network business may be seen consisted of different tasks and processes. The categorization may be carried out with different ways depending on the organization or the viewpoint of the study. The key function for the owner of the utility is network management. Network management can be divided into operations, maintenance, network planning and strategic development. (Lakervi & Partanen 2008)

The target of the novel system discussed in this thesis is to serve all processes presented above. To clarify these objectives, the processes are discussed in more detail in the following sections. Also some future trends including smart grids are studied since the system should be able to serve the future needs.

2.1 Operation

The targets of network operations are to maintain the quality of supply, safety of the system, customer service and economy in short terms. Operation of an electrical network is a versatile optimization process between reliability, economics and safety. In practice this means such tasks as operations planning, network supervision and controlling, outage management and practical implementation of maintenance actions. (Lakervi & Partanen 2008)

Operations planning includes the resource allocation in operations, switching planning of maintenance outages and maintenance of operational systems and devices like SCADA and communications. The planning is done in short periods, even daily, according to the weather forecasts, available resources and the need for different interest groups. (Lakervi & Partanen 2008)

Supervision of the network contains the surveillance of protection and switching devices and following the load flow of the distribution system. Control of the networks consists of switchings made with devices in the network either remotely via remote controlling system or requesting a field crew to perform the task. (Lakervi & Partanen 2008)

Outage management is a task in which the occurred fault is recognized, located and isolated. After isolating the fault, power is restored for as many customers as possible using back up connections and eventually repairing the fault. The customers should also be informed about the occurred fault and provided information about the estimated time for power restoration. (Lakervi & Partanen 2008)

The practical implementation of a maintenance program means proactive maintenance monitoring, periodic inspections and maintenance actions planning. The target of maintenance actions is to prevent faults from occurring. Actions are planned in a way that they disturb customers as little as possible. The maintenance management itself is defined in the following section. (Lakervi & Partanen 2008)

Operation of an electrical network is controlled from a network control centre (NCC) by means of distribution automation. Distribution automation is covered as a whole in chapter 3. The control centre has a key role in network safety. All the switchings made in the network are led by the control centre. (Lakervi & Partanen 2008)

2.2 Maintenance

The primary target of the maintenance process is to maintain network components in such condition that the overall long term costs of the network are minimized. Maintenance can be divided into preventive maintenance and corrective maintenance. Preventive maintenance is carried out as time based (TBM) or condition based maintenance (CBM). (Lakervi & Partanen 2008, p. 228)

In corrective maintenance, maintenance actions are performed only on the occasion of a component failure. This is a practical strategy for low cost components whose malfunction does not compromise the operation of the significant parts of the network. Also components which can't be overhauled or components which condition is challenging to measure are often treated this way. In corrective maintenance, the faulted component is often replaced completely instead of repairing it so that the labour costs needed are minimized. (Aro et al. 2003, p. 173-174)

The purpose of preventive maintenance is to avoid component failures. In time based maintenance, the actions are scheduled for fixed time intervals. In practice this means for example periodic inspections for network components. Also some of the known weak points of a component may be fixed within a certain time period. (Lakervi & Partanen 2008, p. 228)

Condition based maintenance targets to schedule the maintenance actions according to components' condition. This requires measurements or other indications from every component in which this strategy is applied to. Therefore it is not possible to apply this strategy for all components if there are no reliable indicators available. The metering may be carried out with on-line measurements or periodic inspections. Also some advanced analysis may have to be applied to get information about a certain component's condition since the measurement usually does not correspond to the component's condition directly. (Verho 2012)

The preventive maintenance may be enhanced with a component reliability analysis. This strategy is called reliability-centered maintenance (RCM). The idea is to prioritize the maintenance actions to components according to their criticality and the costs caused by the failure. In other words, components, which failure have greater impact on the network operation will have more attention. When this is combined with CBM, the result is called risk based maintenance (RBM), which is often the solution to be pursued. (Verho 2012)

According to the decision of Ministry of Trade and Industry (5.7.1996/517), nowadays Ministry of Employment and the Economy, a DSO has to compile a maintenance program. The main purpose for the maintenance program requirement is to maintain the safety of the networks. The maintenance program should answer how different acts, standards and recommendations are satisfied. It determines principles for example how the periodic inspections, measurements and services are scheduled.

Traditionally most of the maintenance actions have been performed as time based. Nowadays more often the need for maintenance is determined with periodical inspections. Hence the actual service and maintenance actions are carried out as condition based according to the inspection results. The time period for the inspections is defined separately for different component types according to their known failure rate, criticality and recommendations.

The traditional way for performing inspections is to physically visit the components. While the network length is great and the distances are long, alternative ways for the inspections have been studied to reduce the labour work required. Several DSOs have adopted helicopter inspections for the overhead lines, substations and switching stations. The helicopter inspections may be carried out either with the inspectors on board or with high quality cameras and laser scanning devices. The benefit of the latter is the possibility to analyse the data further and development of analysing algorithms. An automated analysing algorithm for line corridor clearance for example is under development (Heinonen et al. 2012).

In the survey performed by Toivonen et al. (2005) is found that the effectiveness of the condition data management has a great impact on the chosen maintenance strategy. The more effective is the data management, the more advanced maintenance strategies could be applied. In companies with no comprehensive condition data management with an information system, the maintenance was carried out mainly time based. Companies with an information system for condition management, maintenance actions were performed based on the condition of the components.

2.3 Network planning and strategic development

The foundation for network planning and long-term development is the selected network strategy. Strategic development is the task defining the network strategy and network planning applies it. The network strategy describes the factors from outside as well as internal targets. External factors are development of supporting technology and society, the load growth, environmental issues and the regulation by the authority. Since the life cycle of the network components is relatively long, the external factors have a great impact on network developing principles. (Lakervi & Partanen 2008, p. 216-217)

Internal factors consist of the general principles and calculation parameters chosen for the network development. Examples of these parameters are chosen voltage levels, the earthing system in the medium voltage network, the period under review and economic parameters like interest and economic life cycle. Network structures and component types applied as well as the level of automation are also strategic choices. If a certain component is noted to be unreliable, it can be removed from the network immediately or within a certain time period. The present electrical and mechanical state of the network sets a starting point for the strategic planning. When the present state of the network is known, alternative developing options can be made and compared. After the optimal solution is found the next step is to form an investment program. The resources for the network development are limited, so it is crucial to prioritize the targets. (Lakervi & Partanen 2008)

Strategic planning also requires co-operation with multiple interest groups. At corporate level, the strategic planning has major impacts on the operations, construction and economics. Outside the company, the development should be carried out together with other basic infrastructure utilities like telecommunication companies and municipalities. (Lakervi & Partanen 2008, p. 228)

While the strategic guidelines are clear, they are to be realized in network planning. The principles are applied to both new building and rebuilding the existing network. The objective of the network planning is to unambiguously define the form of the investment: Dimensioning the components for the network and determine the time for the project to realize (Lakervi & Partanen 2008, p. 64).

2.4 Smart grids and future trends

The smart grid is an umbrella term gathering a wide range of development under it. It is a continuum, which may be seen to began 1970's when the first generation of SCADA systems were implemented. So the term is relatively recent while the technological evolution has been in progress for a long time. Järventausta et al. (2011) have considered the present state of the Finnish distribution network as the first generation of the smart grid. However, there is no standard definition for the term and the content depends on the context. Commonly used attributes for defining smart grids are effectiveness, controllability, reliability and flexibility. These objectives are pursued implementing novel network structures and devices, adding automation, communication and information systems to the network. Electricity market perspective is usually closely included in the smart grid discussion but in the context of this thesis it is ignored. In conclusion it can be stated that smart grid should satisfy all the demands in future for every party of the distribution network: producers, consumers and other interest groups. (Sarvaranta 2010; Parkkinen 2011)

What is notable concerning this thesis, is the increasing amount of data collected from the distribution network. While the utilization of the process data is not as comprehensive as it could be even at present, the future entails more challenges as well as possibilities. Another aspect of the smart grid is distributed intelligence in the distribution network presented by Valtari & Verho (2011). This means that some of the decision making is done by the intelligent electronic devices (IED) at a substation. This enables a faster response to transient situations but requires more information to be exchanged between devices. Also the centralized control system, as SCADA today, would not necessarily receive as much data as it does at present or at least the data received would be quite different than nowadays. This is something which should be taken into account when considering the novel information system like the one presented in this thesis.

At the same time with smart grid development, the society becomes more and more dependent on electricity. The very recent indication was seen at the end of 2011 when southern Finland experienced severe weather conditions right after Christmas. Two storms, named Tapani and Hannu, affected approximately 570,000 customers and aroused a lively public discussion about the preparedness for major disturbances. Two years before, in the summer 2010, four storms hit the Southern and Centre of Finland and approximately 481,000 customers were affected in one way or another. (Energy Market Authority 2011a; Finnish Energy Industries 2012)

These major disturbances have led to actions towards legislative reformations. The Ministry of Employment and the Economy has proposed limit values included in the law for the duration of an interruption experienced by a customer, for example. DSOs' are to be prepared a development plan to satisfy these limits until the end of 2027. Since the year 2003 a standard compensation practice has been implemented to compensate the harm experienced by the customers during an interruption (17.3.1995/386). The compensation is stepwise increasing and it is applied after an interruption has lasted 12 hours or longer. The standard compensation practice is also to be improved so that the maximum compensation value is increased. (Työ- ja Elinkeinoministeriö 2012)

Before the legislative reformations, the reliability of the supply has been taken into account by the economic regulation by Energy Market Authority. The interruptions have been taken into account since the second regulatory period 2008-2011. For the third regulatory period 2012-2015 the effect of interruptions was further increased. (Energy Market Authority 2007, 2011b)

However, even before these two drivers mentioned above, DSOs and their interest group Finnish Energy Industries have proactively carried out measures for improving the reliability of the supply. A study by Partanen et al. (2010) about the criteria and targets for the reliability of the supply of electricity distribution was finished 2010, for example. The outcome was reliability guidelines for network planning for different types of areas and these have been applied by the DSOs since.

2.5 Decision making

The network utility business, as any other business, includes a great amount of decision making at various levels. The subject which the decision concerns may vary a lot: A switching in the network control centre in some tens of seconds to strategic guidelines for tens of years. In addition, the initial data for the decisions is increasing as will be concluded later on in this thesis. These altogether set challenges for decision-making, which is covered in following. The quality of initial data is crucial for decision making. In general, data with poor quality leads to poor decisions and therefore the quality should be taken into consideration.

2.5.1 Human as a decision-maker

Human beings are relatively subjective decision-makers. Their decisions are influenced by power, incentives and ambiguity, for example. The information processing capacity of a human is also limited and significantly affected by stress and time pressure. It is also stated that quite a few decision makers cannot even clearly define their objectives or preferences. (McNurlin et al. 2009, p. 424)

The electric utility industry is not an exception. Traditionally, decisions, especially in network operation, were often made based on personnel's intuition and educated guesses. The reason is the lack of better knowledge since there was no information available. Nowadays the volume of data has increased and the problem is more like to process it into information and further to support the decision-making process.

Another point of view is the tacit knowledge and the special expertise of experienced professionals. The educated guesses based on that knowledge are often precious to the business and these properties are challenging to model at root.

2.5.2 Technologies-supported decision making

The issue with technology-supported decision making is to determine the way that information systems can be used to enhance the decision-making process. IT systems can be used to help the decision maker to get the information he needs, defining the problem, clarify the preferences, process complex reasoning and evaluating the impacts of the decision beforehand. The first step was to apply IT in easily discernible procedures, such as data manipulation, sorting and different what-if analysis. The major decisions were still made by humans.

While systems developed into more sophisticated, more advanced analysis like goal-based decisions using integrated data-intensive systems have become available. In other words, previously the user had to determine which procedures he could carry out with IT and with what data, today's systems can suggest a complete solution. These previous generation systems can be spreadsheets with some filtering and sorting functions, for example. The next generation systems are discussed in following. (McNurlin et al. 2009, p. 424-427)

The systems for supporting decision-making can be categorized into five groups: Decision support systems, data mining, executive information systems, expert systems and agent-based modelling (McNurlin et al. 2009, p. 424). From these, the executive information systems are neglected since they are designed to support the work of executives and therefore not interesting in the scope of this thesis.

The principle of a decision support system (DSS) is to help decision makers with ill-structured problems through interaction with data from different sources and analysis models. The data is often collected from different databases. Different models and patterns are also stored to a specific database. When the data is processed with the models and analysis tools, added value for the decision making is provided. Another key feature for the system is the user interface. It should enable non-technical users to exploit the system efficiently. (McNurlin et al. 2009, p. 427)

The most typical use of a database is users entering queries to obtain information to support their decisions. Recently, another approach has become more popular since the processing capacity has increased. The late approach is to let the computer find unknown correlations, patterns, anomalies and clusters of data that users are unaware exist. Nowadays the most common type of data mined is customer data because it can help companies to serve their customers better. The data mining can be considered as a part of a successful DSS. (McNurlin et al. 2009, p. 432-433)

Expert systems are systems applying artificial intelligence. In other words, it tries to emulate human, or other actors and events, behaviour like reasoning and communication. The issue with the expert systems is the modelling of the intelligence. This is often something which have previously carried out by specialists with a long experience and needless to say that the modelling could be complex. (McNurlin et al. 2009, p. 440)

Agent-based modelling is a simulation method for studying emergent behaviour. Emergent behaviour consists of a large number of independent decision makers performing tasks. Traditionally, software has been a preprogrammed tool executing predetermined tasks. Agent-based modelling is rather considered as an autonomous assistant simulating human characteristics. The systems consisted of a large number of agents are relatively complex and lead often to unexpected results. That is often a desired feature and agent-based modelling is used to predict market behaviour, for example. (McNurlin et al. 2009, p. 446-447)

However, the categorization of different systems is not precise and some overlapping and combinations exist. DSSs have many similarities compared with the expert systems at the same time including data mining and agent-based modelling features. In fact, the desired ensemble is often achieved with mixing the methods. The target for better data management is so called real-time enterprise. The ideology behind the term is that the companies know how they are doing at the moment instead of waiting for weeks or months analysis to be completed or results seen in the real world. (McNurlin et al. 2009)

Some examples of the systems described above can be found in the electric utility industry system environment. The DMS can be held as an example of the decision support system and recently introduced FLIR systems are expert systems. Data mining has not as clear examples but some customer information systems might include such features.

2.5.3 Data quality

When discussing a decision-making process, the quality of initial data is essential. In this case, it means the quality of measured and transferred process data from the distribution network all the way up to the decision-making system. If the initial data is incorrect, it is impossible to refine to useful information.

In principle, the data quality includes such things as how right and correct the data is for a certain purpose. Furthermore, this data should be accessible and available at the right time. (Redman 2004)

As stated above, data quality has multiple dimensions. A categorization of these dimensions is presented in table 2.1. The table includes the commonly recognized dimensions but the categorization is not unambiguous and some other dimension can be found depending on the point of view. (Batini & Scannapieca 2006)

Table 2.1. *The most common dimensions related to data quality (Batini & Scannapieca 2006)*

Dimension	**Definition**
Accuracy	The closeness of the data and the represented real-life phenomenon
Completeness	All the defined attributes of data are presented (column completeness). The population is studied thoroughly (population completeness)
Consistency	The semantic rules for the data are complied
Currency & Timeliness	The up-to-date data is accessible when needed

Data quality is often referred to accuracy of the data and it can be stated the most important dimension also in this case. Advanced algorithms will not be able to add value to the decision-making process if the measurements are inaccurate or the data is altered in transfer. The accuracy of the data should be ensured with specific validation procedures. (Batini & Scannapieca 2006, p. 20)

In general, for the data being complete, it should be sufficient breadth, depth and scope for each task it is applied to. It is strongly related to the purpose of the data usage and therefore it should be considered case by case. (Batini & Scannapieca 2006, p. 23-24)

The consistency of data is an issue with systems, in which the users add values manually and the input has no restrictions. While discussing process data which is collected automatically by other systems, the consistency can be ensured by defining the formats for the data. (Batini & Scannapieca 2006, p. 30-31)

Data types can have different lifetimes. Data can be stable over the time, long-term-changing or frequently changing. The currency measures is the data updated in a suitable frequency. The timeliness concerns the availability of the data. Even the up-to-date data has no use if it is not available at the time needed. (Batini & Scannapieca 2006, p. 28-29)

2.6 Proactive condition monitoring

All the factors mentioned in previous section altogether set targets for better reliability for distribution networks. DSOs are enthusiastically looking for new solutions to improve the reliability of the supply and power quality and for these objectives also this thesis is giving its contribution. By this thesis' point of view, the smart grid could mean the advanced utilization of eventually increasing process data. While applied to maintenance purposes, the reliability of the supply could be improved.

However, proactive condition monitoring enables much more than maintenance in the form of actual repairing and servicing. The quality of supply is consisted of the voltage quality, interruptions and the customer service (Lakervi & Partanen 2008, p. 248). Maintenance can be seen in a more comprehensive way including improvement of the weak points of the network and quality of the supply. The main target for the utilities is to serve their customers better by providing better quality of supply. Applying novel technology enables improvement of the voltage quality and reduction of the interruption time and number of interruptions. With wider knowledge of the state of the network, also more precise information can be offered to customers and thus the quality of the supply is improved as a whole.

While pursuing the target of better quality of supply, it involves not only the maintenance but also the other network management processes presented earlier. The actual maintenance is naturally important since the component failures have often a visible impact on the quality of supply. More far-reaching results can be achieved also with improving actions and knowledge at other levels. The quality of the supply in existing network can steer the investment planning and monitoring the voltage fluctuation, harmonics and other disturbances offers possibilities for better customer service, for example (Lakervi & Partanen 2008, p. 249). Traditionally, the voltage quality issues have not been noticed until customer claims. By monitoring the voltage quality and proactively carrying out measures improving it including informing the customers, better customer service can be achieved.

3. DISTRIBUTION AUTOMATION

Distribution Automation (DA) refers to the management, operation and supervision of the electricity distribution network (ABB 2000). While discussing proactive condition monitoring, DA offers the initial data for the analysis. The data is created in various metering devices or it can be status values of different actuators. Before the data is accessible, a data collection and transfer system is needed. DA answers these requirements.

A comprehensive DA concept includes all levels from company level to a customer forming a hierarchical structure as illustrated in figure 3.1. The number of the devices increases while moving downwards on the pyramid. Also the volume of data sources increases at the same time. While the volume of data varies among the levels, different measurement and handling solutions for the data should be used in different levels to achieve a techno-economic optimum.

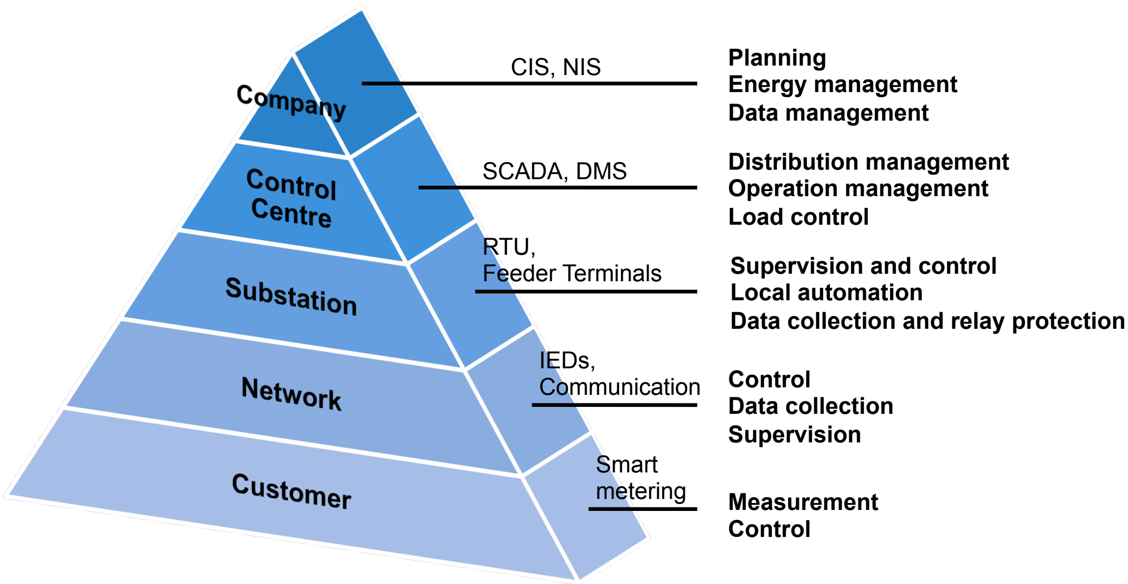


Figure 3.1. *The general hierarchy in distribution automation adapted from ABB (2000) and Northcote-Green & Wilson (2006)*

The main tasks of each level and tools for their treatment are also described in figure 3.1. The tasks, however, are not tightly tied to the levels. A task may be spread at many levels and the level where the task is performed may vary among DSOs.

The function of an electricity distribution system is to deliver electrical energy with suitable voltage from the nation-wide transmission system to the customers.

The electricity distribution networks have been spread in wide geographical areas. Specific challenges to the Finnish distribution system are additionally broad forests, harsh winter seasons and a large amount of overhead lines closing to the end of their life cycle (Järventausta et al. 2011). Since the network is desired to have a centralized control, this has altogether led developing and exploiting distribution automation on a large scale. Automation enables the centralized supervision and control of the network remotely from the control centre. (Lakervi & Partanen 2008, p. 232-233)

3.1 Electricity distribution system

The electricity distribution system consists of two sections like any other automation system: The primary process and the secondary process. The primary process includes all the actuators in the network such as transformers, overhead lines, cables, switching gear, fuses, reactors and capacitors. The primary process in electricity distribution may be categorized into HV (High Voltage), MV (Medium Voltage) and LV (Low Voltage) networks according to the voltage level. Typically applied voltage levels are 110 kV in HV network, 20 kV in MV network and 0,4 kV in LV network. Also some additional voltage levels are in use thus far, often for historical or geographical reason, but the levels are converging and the exceptional levels are disappearing. (Lakervi & Partanen 2008)

The medium voltage network may be considered the most critical part of the distribution system since even 90 % of outages experienced by the customers are derived from faults in MV network. A common network topology at MV network is the open-loop arrangement. The structure of the network is build as a loop, but under normal operating conditions the loop is open at a certain point. At the electrical point of view the network is operated as a number of radial feeders. This configuration offers a back-up possibility if a fault occurs between the busbar and the open point. In rural area, a purely radial configuration without a back-up interconnection is in common use especially in LV networks. Ring topologies are becoming more common while distribution automation, especially sophisticated protection systems and communication technologies, is evolving. (Lakervi & Partanen 2008)

The secondary process consists of devices which are used to monitor and control the primary process. These secondary devices form an interface between the processes. These devices in general are called IEDs (Intelligent Electronic Device) (Northcote-Green & Wilson 2006). Traditionally, the remote functions are limited to the medium voltage network level but smart metering is about to extend those functions to the low voltage network level as well. (Lakervi & Partanen 2008)

Examples of these devices are relays, instrument transformers, sensors, data transmission systems and information systems. These two processes and the boundary between them are illustrated in figure 3.2.

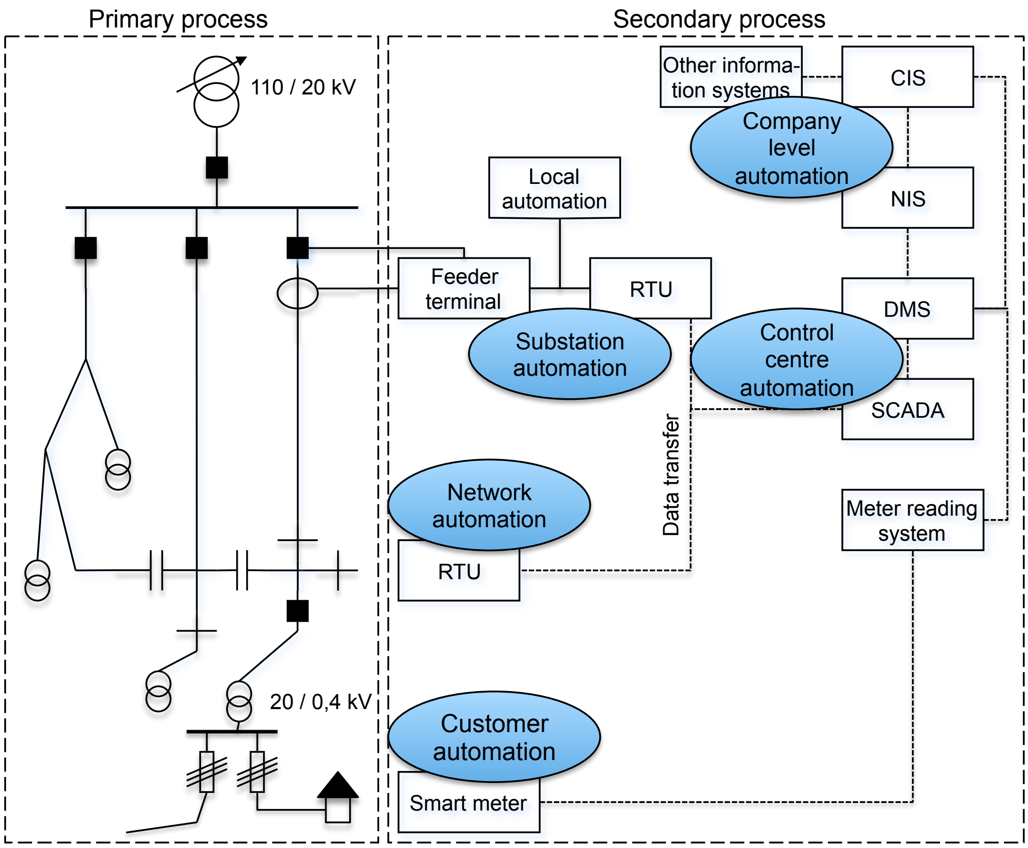


Figure 3.2. *The processes in electricity distribution adapted from Lakervi & Partanen (2008)*

The distribution automation can be further divided into company level automation, control centre automation, substation automation, network automation and customer automation. From these, control centre automation, substation automation and network automation are studied more thoroughly in the following sections. In the scope of this thesis, customer automation is considered as smart metering although it usually includes a lot more: Load control, demand response and active resources for example. Also the information systems of the company level automation are presented briefly.

3.2 Substation automation

Substation automation can be further divided into device level automation and station level automation. Examples of device level automation are metering, voltage control, quality analysers and earth fault current compensation. Station level automation includes the local controlling of the substation, sequence controls, alarm centre and remote control communication for example. (Lakervi & Partanen 2008)

A detailed structure of a substation with distribution automation is represented in figure 3.3. There is illustrated a substation with a single main transformer and a single busbar with the primary process components, automation components and their connections to each other. The rectangles in the figure represent logical functions of a substation automation entity and they can be included a single physical device, called IED. Blocks ”Protection relay”, ”Measurement” and ”Disturbance recorder” for example are usually included in the same device when it comes to the modern feeder terminals. The solid lines in the figure illustrate the connection between primary and secondary devices which are hard-wired. The dotted lines represent communication between secondary devices and it can be carried out different ways depending on the technology used and whether the functions are located in a single device or not.

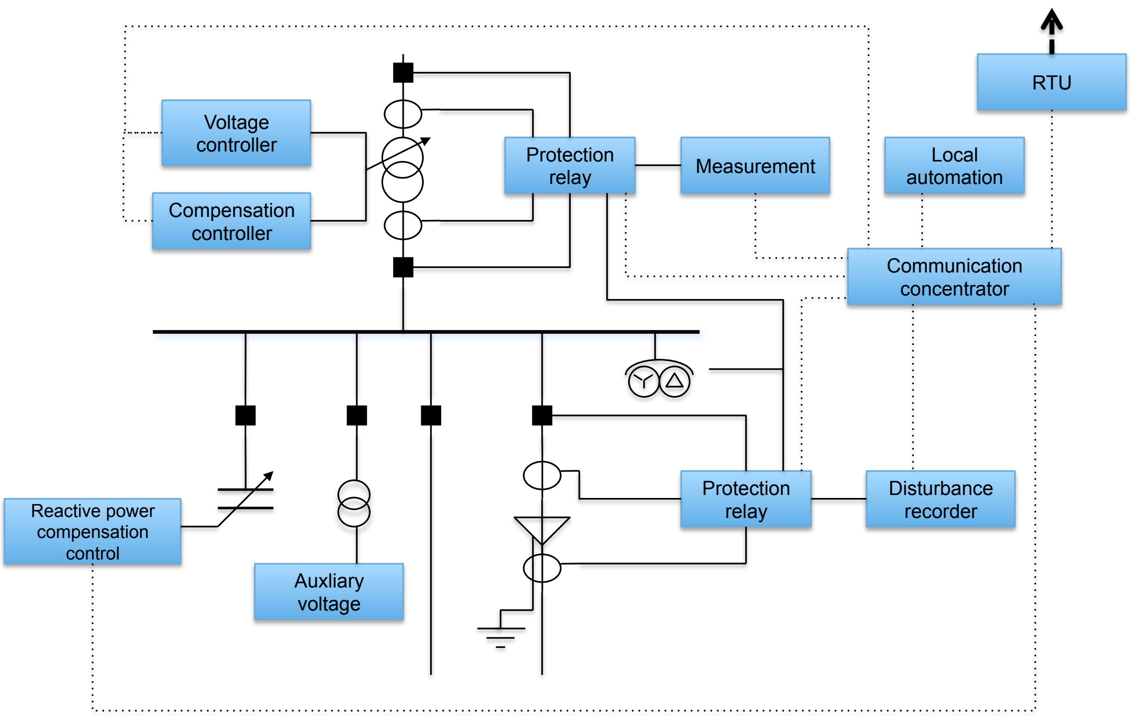


Figure 3.3. *Substation automation devices and data links (Verho 2011)*

Protection relays have their roots in early 20th century, the era of the first electricity distribution systems (Verho 2011). The first generation of protection relays was electromechanical relays. They include moving parts which require continuous maintenance and the inertia restricts the rate of operation. Electromechanical relays are single-phased and every feature require a dedicated device. This leads to complex wiring but the redundancy can been seen as an advantage. The electromechanical relays get the energy for their operation from the measurement circuit, so there is no need for the external power supply. (Mörsky 1993)

The next generation of protection relays were based on analog electronics and are entitled as static relays. They do not include any moving parts which enables faster operation and more accurate settings. The better performance enables also more advanced protection functions being applied. However, a dedicated device for every function was still required. The requirement for an external power supply and the large amount of analog components can lead to reliability issues. (Mörsky 1993)

The development of microprocessor technology enabled integration of different protection features into a single device. The major advantage of these devices is self-diagnosis which enables inoperative protection been discovered before actual fault occurs. Another development step was to include other features in the relays in addition to protection, like measurements. (Mörsky 1993)

Modern microprocessor-based relays are called feeder terminals and they represent focal components in modern substation automation. It may be seen as a part of station level automation, but it also has device level automation functionalities. If a fault occurs, feeder terminal acts as an independent device and it cuts off the supply according to its configuration parameters. At the same time it is a vital part of distribution automation while it transmits measurements, alarms, time stamped events, disturbance records and state values to the upper level systems. Although all the new installations are carried out with feeder terminals, all the early technology can still be found from the distribution networks today. (Verho 2011)

The measurements of a feeder terminal include voltages, currents, frequency, real and reactive power, power factor and energy transferred. Modern IEDs also offer some power quality measurement features like voltage unbalance, harmonics and voltage variation. Almost every modern microprocessor based feeder terminal device include a disturbance recorder. It enables recording of the waveform of an analog quantity. Since the limited memory and processing capacity, the waveform can be recorded for a certain short time period. The recording can be triggered when the measured quantity falls or exceeds the chosen value or it can be triggered manually. The disturbance records are often provided in a standard format known as COMTRADE which enables the processing with third party software. (ABB 2011; Vamp 2011)

Another vital component in a distribution automation system is the RTU (Remote Terminal Unit). It is a data transfer device linking the substation to upper level systems. It gathers the measurements and other information from the substation equipment and transmits it to upper level systems and it also delivers controls and setting values from upper level systems to the substation equipment.

The remote operation of the network requires a reliable data transfer link between different devices and with the upper level systems. These practices are further discussed in sections 3.6 and 3.7.

3.3 Network automation

In addition to substation automation, there is also automation along the MV network. The network automation consists of all the automation in the MV network apart from the substation automation. Mainly, this means remotely controllable switching gear but also fault indicators are becoming more general. (Verho 2011)

Remotely controlled disconnectors have reduced significantly outage time experienced by the customers especially in long feeders in rural area networks with high interruption frequency. (Lakervi & Partanen 2008)

Though interruption time experienced by customers may be reduced with a remotely controlled disconnector, it does not have effect on the number of interruptions experienced by each customer. If also the interruption frequency is desired to improve by means of network automation, a remotely controlled recloser offers a solution. These are usually installed in the middle of the long overhead feeders in the rural area. The remote recloser divides the feeder into two independent protection zones. If a fault occurs in a line after the remote recloser, customers before it are not affected by the interruption. (Lakervi & Partanen 2008)

Network automation also includes fault detectors and measurement devices which are becoming more common for example in secondary substations. Especially in the cabled network, fault detectors can reduce fault location time significantly. The first generation fault locators were based on measuring the electromagnetic field near the conductors. The basic idea is to indicate whether the fault current passed the locator or not and iterate the fault location based on this information. The accuracy of the over current indicator based fault location is proportional to the number of the devices along the feeder. These devices were even capable of remote communication but in general the field crew had to access the fault locator locally since there was no communication system available in secondary substations. The next generation was including meters which were able to record the fault current value passing it but still the devices should be read locally. The devices such as Pihi (Elkamo Ltd.) were able to record the measured values for a certain period and when exported to a laptop, a more thorough analysis could be carried out. By these means, the DSO had information about the passed overloads of the secondary substation transformer for example. (Mörsky 1993; Löf 2009)

In addition to line faults, also some other events can be interesting. The development of the secondary substation monitoring devices has improved the possibilities to monitor distribution transformers. Especially in pad-mounted substations and transformers located in the basement of a building, a thermal overload is a common cause for a failure. However, the electrical quantities are not sufficient in all situations when analysing the thermal loading of the transformer. The ageing of the transformer is proportional to the temperature of the insulation of the transformer and in addition to loading currents, the ambient temperature has a major impact on the temperature of the transformer. Especially in the secondary substations located in the basement of a building with forced ventilation, the temperatures may rise very quickly in ventilation failure situations while the loads of the transformer may be relatively low. (Pylvänäinen 2010; Nieminen 2011)

Several vendors have developed secondary substation monitoring devices based on feeder terminal technology. These devices are simplified versions of a protection relay with versatile measurement features. The major advantage of this kind of approach is that these devices may be connected to the control system via a GPRS (General Packet Radio Service) connection for example and this enables real time measurements and alarms been sent to the control centre. Also fault location functionalities could be improved by adding more measurements along the feeder. There are also algorithms for locating earth faults which have been challenging to locate with primary substation equipment alone. These functions also require upper level functionalities. (Hyvärinen et al. 2009)

These systems are applied by several DSOs operating city area networks where the network is mainly cabled and field crew movement may be difficult during traffic peak hours. Another major advantage is the possibility to reduce transformer fire risk by monitoring the temperatures of the transformers in addition to loading. This is crucial especially to secondary substations located in the basements of apartment or commercial buildings. (Hyvärinen et al. 2009)

Nieminen (2011) has carried out a questionnaire about secondary substation automation needs and wishes for DSOs operating in Finnish city areas (EK12 group). The questionnaire consisted of 32 proposed secondary substation automation functionalities which the respondents graded in scale one to five. The clear top four functionalities were a fault locator with upper level system integration, remotely controllable switchgear, fire alarm for the secondary substation premises and monitoring ten minute averages of currents and voltages in secondary substation.

The secondary substation monitoring devices are able to measure the Total Harmonic Distortion (THD) of the transformer loading currents. Since the non-sinusoidal load strains the transformer more than pure sinusoidal load which are measured by standard, a more comprehensive monitoring of the transformer may be applied. (Pylvänäinen 2010)

3.4 Smart metering

In the scope of this thesis, customer automation is referred to smart metering or AMR (Automatic Meter Reading). At least in the future, customer automation includes a broader range of automation functionalities such as load control and HEMS (Home Energy Management System) but these are not interesting for the topic of this thesis. The term AMR is still in general use though the infrastructure enables such a wide range of functionalities in addition to reading the energy meters remotely.

The concept of remotely readable energy meters is fairly old. It has been exploited since late 1980's for the largest customers of a DSO. A drastic change has occurred in the late 2000's. According to the decision of the Council of State of Finland (5.2.2009/66), 80 % of the consumers should be involved in the remotely read hourly measured energy by the year 2014. However, Elenia has had smart meters installed in all of their 400,000 customers since 2009. While the infrastructure already exists, it is desired to exploit as comprehensively as possible. Numerous studies about AMR utilization have been carried out from various perspectives.

Smart metering enables not only energy consumption measurements in the hourly basis but also measurements for voltage quality, registration of outages and alarms. In addition to billing, hourly measured energy consumption may be used to generate individual load models for each customer. This enables more accurate load flow calculations compared with the previous method using customer type related standard load models. The state estimation of the distribution network may be improved with voltage quality measurements and alarms from the smart meters. This data enables novel algorithms to recognize such faults which traditional protection was not able to detect at all or location was inaccurate or unreliable. (Lakervi & Partanen 2008)

3.5 Information systems in distribution automation

In general, an information system means an entity which consists of devices, software, databases and the interconnection between these. Its tasks include gathering, handling, storing, analysing and relaying information. In certain context, the user of the information system may be seen as a part of the information system.

Focal information systems for network operation and their interconnections are presented in figure 3.4. The information transferred between the information system entity and the process is described as well as the related functions of each information system. Different vendors may have their own vision of the purpose of each system and this may result in overlapping features. Every system presented in the figure include a database of a sort. However, the main data warehouses are highlighted with a ”DB” block.

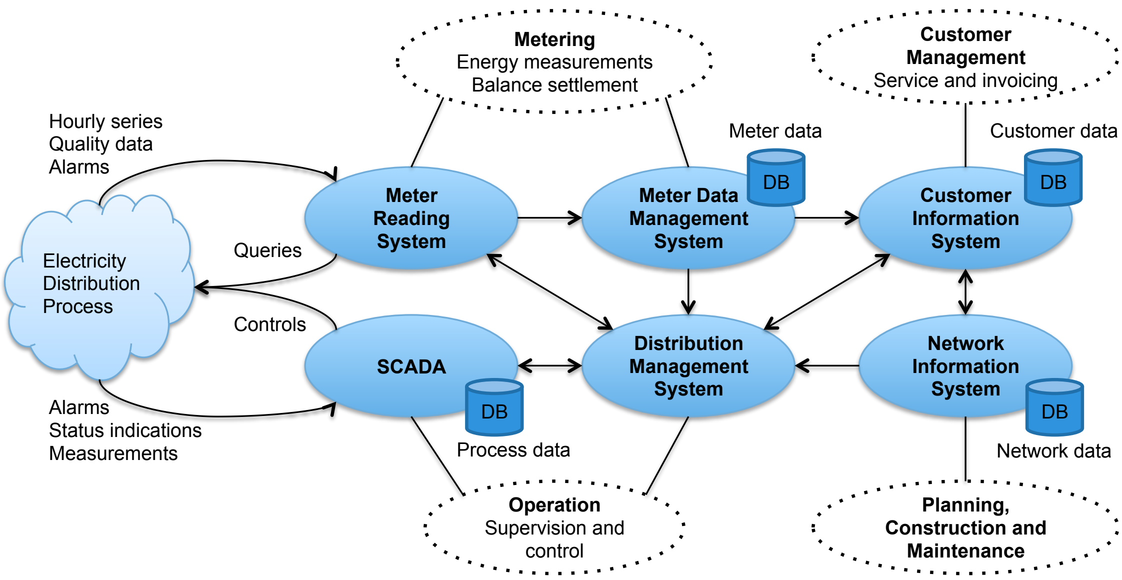


Figure 3.4. *Information systems of a DSO and their interconnection*

The novel solution for process data management presented later on in this thesis leans intensely on DSO's existing information systems. Therefore the present information system environment is described. In the following sections SCADA (Supervisory Control And Data Acquisition) system, Network Information System (NIS) and DMS (Distribution Management System) are discussed more thoroughly and other systems briefly.

3.5.1 SCADA

The SCADA is a system for distribution network operation, which main objectives are the real-time monitoring and control of the electricity distribution process. More precisely it acquires data from various sources, preprocesses and stores it to a database which makes it accessible to different users and other information systems. It is also used to relaying control signals to the process so it requires a two-way data transfer connection. A SCADA system consists of a master system, RTUs located in substations and communication between these. It has a user interface for the operators in the control centre and usually all the switchings are performed with it. (Northcote-Green & Wilson 2006)

The acquired data is handled as events. SCADA receives the events from remotely controlled devices automatically and the state values of manually operated devices are fed into the system by an operator. With all these events, the SCADA system maintains up to date information about the switching state of the distribution network which is essential for the operation of the network. The SCADA system operates in real-time and it is responsible for many crucial functions of the network operation. These set a high demand for the reliability of the system especially in the occasions of interruptions in other systems and simultaneous faults and events in the network. In principle, the electricity network could be operated without any other information systems but SCADA. The redundancy demand is often fulfilled with hot standby servers, communication front ends and operator desktops so that a failure in any component does not compromise the operation of the system. Also the power supply of the system is ensured with UPS (Uninterruptible Power Supply) devices. (Lakervi & Partanen 2008; Northcote-Green & Wilson 2006)

The gathered process data is stored to a process database. The database has high performance demands and therefore the capacity is often limited. The data often have a high rate of change and for that reason only values for a relatively short period are stored. Often the data is also archived to a historical database for further, non real-time based processing.

3.5.2 Network Information System

Network Information System is a name for a system which upholds information about network components, their economic and technical characteristics and the location of the components (Väre 2007, p. 48). NIS has its roots in network asset management and component databases. Later on information about geographical location and interconnection of the network components were added to the system. Therefore another common name for the system is AM/FM/GIS (Automated Mapping/Facilites Management/Geographical Information System). (Lakervi & Partanen 2008, p. 265) In this thesis, name NIS is preferred.

State of the art NIS consists of a network database, database management system and applications exploiting the database. With all the combined information, NIS is able to calculate steady state values for load flows and fault currents. The user interface is usually map-based and the results of a calculation can be presented illustratively on a map. (Lakervi & Partanen 2008)

In addition to data warehousing, other main tasks for a NIS are reporting, documentation, design and calculation. The network calculation can be divided into the calculation of the existing network and calculation of a designed network. The purpose of calculation of the existing network is to find out if the network meets the technical boundary conditions and it is operated in the most optimal way. At present a reliability analysis is often done to the existing network. These are altogether inputs to the long-term development of the distribution network. Also applications for maintenance, construction may be included. All these are handled with additional applications integrated into the NIS. The final ensemble depends on the vendor of the system and the need of the utility. (Väre 2007; Lakervi & Partanen 2008)

3.5.3 Distribution Management System

Distribution Management System (DMS), also known as Energy Management System (EMS) especially in North America, is a supporting tool for decision-making for the operational staff of a DSO. The main idea is to combine data from other systems and process it to gain advanced information to support the operation of the network. (Lakervi & Partanen 2008)

The key function for the DMS is integrating data from both SCADA and NIS to produce a real-time view of the distribution network system. A static network model is built from the data available in NIS. This includes data about component characteristic values, location and interconnection. When real-time measurements and status indications are added to the static model, the result is a dynamic model including the information about the electrical and topological state of the distribution network. Other important data sources are Customer Information System (CIS) and Meter Data Management System (MDMS). The CIS is used to improve the customer service. The operator may locate the calling customer according to his/her name and gain information about the distribution network status related to this customer and data about past outages and power quality. (Verho et al. 1997)

In Finland, the development of the DMS has gone through five layers: a user interface, application functions, models and calculation methods, data interfaces and data sources including external systems. When data from various sources is combined, more comprehensive calculations and estimations may be carried out compared with calculations made in a separate system. The applications of the DMS may be categorized as follows: Network state monitoring, operations planning and fault management. Network state monitoring includes applications for topology management, electrical state monitoring, simulations and field crew management. For operations planning, DMS includes different optimization applications and tools for switching planning. The basic functionalities for fault management are event analysis for different fault types, fault location based on data from the relay, switching planning for fault isolation and power restoration, outage reporting and customer service during the fault. (Verho et al. 1997)

The Finnish approach has strongly relied on distribution automation. This approach has been entitled to a non-customer oriented approach, since it does not require any actions from the customers. However, other approaches for the DMS development can be found. A customer oriented approach was based on trouble call management systems. In these systems, the faults were located according to the location of customers reporting the fault. Altogether, in present DMS configurations all these functions are brought together resulting both customer oriented and distribution automation utilizing system. The basic functionalities of the DMS can also be categorized as follows: Control room operations management based on real-time network diagram display, full SCADA integration providing information about the whole distribution network, advanced applications such as load flow and fault calculations and the outage management. (Northcote-Green & Wilson 2006, p. 31-39)

Applications of the DMS are developing continuously while more information about the distribution network becomes available. An example is a FLIR (Fault Location, Isolation and Restoration) feature which Elenia has implemented at the end of the year 2011. After a half year in production, FLIR has isolated over 400 faults and thus eased the work of control centre personnel.

At present, the user interface to the distribution network consists of both the SCADA system and the DMS. The actions are carried out with SCADA although the DMS's interface to SCADA enables the same actions being performed from the DMS. The DMS is used only for a supportive tool. The development vision is that there should be only one system forming the user interface and that system would be the DMS while SCADA is left to the background.

3.5.4 Other systems

Depending on the utility, a wide range of other information systems may be in use. In Elenia, a strategic approach is the extensive exploitation of information systems. The interesting information systems, in addition to ones described above, relating this study are the customer information system (CIS), meter reading system (MRS) and meter data management system (MDMS).

Previously, the CIS was focused on billing but after the deregulation of the electricity market these functionalities were inadequate. Nowadays a customer information system is a wide collection of applications related to customer management and more comprehensive term Customer Relationship Management (CRM) is also applied. At present, the main objectives of this system have increased covering now billing, customer service and guidance, management of contracts and marketing. CIS may be considered even the most important information system at the business point of view because the billing and economics are based on the customer information system (ABB 2000). The energy consumption data of CIS is also used for the load estimation of the network although smart metering and meter data management system (MDMS) is taking this responsibility. (Toivonen 2004)

Since the smart metering has become more general and the measurement is done in the hourly basis, the amount of measurement data has increased exponentially. The customer information systems were not capable of handling the measurement data and specific information systems have been developed for those purposes. The systems in question are Meter Reading System (MRS) and Meter Data Management System.

A meter reading system consists of smart metering devices at the customers' premises, a data transfer system and a central system gathering the data. Most common data transfer media is GPRS and PLC (Power Line Communication). Since different vendors often have proprietary communication protocols for their equipment, parallel systems are required if a DSO has multiple vendors' meters (Kärkkäinen et al. 2006). When the data is collected, it is delivered to the meter data management system for further processing.

The foundation of a meter data management system is formed by measurement database and communication interfaces to meter reading systems. The database maintains the meter readings, register reads, interval records, outage and restoration events and event logs. The data collected from different vendors' systems is converted to the same format. In order to utilize the data as widely as possible, the system should provide access to the data for other systems as well. The system might also include tools for data processing like analysis, estimation, validation and reporting applications. (eMeter 2012)

3.6 Information system integration

The business environment has developed and is still developing and this requires flexibility from DSOs. The flexibility from a DSO requires flexibility also from the information systems. The information systems of a DSO include large amounts of data. A flexible utilization of this data requires integration and communication between systems since the upholding the same information in multiple locations is inefficient and the risk to lose the integrity of data is high. (Becker et al. 2000)

The basic idea of this thesis is also the flexible utilization of data already existing in the DSO's present systems, so some integration issues are encountered. In following, some data exchange principles are discussed as well as some principles of information networks. However, the discussion is maintained at a general level neglecting communication protocols although the field communication system used by Elenia is presented in section 4.1.

The operational environment of information systems is typically consisted of systems from different vendors. Since no common standard for system integration or communication is available, this has led to case-specific point-to-point integration as a need for integration has come up. Toivonen et al. (2005) rises the lack of open interfaces as the biggest problem in the information system environment in the electric utility industry. Software updates cause also problems since they weaken the interfaces. Software vendors' business attitude might cause also challenges from the DSO's point of view. Vendors concentrate on selling their own products instead of cooperating with other vendors competing in the same field of business.

The need for the integration arose particularly at the time when distribution management systems were introduced. The nature of the DMS is to gather and combine data from different sources acting like an information hub in the system ensemble. Therefore it was concerned with many types of data exchange interfaces which might be a challenge on the implementation level but also a possibility for the overall. (Keski-Keturi 2011)

A typical DSO's control centre carries multiple proprietary protocols and case-specific interfaces. At times there are custom solutions tailored for a single utility company since the similar software combination is not used anywhere else. Also the implementations may be inheritance from several decades and various technologies with outdated or lacking documentation. Needless to say that changes made to these kind of environments could be very expensive requiring special development work and possibly involvement of an external consultant. (Keski-Keturi 2011)

While the complexity of the system environment increases, the risk for system crashing increases as well. In the basic utility business like electric supply it is crucial to ensure the reliability of the system entity as far as possibly because the consequences of a system failure are unacceptable.

3.6.1 Data exchange

Data exchange methods enable data transfer between information systems. The variety of exchange methods exist since the need for the data exchange differ by nature. The suitable and the most efficient method for the exchange depends on the volume of data, the system environment and the characteristics of the exchange. The exchange could have a real-time or an on demand requirement for the transfer, or in some cases it is sufficient to perform it by scheduled batch run. Methods discussed here are file transfer-based data exchange, database sharing and different middleware options.

File transfer-based data exchange

File transfer-based data exchange is the oldest and the simplest method for creating a communication interface between information systems. The basic idea is that one system creates a file including the data wished to transfer. The file created is moved to a location where another system has access and it imports the data. The systems can operate under the same operating system with the same file system where no file transfer is needed or the files can be transferred over the network with FTP (File Transfer Protocol) for example. The files may be categorized into binary files and human-readable text files. Binary files include for example numeric types describing the internal memory representation of the data. Binary files may be used if the data exchange occurs in similar system environment. The binary files are difficult to parse if the specific format is unknown. (Manouvrier & Ménard 2008)

Text files can be further divided according to their structure to flat formatted and hierarchical files. Flat formatted files can have fixed length for items, variable length with a counter indicating the length of each item or items may be separated with a specific delimiter. A commonly known example of hierarchical files is XML (Extensible Markup Language) file type. Hierarchical file types enable the better reusability of the files but the performance is poorer in comparison with flat files. (Manouvrier & Ménard 2008)

Database sharing

A database is a shared collection of logically related data with the description of it. The main principle is to share data for multiple users with a minimum amount of duplication. The description of the data is called metadata - data about data. A database system consists of the database itself, database management system (DBMS) and applications interacting with the database. The database management system is the tool for controlling the database. It enables users to define, create, maintain and control access to the database. A specific query language is used for the controlling. The most common query language is the Structured Query Language

(SQL). (Connolly & Begg 2005)

Many advantages support the use of database systems. Some of the major advantages compared with file-based systems are the control of data redundancy and following data consistency. Sharing the data for multiple users is simple with advanced access control and it enables better usability for the data. The potential complexity and the size of a database system may be seen as disadvantages. In a poorly designed database also the performance may be worse despite the optimized algorithms provided with the system. (Connolly & Begg 2005)

Adapters, middleware and APIs

Adapters are used to convert the format of the data if no common communication or data exchange method exist between information systems.For example, if two information systems need to be integrated: One using file-based data exchange and another message-based communication which is discussed in more detail below. The objective of the adapter is to use appropriate transformations and exchange methods in order to interconnect the systems without the need for the modification of the existing systems. (Manouvrier & Ménard 2008)

Another type of communication is message-based data exchange. Usually message-based communication is carried out with a middleware located between the systems as a translator. The main idea is to hide the complexity caused by different devices, operating systems and networks under a common interface and hence make the maintenance of the whole much simpler. In other words, message-based communication raises the abstraction level. In general they offer data exchange service by receiving messages from one application and relaying to the right recipient. In addition to data exchange, they may offer different solutions for conversions, surveillance and security. A disadvantage adding another system in the middle of the data flow might be the deteriorated performance of the overall system. (Tanenbaum & Van Steen 2007; McNurlin et al. 2009)

A simple type of middleware is remote procedure calls (RPC). In principle, it offers a possibility to call a function in one application so that the execution of the function is performed in another system. The communication is always between two applications which are called the client and the server. RPCs are widely adapted in distributed systems. Because the synchronous nature of the RPC method, it is not always an appropriate method since the client is blocked until the request is processed. (Tanenbaum & Van Steen 2007)

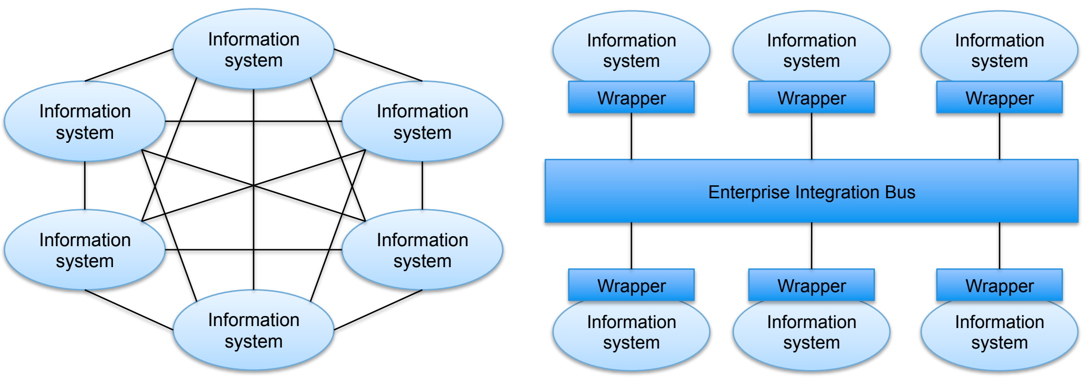
The message-oriented communication solves some issues which synchronous RPC might arise. The basic idea is to insert messages to specific queues instead of synchronous processing. The message-oriented middleware (MOM) takes care that the messages are delivered to their recipients eventually. MOM might also encompass services for the confirmation of the delivery and better recovery from failures. It has better scalability compared with RPC. (Tanenbaum & Van Steen 2007)

Application Program Interface (API) is an interface like the middleware. The difference is that API lies at program code level which allows the programmer to write to, connect to and utilize the interfaces of the software in their application. (McNurlin et al. 2009) These applications may consider the operating system, other information systems or another applications in the same system.

3.6.2 Integration solutions

While implementing a novel information system into an existing system environment, one should have some understanding about the ensemble. Like stated before, the information system environment has developed from a number of separated systems towards an integrated ensemble. New interconnections between systems have been implemented as more requirements for the data from different sources have been formed because of the development of high level applications. The result is eventually a mesh type network which consists of $N(N-1)/2$ interconnections, where N is the number of information systems. A mesh network is illustrated in figure 3.5(a).

There is no single integration solution which fits in every situation. System integration is nor a product which can be bought as a complete product. The characteristics of data exchange demands vary and therefore the suitable methods for the exchange as well. The integration solution should support different data exchange methods while the structure of the system is explicit and simple enough for the maintenance point of view.



(a) Mesh network (b) Integration bus

Figure 3.5. *Two common approaches to information system integration adapted from Becker et al. (2000)*

A commonly approved development trend by the industry is a service bus based integration, so called Enterprise Service Bus (ESB) (Becker et al. 2000; EPRI 2009; Koto 2010). A transition towards Enterprise Service Bus based integration sets some requirements for the new systems. In principle, this requires a unified data model being used among the information systems instead of vendor specific solutions.

Ongoing standardization tries to satisfy this requirement with Common Information Model (CIM) which is covered in more detail in section 5.1. Existing systems not capable of operating with this data model by default are extended with a specific wrapper acting as a translator between the system and the bus. (Becker et al. 2000) The principle of bus-based integration is illustrated in figure 3.5(b).

3.7 Communications

Communication is a vital part of distribution automation with centralized control. The data produced by different sources along the distribution network is not exploitable if the link between the sources and the processing system is missing. In general the requirements for the communication are related to reliability and accessibility. The capacity of the communication system has not traditionally been as essential. Since the measurements and monitoring are expanding with an increased sample frequency and novel applications, the amount of data is increasing and more bandwidth is also needed. (Northcote-Green & Wilson 2006)

Electric utility industry has used a great variety of media for communication. This is a consequence from different demands for the quality of service of the communication and development of the technology over the years. A specific requirement to the distribution automation communications is that the system should be accessible in case of storms and other disturbances when the other basic infrastructure is interrupted. Therefore exploiting the public communication infrastructure is doubtful while these systems are not redundant enough.

The physical links may be categorized into wired and wireless types. Some of the most common systems and their features used in Finland are present in table 3.1 though some of them are old-fashioned and rare nowadays.

Fibre optics is a popular choice since it is possible to use optical fibre composite overhead ground wires (OPGW) for high voltage regional transmission networks. These are lightning shielding conductors with a tubular structure with one or more optical fibres surrounded by conducting wires. The light pulse carrying data on optical wires is not disturbed by the magnetic field generated by the electrical current of a lightning impulse or the load current of the phase conductors. (Kannus 2012)

The throughput of a fibre-optic link depends on the technology used, the distance the data is transferred and the number of the fibres in the link. One single-mode fibre used in high distances is capable to the throughput of several Gbps. For a multimode fibre, the throughput is less and therefore it is used for only short distances, between the devices of a substation for example. With multiple fibres and various wavelengths used the capacity may be several Tbps. (Uotila 2010) The capacity of the fibre optics is so massive at the DSO's point of view that often the capacity is leased to a telecommunication utility and the DSO is just a client of that utility.

Table 3.1. *The most common communication media and their typical data transfer rates (ABB 2000; Northcote-Green & Wilson 2006; Uotila 2010; Verho 2011; Skylogic 2012; GSMA 2012)*

Media	**Transfer rate**
Wired	
Fibre optics	2 Gbps - 3 Tbps
Local Area Network (LAN)	10 Mbps - 1 Gbps
Data services in public networks	$\leq$ 1 Gbps
Leased line	9,6 kbps - 2 Mbps
Integrated Services Digital Network (ISDN)	64 kbps - 128 kbps
Dial-up line	$\leq$ 64 kbps
Power Line Carrier (PLC)	15 bps - 36 kbps
Wireless	
Satellite link (GEO-system)	$\leq$ 10 Mbps
Radio link	$\leq$ 2 Mbps
Radio telephone	1200 kbps
VHF/UHF narrow bandwidth data radio	9,6 kbps - 19,2 kbps
Global System for Mobile Communication (GSM)	9,6 kbps
General Packet Radio Service (GPRS)	40 kbps
Enhanced Data rates for GSM Evolution (EDGE)	400 kbps
High Speed Packet Access (HSPA)	10 Mbps
Long Term Evolution (LTE)	100 Mbps

A great variety of wired connection protocols are applied over the years. They differ in bandwidth, terminal equipment and wire type requirements and limitations with the distances. Power Line Carrier (PLC) uses the distribution line, MV or LV network, as a transmission path for the signal. The advantage is already existing complete network to the all points of the network. The greatest drawbacks are the relatively low bandwidth since the electricity network is optimized to operate in 50 Hz and therefore there are challenges with communication frequencies usually much higher than that. Another limitation for the use of PLC in distribution automation and especially in fault management is the dependency of the power line. In occasion of a fault, when the connection is needed, it is not available. At present in distribution utilities, PLC is mainly exploited in smart meter communication. (Northcote-Green & Wilson 2006)

Over the years, there have been also multiple wireless solutions in use. The solutions differ according the application since the requirements for bandwidth, latency and coverage vary. Radio link has been used between the substations in rural area and the control centre (Verho 2011). In disconnector stations the wireless communication evolution has gone through the radio telephone network, VHF (Very High Frequency) and UHF (Ultra High Frequency) data radio systems and the most recently GPRS or similar packet data radio services. (Northcote-Green & Wilson 2006; Verho 2011)

Satellite links have global coverage and they offer a relatively independent technology compared with regional solutions. The capacity of the connection is dependent of the need and it may vary significantly. The data signal has to travel long distances and therefore the latency of the satellite system may form an issue. The most common applications use the geostationary earth-orbiting (GEO) satellite fleet. These satellites maintain their position to the earth, so the motion of ground antennas is not needed.

4. PRESENT STATE OF PROCESS DATA MANAGEMENT IN ELENIA

The distribution automation system was presented in general in chapter 3. This chapter focuses on studying how these possibilities are utilized in Elenia. At first, the communcation network of Elenia is presented in section 4.1 since it has a key role in transmitting the data from the network to the centralized system, where it is exploited. Sections 4.2 - 4.4 present the data collected from each part of the distribution network of Elenia at present. Section 4.5 covers a study about the exploitation of the collected data and development visions which exist among different users. These visions are refined to functions and their resources in section 4.6.

4.1 Communication network

Since Elenia is operating mainly in rural areas, the distances between substations and other connection points are relatively long. Elenia has acquired its network assets within small parts and previously there were tens of data exchange protocols and media used. Elenia does not have its whole distribution area covered by its own regional transmission network and therefore there is no OPGW connection available in substations. Nor a comprehensive fixed line network exists and building such is not economically reasonable at present. For these reasons, the communication network was renewed with wireless technologies. The current field communication system used by Elenia is presented in figure 4.1. The whole communication system is outsourced to a service provider, who carried out the renewal project for the whole communication network during 2009-2011. The contractor owns and maintains the system as well as chooses the suitable technologies to meet the service-level agreements set by Elenia.

The link between the control centre and substations is crucial for network operation and therefore it is duplicated. The primary connection uses 3G wireless broadband of the cellular network because of greater bandwidth and lower latency compared with the satellite connection. To increase redundancy, two separate network service providers are involved. Each connection point can establish the connection using the network service provider which has better coverage at that point in that particular moment. This is also illustrated in the figure. At present, the 3G network connection provides bandwidth mentioned in the figure. The bandwidth depends considerably on the network coverage at that point, which increases the

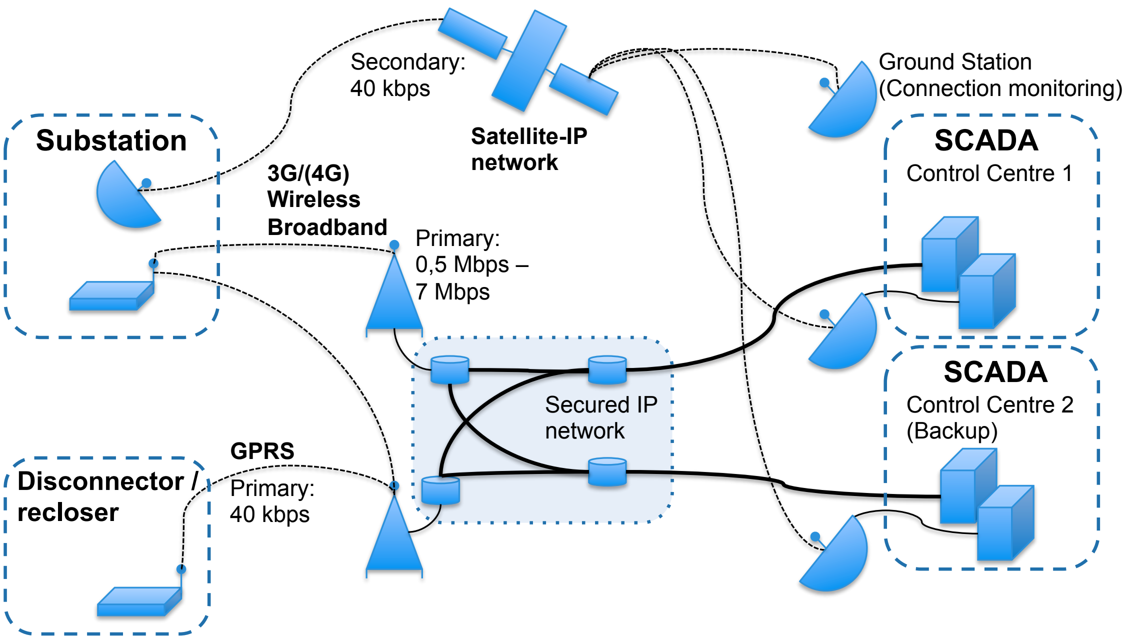


Figure 4.1. *The field communication system used by Elenia*

range of variation in the bandwidth along the network. The coverage is extended by the network operators continuously and transition to 4G technology is expected in a few years. The devices installed in the substations are capable of handling 4G connections, which will provide the bandwidth of tens of Mbps. In case of an interruption in 3G connection, an automated changing to the satellite link is carried out. The network switching stations and other points with the network automation are connected via GPRS and there is no back up connection available. If the connection is interrupted, a field crew visit may be needed to complete the switching.

Traditionally, the communication network has been a bottle neck for extensive process data utilization such as fetching disturbance records in a large scale. In conclusion it can be stated that the present communication network used in Elenia is capable of meeting the present and future demands of transferring continuously increasing data volume.

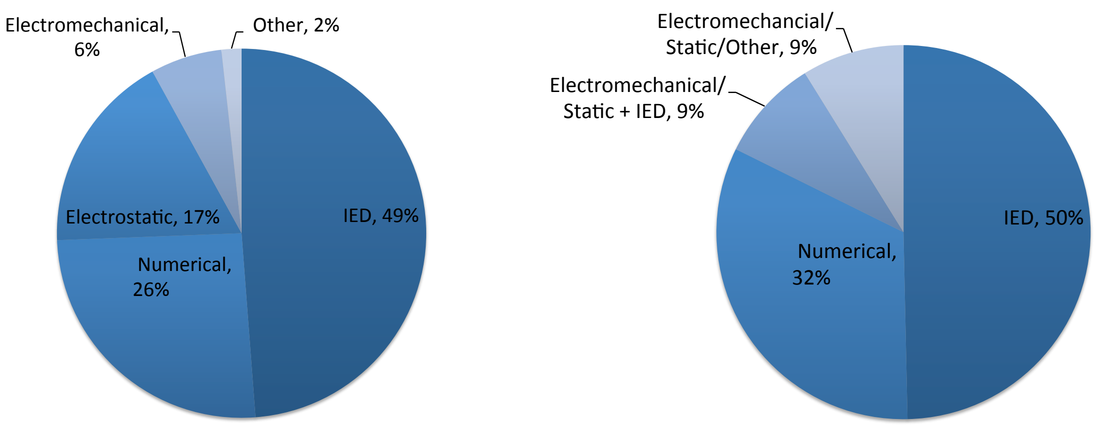
4.2 Substations

The foundation of the process data consists of real-time measurements, status values, alarms and control signals transferred between the process and SCADA system. The main purpose of this data is to enable centralized operation of the network. The vast majority of this data is gathered from substations. The data needed to enable the centralized operation of the network does not include condition related data. For this reason, specific condition data has been gathered relatively little but this is on the rise. In addition to these, also disturbance records and quality data can be collected. For a more comprehensive view, the data types collected are presented in table 4.1 with some examples. Although the data gathered from the network is stored to a historical database, the exploitation of the data mainly happens in real-time in the network control centre. If some abnormal events occurred, the historical data could be processed manually while looking for the explanation. The data is not systematically analysed since there have not been tools available.

Table 4.1. *The data types collected with SCADA at present*

Type	Examples
Status value	Circuit breakers, disconnectors
Alarm	Relay tripping, over or under voltage
Control	Control signals for switching devices from NCC
Measurement	Currents, voltages, powers
Disturbance record	Selected quantities concerning a disturbance
Quality data	Interruptions, voltage sags and swells

The data available from the substations is dependent on the technology used in the substation. The recent generation of IEDs enables a great variety of measurement features and communication options to the upper level systems. The devices of the previous generations do not enable as much data collection and therefore there are fewer possibilities for advanced analysis. The substation technology can be divided into four generations according to the type of protection relays. These types were introduced in section 3.2. The distribution of protection relay generations in Elenia at the end of 2011 is presented in figure 4.2(a). The total amount of relays included in the figure is 1996. In figure 4.2(b), substations of Elenia are categorized according to their relay technology.



(a) Distribution of protection relay generations in Elenia (1996 pieces in total)

(b) Substations categorized according to relay technology (147 pieces in total)

Figure 4.2. *Relay generations in substations of Elenia*

Half of the substations are equipped with IEDs and 33 % with numerical relays in all bays. 18 % of the substations have electromechanical or static relays which are similar from the SCADA point of view. Half of these substations have a modern IED installed in the feeder bay enabling fault reactance measurement and delivery to DMS for fault location calculation, for example. The total number of substations involved in the study was 147. In conclusion, it can be stated that the modern substation automation covers the network more extensively than the total amount of different relay types indicates.

In figures 4.3-4.5, an annual accrual of events and alarms from substations with different types of relays is presented. Events are divided into three classes according to their SCADA prioritization. The alarms are divided into two classes only with the most recent type of relays. With the older technology, there is only one class for the alarms. The prioritization of the events has so far been inconsistent. In practice, this means that an event for a similar occurrence from two substations may have different priority classes. This affects the distribution of the event classes.

The categorization and the total amount of events are presented in table 4.2. The number of the feeder bays of each substation and the total number of different events during the studied period are also included in the table. To gain some information about the development of the process data, a fraction of event types and number of bays is calculated. The result shows that the more recent technology is used in feeder bays, the more data can be collected. The correlation is not absolute but some relation can be seen in the increasing amount of data gathered. The events include both status values and control signals. Depending on the type of the event, there might be also a measurement attached. However, there is a great variety of measurements, which are not handled as events and therefore they are not included in the following.

Table 4.2. *The categorization of SCADA events and annual accrual for three substations*

Type of relays	**Bays**	**Event types**	**Types / Bays**	**Events** Lo	Med	Hi	**Alarms**	**Total**
Electromechanical	21	113	5.4	4361	303	525	347	5536
Numerical	13	210	16.2	2812	1670	1228	988	6698
IED	10	183	18.3	3667	1026	245	259	5197

The events are categorized for this thesis according to their source and a few simplifications are made to clarify the main point. The events concerning the state change of the on-load tap changer (OLTC) are neglected from the following charts from the stations where it is registered. This is because of the large number of events of this type. In the substation with electromechanical relays, OLTC operation covers 83 % of all events from the substation. In the substation with IEDs, OLTC events cover 52 % of all events. Also the spare feeder bay events are neglected since they are not interesting. The substation with electromechanical relays does not have earth fault current compensation devices and therefore there are no events concerning Petersen coil. In two other substations, such devices exist and the majority of the events concerning Petersen coil are related to the normal operation of the compensation device. All the neglected data is however included in the table above.

Naturally, the amount of events varies over the years and the absolute number of different events is not interesting. The differences between data collected from substations with technology of different generations should be studied instead. Also the number of line feeders have effect on the total number of events from a substation.

Faults occurred during the studied time period have a considerable effect on the total number of events in a substation. The number of faults in each studied substation are collected to table 4.3. The figures consist of fast reclosings, delayed reclosings and permanent faults in HV and MV network which led to a circuit breaker operation. The faults are also examined with the number of line feeders in each substation. This gives some information about the fault frequency in each substation. If this is compared with the total amount of events in table 4.2, a correlation with the number of faults and the total number of events in a substation can be seen.

Table 4.3. *Faults during the time period in studied substations*

Substation	**Feeders**	**Faults**	$\frac{\textbf{Faults}}{\textbf{Feeders}}$
Electromechanical	7	76	10,86
Numerical	8	91	11,38
IED	5	40	8,00

In figures 4.3-4.5, the sources marked with E are HV bays and sources with J are MV bays. The MV bays are typical line feeders unless otherwise stated. The feeders are consisted of different network types: Cable, overhead line or a mixture of them. All of the substations are equipped with a single primary transformer.

4.2.1 Electromechanical and static relays

The electromechanical relays represent the oldest technology in use. There are still few substations where the protection is carried out by these ancient devices. In some substations, devices from this generation act as backup protection. Electromechanical relays do not offer any measurements or communication features by themselves and all the data gathered from these substations are done with auxiliary relays or more recent measurement devices added to the substation afterwards. In Elenia, the last few primary substations with the electromechanical relays are going to be renovated with new technology IEDs in a few years but, however, some switching stations and customer-owned substations will still be equipped with these old-fashioned devices for a long time. At the SCADA point of view, the static relays are similar to the electromechanical relays since they do not offer any measurements or other data by themselves and they cannot be connected to the station bus. Like in the case with electromechanical relays, status values are collected with auxiliary relays and measurements with additional devices. An annual accrual of the events of a substation with electromechanical relays is represented in figure 4.3.

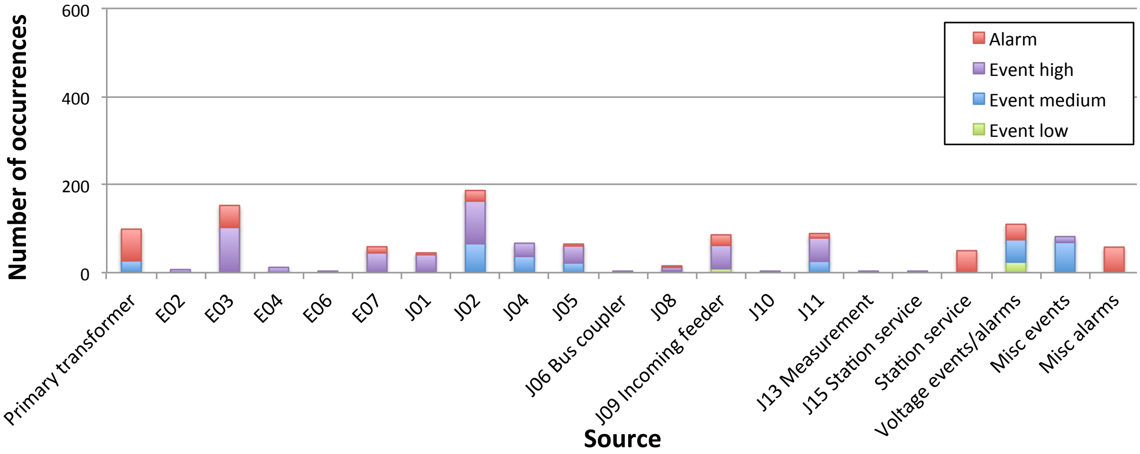


Figure 4.3. *Events of a year from a substation equipped with electromechanical relays*

In this substation, like in the majority of the substations of Elenia, there is a modern IED installed in the bay feeding the busbar (J09 Incoming feeder), even though other feeders are equipped with older technology. This enables, for example, measuring the fault reactance in case of an interruption. Even though the modern IED would enable additional data to be collected, relay pick-ups for example, these are not utilized and therefore the number of occurrences does not stand out in the figure. The substation has 3 incoming HV feeders and therefore there are more HV terminals than in the other two substations. The substation has seven outgoing MV line feeders.

The data concerning the feeders consists of the status values and control signals of the relay which are hard-wired to the RTU. Alarms for overcurrent of the feeders and busbar voltage abnormalities are also available. Voltage alarms include under- and overvoltage alarms of the busbar and alarm for the zero sequence voltage. There is no data about the pick-up of the relays or any other further details about the feeder terminal.

4.2.2 Numerical relays

Numerical relays are relatively recent technology and in addition to their main function as a protection device, they also offer some additional features like self-diagnosis and communication features. An annual accrual of the events of a substation with numerical relays is represented in figure 4.4. The substation has a single incoming HV feeder and eight outgoing MV feeders. There is also a shunt capacitor battery for reactive power compensation.

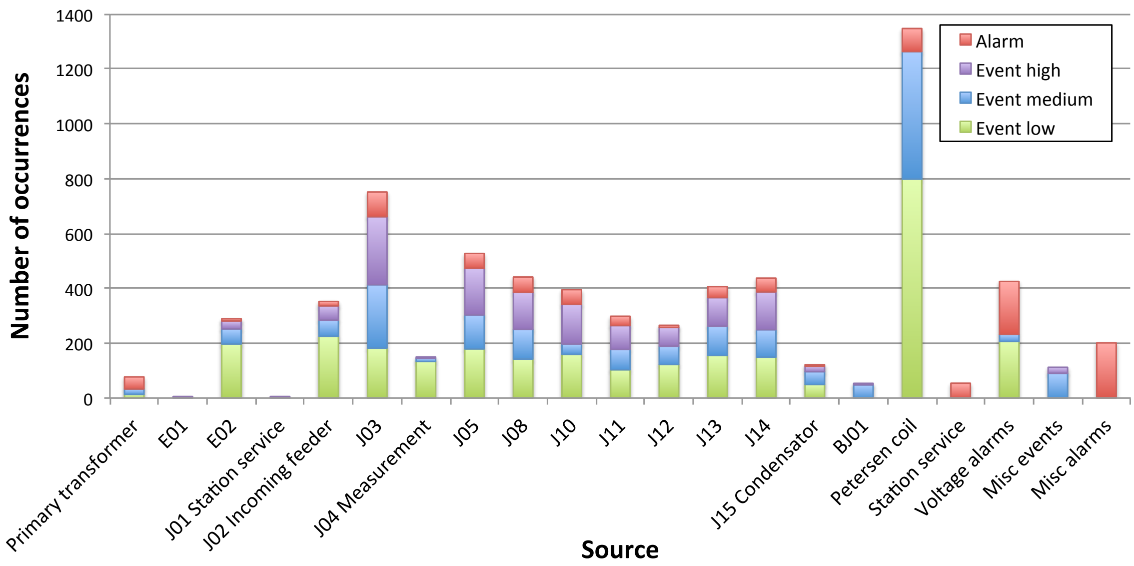


Figure 4.4. *Events of a year from a substation equipped with numeric relays*

The data concerning the feeders consists of status values, control signals and measurements. Also data about relay pick-up and tripping at each protection level is transferred to the SCADA. Alerts are available from voltage and current abnormalities. There are also more remotely controllable features like turning automatic reclosings on or off. In short-circuit faults, the feeder terminal measures the fault current and transfers it to DMS via SCADA for fault location calculation. The relays are connected with optic fibres to the RTU exploiting SPA-bus. Excluding the events from feeder terminals, many status values are still collected with auxiliary relays and measurement devices, for example faults and abnormalities of the station service DC system.

4.2.3 IEDs

IEDs represent the most recent technology in the substation automation. An IED in a feeder terminal may be set to supervise and collect a wide range of quantities. An annual accrual of the events of a substation with IEDs is represented in figure 4.5. The substation has a single incoming HV feeder and five outgoing MV feeders.

The data concerning the feeders consists of status values, control signals and measurements. Compared with the numeric relays, there are more states supervised and more measured quantities delivered. Also data about relay pick-up and tripping at each protection level is transferred to the SCADA. The IED has additional inputs for the status values of the other components of the bay and information about their state can be transferred to the SCADA via the IED. In short-circuit faults, the IED measures the reactance of the faulted feeder and transfers it to DMS via SCADA for fault location calculation. The IED has an integrated fault location function but it is not applied since more accurate result can be achieved with DMS. In most recent solutions, IEDs are connected to a network switch via ethernet.

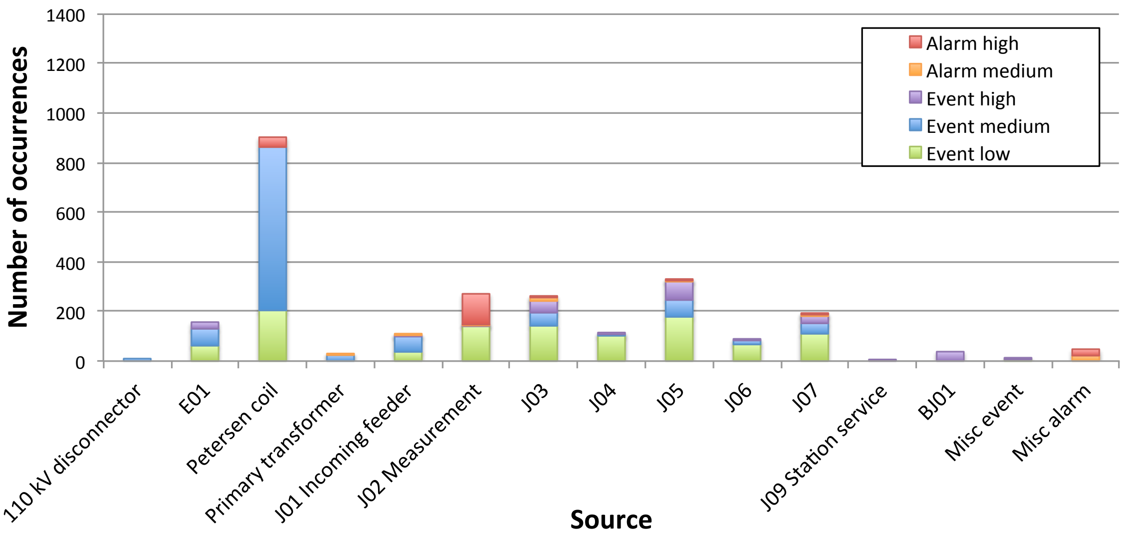


Figure 4.5. *Events of a year from a substation equipped with IEDs*

This represents a station bus applying substation automation standard IEC 61850. However, excluding the feeder terminals, a variety of additional data is still gathered with auxiliary relays and hard-wired to the RTU since those devices do not have suitable communication options.

4.2.4 Disturbance records

A more advanced approach to the exploitation of process data is the use of disturbance records. Like presented in section 3.2, almost every modern IED-based feeder terminal has a disturbance recorder included. In Elenia, there has been a specification for disturbance recorder settings since the beginning of 2012. Before that, disturbance recorders have been set with the perception of each fitter. So, at present the acquisition of disturbance records cannot be guaranteed even if the substation has capable devices. However, the situation will be improved in a few years, as the settings are corrected during periodical testings. (Pekkala & Uurasjärvi 2012)

At present, SCADA system is not capable of fetching disturbance records straight from the IED. So, disturbance records should be fetched via the service bus of the substation or even visit the site and manually export the data from the feeder terminal with proprietary software. Despite the disturbance records can be stored and viewed in a standard format, COMTRADE, vendor-specific systems are still needed and the fetching requires special know-how and it cannot be carried out in the network control centre. (Koivuniemi 2012)

At present in Elenia, disturbance records are mainly used after an unusual interruption or another abnormal event and no systematical analysis is done since the fetching is so complicated. Although the exploitation of disturbance records is studied relatively widely, automatic analyzing algorithms have not been widely applied. In most cases, the analysis is carried out visually by personnel with special expertise.

4.3 Network automation

In addition to substations, data is also available from modern remotely controlled disconnector stations and network switches. By far, the data from the network is collected from disconnector and switching stations. Elenia has not installed secondary substation measurements so far but there are interests in low-cost fault indicators. These could be included in the new-building concept of secondary substations. Some secondary substations are equipped with remotely controlled disconnectors and therefore a communication link to SCADA already exists. In these cases, adding a fault indicator afterwards would be economically reasonable.

In the next two subsections, an annual accrual of the events from a network switch and a modern disconnector station are presented.

4.3.1 Disconnector stations

The data from the network automation has its main focus on operational purposes. However, compared with the substations, there is even more condition related data available from the modern type of disconnector stations. For example, travel time during the state change of the disconnector, energy consumed by the motor during the state change and battery charging voltage and current are specific condition-related quantities measured at disconnector stations (Viola Systems 2012). Even if there is condition data available, the analysis is carried out manually by the maintenance personnel and there is no sophisticated analysing algorithm generated.

Elenia has three different types of disconnectors installed. The most recent generation is included in the field communication system and provides the features described above. Elenia has about 2600 disconnectors of this type. In addition to these, there are 410 pieces of previous generation of remote controlled disconnectors in use. These provide some of the features described above but not as extensively as the most recent ones. The majority of disconnectors are not equipped with any remote functions or measurements and are totally manual. At present, there are little over 11 000 pieces of this type of disconnectors. The manual operated disconnectors are renewed with the fieldcom-type disconnectors gradually. However, the majority will probably remain manually operated even forever. Manually by live work operated separation points may be held a certain type of disconnectors as well. Naturally, these do not include any measurements or indications about their state and these are used only if there are not suitable disconnectors nearby. Elenia has little over 2800 of these installed along the overhead lines. The distribution of the disconnector types is presented in figure 4.6.

In figure 4.7 is presented an annual accrual of events from a disconnector station with three disconnectors. The events related to the SCADA connection establishment and closure are neglected since there have been over 3000 occurrences of such event during the studied period.

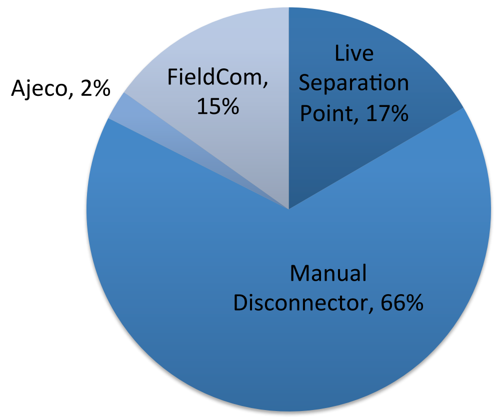


Figure 4.6. *The distribution of different types of disconnectors in Elenia*

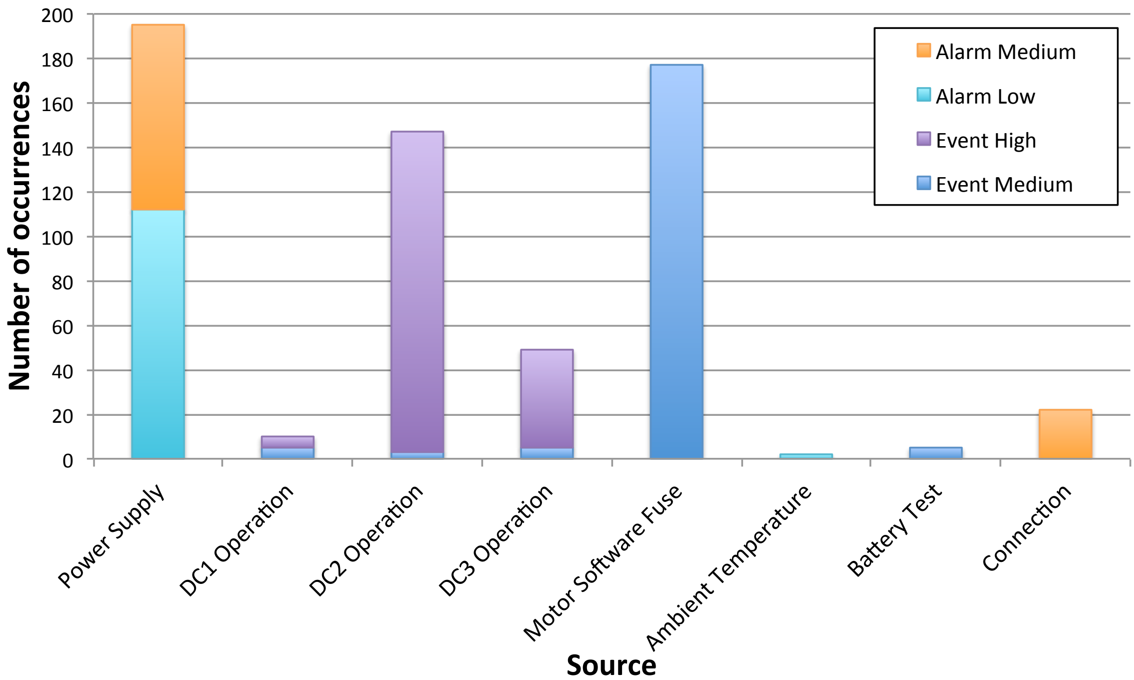


Figure 4.7. *Events of a year from a disconnector station with three disconnectors*

The data of the studied disconnector station is divided into four classes: Two classes for alarms and two for events. Power supply events include alarms for missing power supply and events related to the battery charger operation. The disconnector station equipment include a battery test feature and it is performed once a year. The target is to measure the capacity of the batteries. The operation category consists of the events of the normal operation of the disconnector. These are status values and control signals, for example. The ambient temperature of the station cabinet is measured and alarms for a certain threshold exceeding are also configured. The remaining connection alerts are related to longer term interruptions in SCADA connection.

There are no measurements for line voltages or currents at disconnector stations. The measurement of the voltages and currents of the motor of the disconnector enables a software fuse feature. If the movement of the disconnector is stiff, the energy consumed by the motor increases and it could trip the motor protection fuse. This fuse has to be reset locally and therefore it requires a field crew visit. The software fuse stops the motor and prevents the actual protection from tripping. The software fuse can be reset remotely and no crew visit is needed. The number of the software fuse operations has been relatively high during the studied time period and it does not represent the typical conditions.

4.3.2 Remote reclosers

The data from a remote recloser installed along the feeder does not include as much condition related data as disconnector stations. However, there are functions to measure the wearing of the circuit breaker and measurements for battery voltage and charging current. There are also continuous measurements for currents and voltages before and after the circuit breaker as well as active and reactive powers. However, even these are available at SCADA in real-time, they have proved to be inaccurate and therefore not utilized in the network management. They could be applied mainly to check whether there is current flowing through the recloser or not. The events and alarms of a year are presented in figure 4.8. Elenia has 124 remote reclosers installed at present and all of these have described features. Two different type of monitoring and control units are used in these stations and therefore the data available varies a little.

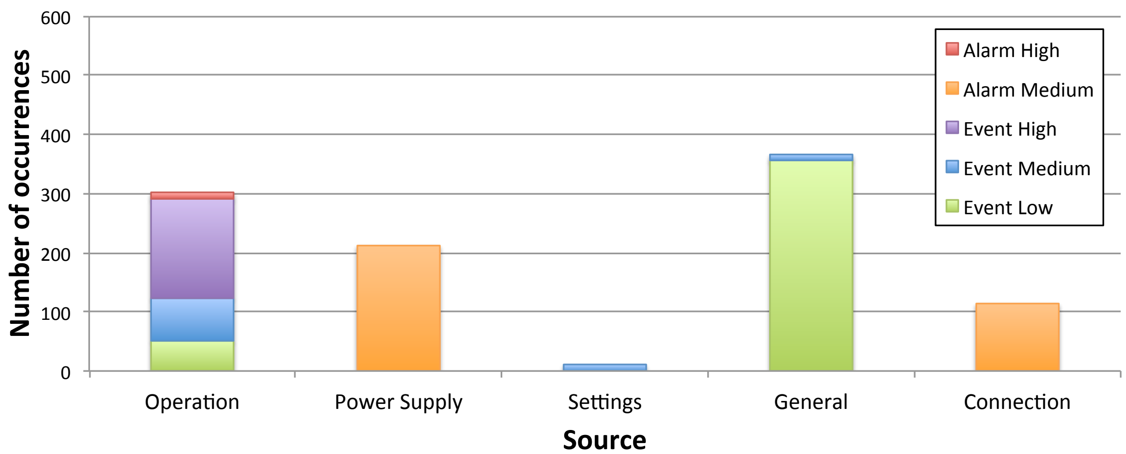


Figure 4.8. *Events of a year from a recloser station*

The events from the recloser are divided into five classes: Two for alarms and three for events. The normal operation of the recloser includes such events as pick-ups, trippings, controls and status values. Power supply events consist of alarms related to the battery system. General events include events about the recloser status and the opening of the cabinet door. The connection events are related to SCADA connection interruptions. Setting events include events for the alteration of the setting values of the relay.

4.4 Smart meters

Another source for process data is the smart meters. The main objective for the smart metering has been measuring the energy consumed by a customer. The average power consumed in every hour is registered resulting in an individual power curve. These curves are transferred to the MDMS and further to NIS where they are used in network calculations and also to the web service available for customers. It takes a month on average to have the series transferred to NIS. (Kauppinen et al. 2012)

Elenia is using Iskraemeco MX372 meter family at present. It is a multifunctional meter enabling not only the energy measurements but also voltage and outage supervision functions and GSM/GPRS communication. The quantities measured by these meters are presented in table 4.4.

Table 4.4. *The quantities measured by Iskraemeco MX372 smart meters (Iskraemeco 2012)*

Quantity	Description
Energy	Cumulative and hourly profiles
Power	Active power in both ways, inductive and capacitive reactive power
Average RMS voltages	10 minutes
Peak and minimum voltage	Daily, with time stamps
Under and over voltage	Compared with defined thresholds
Voltage unbalance	
Phase faults	
Short interruptions	Less than 3 minutes and total time without power supply

Even though the meter measures the RMS value of the voltage every 200 ms, only the 10-minute average is delivered to the MDMS. The meter also registers the number of exceedings the defined voltage limits. In Elenia, these limits are defined according to the standard SFS-EN 50160 as follows: ± 5 %, ± 10 % and -15 %. (Mäkelä 2011; Kauppinen et al. 2012)

While the meters are capable of measuring two-way active power and reactive powers, these features are not utilized in Elenia so far. This requires extensions to MDMS and those have not seen beneficial enough at this point. The voltage quality data is collected and stored in MDMS which enables reporting it if a customer complains about the power quality, for example. (Kauppinen et al. 2012; Lähdeaho 2012)

4.5 Advanced utilization of process data

The present state of data provided by the SCADA and smart meters were described above. In following, the data utilization is approached from the user perspective.

The present state and the visions for the advanced process data utilization in Elenia are studied by way of interviews of the personnel. The result of the interviews are categorized according to teams in Elenia. The full list of interviewees is available at the end of the references.

4.5.1 Control centre

The network control centre team operates with both SCADA and DMS systems at present. However, there is an intention to remove the SCADA user interface from the control centre at some point.

The first step towards improved utilization of the process data is to streamline the SCADA events and alarms. At present, there are inconsistencies in the priorities of similar events between the sources. The data flow in the event list of SCADA should also be studied since the crucial alarms may be left unnoticed because of overwhelming data flow. (Ihonen 2012; Pohjosenperä 2012)

There is a need for a tool for repetitive reclosing analysis. Repetitive reclosings can be held as an indicator for a developing fault if the faults are located to a certain place. At present, the data about the number of reclosings is available after the reclosing report made by maintenance engineer monthly. The report includes only the number of reclosings at each feeder and the cause have to be deduced separately. The exceptional number may have a reasonable explanation, lightning for example. In addition, the related fault location value would also be valuable. The analysis could also include fault location data for relay pick-ups if the location is successful. (Ihonen 2012)

Like described earlier, disturbance records cannot be utilized in operative disturbance management, because the SCADA system does not provide the records instantly. Instead, they are used in the secondary analysis of the fault more often. At present, disturbance records have been applied in analysis several dozen times per year but there are expectations for the potential of the records if the fetching could be improved. It would be advantageous for the operator to have the possibility to view the disturbance record in every situation when the disturbance recorder is triggered. It has been noticed that certain faults could be foreseen from the recordings in advance before they develop to actual faults. Since the disturbance record does not add value to every abnormal condition, it should be in the operators' decision of viewing the record or not. (Ihonen 2012; Pohjosenperä 2012)

The station service DC-system has a key role in network operation. On the occasion of a failure in DC-system, the whole secondary system in the substation is compromised. Therefore it is crucial to maintain these devices in a good condition. It would also be beneficial to have some indications about the condition of the DC-system: the charger and the batteries. (Ihonen 2012)

DSO is responsible for compensating the harm to the customers followed from a long interruption according to the standard compensation practice. Before the compensation can be paid, the realized length of the outage experienced by each customer should be validated with the logs of the DMS and the smart meter. At present, the logs of the smart meter and outages in DMS are compared manually. It would be more efficient to have the logs in the same system so that they could be compared automatically. Another issue is the limited storage capacity of the smart meters for long interruptions. If a certain customer have experienced many long interruptions in a short period, the log may be overwritten before it has been read to the MDMS. Therefore the outage log should be read more often. (Lehtinen 2012)

Some expectations are set also for the alarms from the smart meters. At the present, there are no spontaneous alarms in use, since there are no processing algorithms available for the alarms. Due to errors in installations and a large amount of meters, decisions cannot be made according to the alarm from an individual device and the large amount of alarms are hard for operator to handle. Instead, the large amount of alarms should be preprocessed in order to gain reliable information for supporting decision-making. The most interesting features would be detecting conductor breaks and neutral conductor faults. (Pohjosenperä 2012)

4.5.2 Operation planning

The main task for the operation planning team is creating switching programs for different purposes. In Elenia, some contractors compile switching programs by themselves and operation planners verify these programs before they are executed. The switching programs are managed with DMS, which is the most important system for the operation planners. Because of real-time measurements are not transferred to DMS from the SCADA system, operation planners often check the load situations from SCADA. (Luoma & Kupila 2012)

Process data is exploited at some point but the usability of the data is not as efficient it could be. Using two separate information systems makes the process complicated. The ideas for the development of the utilization concentrates mainly on supplying more information via DMS. Loading currents, busbar voltages and their trends could be useful as well as actual data from the state of the disconnector stations SCADA connection. SCADA holds all this data even at present but it is not delivered to DMS. An additional fact supporting this approach is the contractor's switching planning. Contractors do not have access to the SCADA system, so they have to do the planning without its information. This can result in an unideal solution in switching program. (Luoma & Kupila 2012)

4.5.3 Maintenance management

The maintenance management is not a team itself but divided into two teams. However, it is discussed here separately since it forms an independent entity. The maintenance of the distribution network is part of the strategic network planning and the maintenance of substations and regional network is managed by the dedicated field organization.

In general, the information about components' condition and inspection results are gathered to the network information system (Tekla NIS). The actual maintenance work is outsourced and the documentation of the performed actions is done by the contractors themselves. This subjective, visual perception based data collected by personnel is called off-line data since it is manually added to the information system. A great challenge is related to the validation of the information collected. The opposite is online data, which refers to data collected automatically by the means of distribution automation and different measurements. This kind of data is applied very little at present even though some examples can be found like the one described in following. (Rajala 2012)

The data provided by modern remotely controlled disconnector stations is applied to their condition monitoring and service orders. If the motor energy of a disconnector exceeds the threshold value, it will be serviced. The listing is fetched manually from the SCADA database and no other analysis is carried out automatically. The current analysis is not as accurate as desired. It would be beneficial to have some other parameters included in the analysis like the temperature at the time of operation and air humidity, for example. (Rajala 2012)

Substations are one of the most critical components for the network from the reliability point of view. The most critical components in a substation are station service DC-system, primary transformer and circuit breakers, especially on the HV side of the substation. Attention should be paid especially in these components when examining the condition of a substation. (Lehtonen et al. 2012)

The batteries of the station service DC-system are serviced every ten years. In this service, all the batteries are replaced. The impedance of the batteries is annually measured by contractors. If the impedance measurement was integrated into the battery charger which could perform it automatically, it would be interesting to gather the measurements more often for analysis. The main attention in the DC-system is paid to the batteries but recent failures in DC-systems are caused by charger malfunctions. (Lehtonen et al. 2012)

The primary transformer is the most expensive single component in a substation. The technical life time of a transformer is relatively long, approximately 50 years. However, the conditions it has experienced during its use can affect the lifetime dramatically. Therefore there are interests in its condition. The condition monitoring of a primary transformer is such a wide entity that it cannot be covered thoroughly within the framework of this thesis and therefore it is not analysed further.

Circuit breakers are essential components for the safety of the network. On the occasion of a fault, it should be recognized and the supply should be reliably disconnected. This requires reliable operation of the circuit breakers. Periodical testings for protection systems are carried out every three years but in these tests only faulted protection can be revealed. In other words, it does not provide any other information about the condition of the components such as mechanical wearing. Circuit breakers are facing new kinds of stresses in the future when the rate of cabling increases. Extensive cabling can result in more capacitive currents to being switched and this has different effect on the breaker's wearing than the previous circumstances with mainly reactive currents. This should be taken into account when considering circuit breaker condition monitoring. Recent IEDs have functions for circuit breaker condition monitoring and supervising the tripping circuit. However, if the IED in the feeder bay is replaced, the condition data about the circuit breaker is lost. The eligibility of these function is also unverified in practical circumstances and should be studied. For these reasons, the available functions are not utilized in Elenia at present. (Lehtonen et al. 2012; Pekkala & Uurasjärvi 2012)

4.5.4 Network planning

Network planning team is responsible for new-building and reconstruction planning. Network calculations carried out with NIS have a key role in planning. In some cases, it would be interesting to make comparison calculations with fixed parameters and some historical measured parameters. The network is evaluated also with the reliability point of view. In practice this means the exploitation of a specific reliability-based network analysis (RNA) tool developed by Tekla. At present, the parameters used in the analysis are manually compared with realized interruptions and then corrected if needed. An automated comparison between the parameters used and realized data would also be beneficial. (Lähdeaho 2012)

As mentioned previously in section 4.4, hourly-series of smart meters are available and in every day use in NIS. Instead, the voltage quality data is not exploited systematically. It is used occasionally with some spreadsheets for additional data in exceptional cases. The quality data could add value to the dimensioning of the components and support pinpointing the parts of the network which are in the need of reinforcement. (Lähdeaho 2012)

At present, SCADA provides very little useful data for network planning purposes. The events and measurements from the substations are not as crucial for the planning point of view as the measurements at the customer's connection point. In the future, secondary substation measurements could provide advantageous data for network dimensioning and defining follow-up calculations. (Lähdeaho 2012)

4.5.5 Strategic development

The strategic development team is responsible for example strategic guidelines, prioritization for network investments and protection planning. Protection planning includes network calculations from NIS from the protection point of view and analysis of passed disturbances. From this thesis' point of view, the strategic guideline planning is relatively distant while some far-fetched connections to process data could be made. Protection planning instead could benefit the process data analysis.

Disturbance analysis is carried out with variable sources of data. Historical data from SCADA, DMS and related disturbance records are commonly applied. The challenge is to gather all the needed data manually from each information system and the data needs to be analysed separately as well. Since the disturbance records must also be fetched manually from the feeder terminal, the whole analysis is very labour intensive. (Pekkala & Uurasjärvi 2012)

The MV network of Elenia is mainly compensated with Petersen coils. This has effect on the settings of the protection relays. In some occasions, the Petersen coil can be disconnected from the network and the network turns to neutral isolated. These two different situations require different relay settings in order to maintain the network safety. Therefore the settings should be altered while the earthing changes. At present, this is carried out automatically for the relays in substations but if the feeders include reclosers, these settings should be manually altered by the network operator in the control centre. It would be beneficial to have a notice in DMS that the settings of reclosers should be changed or even perform the changing automatically similar to substations. (Pekkala & Uurasjärvi 2012)

4.6 From visions to functions

The data has been collected from the network mainly for the operational purposes but there are some examples for process data utilization for other purposes as well. Secondly, the data collected varies as the technology between different points in the network. However, as can be determined from the interviews, the collected data has unexploited potential even at present and the potential will increase with the increasing process data provided by the new generation devices installed.

The development ideas found in the interviews can be refined into functions of the novel system. The potential functions are collected in table 4.5 with possible data sources of each. As can be seen in the table, some functions share the same resources. These can be held the most beneficial ones for further analysis.

The functions can be categorized according to the execution time requirements. In general, the functions in the network control centre have limitations for execution times. For example, the fault location calculation should be carried out during the delayed reclosing operation. On the other hand, condition monitoring functions require data from a longer period, so the optimization of the execution time is not

Table 4.5. *The potential new functions for novel system concept*

Function	Resources
Improved fault analysis (location, type)	Disturbance records, DMS interruption logs, improved prioritization of SCADA events and alarms, analysis of smart meter alarms
Repetitive reclosing analysis	SCADA events and DMS interruption logs
Power quality analysis	Disturbance records, smart meter logs
Disconnector station condition monitoring	Condition related data analysis, SCADA events and alarms
Protection selectivity analysis	SCADA events and DMS interruption logs
Adaptive protection	Actions based on SCADA events and network topology from DMS
Condition monitoring of substation equipment	Disturbance records, integrated condition monitoring functions of the devices, SCADA measurements and events
Improved switching planning	Measurement data from SCADA to DMS

as crucial. The resources can be divided into three types: Resources, of which data already exist in a single system and only little system development is needed; resources, which require extensive processing of already existing data and fetching the initial data from one external system at the most; and resources, which require data collection from multiple locations and processing. A corresponding classification is presented in tables 4.6 - 4.8. The classification is rough and the almost every resource could be improved by adding more measurements or external data to the analysis.

Table 4.6. *Resources which initial data already exists in a single system*

Resource	Description
DMS interruption logs for repetitive reclosing analysis	DMS already carries data about the reclosings and fault locations in certain fault types.
Improved prioritization of SCADA events and alarms	The prioritization can be made with already existing tools in SCADA.

The resources in table 4.6 can be performed with the present system or only little system development is needed. In practice, repetitive reclosing analysis would require an analysing algorithm to be created to follow the reclosings. The logical prioritization of SCADA events and alarms would improve the usability. The tools for the prioritization already exist in SCADA, so only labour work is required.

The resources in table 4.7 require extensive processing either in a single information system or the data is fetched from one system and processed in another. However, data collection from multiple systems is not needed.

Table 4.7. *Resources requiring extensive processing*

Resource	Description
Analysis of spontaneous smart meter alarms	The interface between DMS and meter reading system already supports transmission of the alarms, but no suitable analysing algorithms for the alarms exists.
Condition data analysis from disconnector stations	The data already exists in SCADA. Analysing algorithms should be developed.

The spontaneous alarms from the smart meters are not exploited at present due to lack of filtering and analysing algorithms. The large mass of meters leads to unmanageable information flow in certain fault occasions and therefore the meter alarms are shown only on request by the operator.

The most recent technology disconnector stations enable condition related data measurement and transfer to SCADA. However, the SCADA does not provide suitable tools for analysing the measured data. It should be considered how the data should be analysed and in which system.

Table 4.8. *Resources which require data collection from multiple systems and processing*

Resource	Description
Disturbance records	It should be ensured that the records can be fetched automatically. A data warehouse and suitable analysing algorithms should be developed.
Improving the SCADA-DMS integration	Adding more data transfer between the systems for reduction of the need for two separate systems. For example real-time measurements and historical data.
Condition monitoring functions of substation equipment	The potential should be mapped and a analysing algorithms should be developed.
Improving of exploitation of smart meter quality data	The voltage quality logs delivered from MDMS to NIS.

The resources in table 4.8 are the most challenging to implement. They require data from multiple systems and processing algorithms to be created. The efficient utilization of disturbance records can be seen very interesting since the records could be exploited as a resource in many functions. A comprehensive analysing algorithm is challenging to develop and this is maybe the biggest issue to be solved.

The SCADA-DMS integration should be considered thoroughly in general. The intention of removing SCADA user interface from the network control centre at some point sets various demands for the interface. Another driver for the full integration springs from the need of state estimation of the distribution network. These issues are studied previously by Kärenlampi (1996) and Lehtonen et al. (2002), for example. In these studies, measurement data from the network is combined with the statistical models to gain better view on the state of the network. Even though the need has been recognized at that time, the interviews show that these have not been utilized in an efficient way currently.

Various substation equipment, feeder terminals in front, have condition monitoring features. Recently, DC-chargers with battery condition monitoring functions have become available. The capability of those features should be studied. Issues may arise around the comparability of the data between different vendors' devices. At present, usually the features are designed to operate locally and the devices are not capable of transferring the data to SCADA.

At present, the voltage quality logs of smart meters are not delivered to NIS. The logs are available on request in MDMS but the comparison with the network calculations have to be done manually.

The off-line data discussed previously in section 4.5.3 and its implementation to the novel information system concept is left out from this thesis but it certainly is worth further study.

5. ADVANCED SYSTEM CONCEPT

As can be determined in chapters 3 and 4, great, eventually increasing amount of data is available in the distribution network. However, the data has no use if it cannot be exploited efficiently. A human being has a limited capacity for information processing. If the large amount of data is wanted to exploit efficiently, information technology should be applied.

The idea of a database-centered condition based maintenance system was introduced by Vuorinen (2012). The focus in this chapter is to determine the main functions and evaluate benefits and drawbacks of different options for implementing the novel system called Proactive Network Management System (PNMS).

The section 5.1 presents some of the major limitations and boundaries which should be taken into account in development of the novel system. These are applicable standards, existing interfaces in the present system environment, the basics of data quality and capacity requirements for the processing.

The features of the novel system are presented in section 5.2. The study is at a very general level and it does not take a stand on the functions desired to be implemented. A more specific description of two of the functionalities is presented in chapter 6 with example cases. The section 5.3 covers an evaluation of different topological options of the novel system.

5.1 Boundary conditions

While creating either a new information system or developing the existing ones, restrictive factors should be recognized and followed. At least two different types of guidelines can be found: Technical and strategic. Technical boundaries are set by the present system environment, existing interfaces between systems and available tools and products. The applicable standards should be taken into account. The role of standards is emphasized when it comes to data exchange between information systems. Another technical boundary is set by the quality of the data during the process and the capacity available for processing the data.

The strategic guidelines can differ from the technical ones. Even though some functionalities could be included in a system from the technical point of view, the strategy can be against it.

5.1.1 Standards

The aim of applying standards is to avoid closed utility-specific system environments. Previously common, tailored implementations are found expensive to maintain and changing a part of the environment is challenging or even impossible. Proprietary solutions lead to strong dependency from a single vendor and this increases risks for business.

The most important standards originate from the International Electrotechnical Comission (IEC). There are several standards concerning the communication and integration of devices and systems in electric utility industry. The core IEC standards for smart grid are listed in reference IEC (2012). The smart grid standards are relatively recent and the work is in progress in many cases. The most interesting standards related to this thesis are IEC 61850 Substation Automation, IEC 62351 Security and standards concerning the Common Information Model (CIM): IEC 61970 Energy management system application program interfaces (EMS-API) and IEC 61968 System interfaces for distribution management (SIDM).

The main goal for substation automation standard IEC 61850 is to enable interoperability between different vendors' devices. This is important since substations are usually multivendor entities. The standard specifies a protocol for data exchange in substations. The primary equipment and substation automation functions are described with a specific abstract object model with common data classes. Also a configuration language for substations is specified to ease the engineering work. Although the standard has abstract properties, it defines strict rules for data exchange and modelling.

The idea of CIM is to enable more agile application integration in electric utility environment. CIM itself is an abstract information model to be used in information systems. It can be used as a reference for data definitions, naming, vocabulary, database design and such. The abstract nature of CIM enables it to be implemented in many ways. It does not specify as strict rules as IEC 61850 in substation automation. (CIMUG 2012)

The ABB DMS 600, for example, is capable of exporting the network data to CIM/RDF (Resource Description Framework) although the internal model remains proprietary and it is not even intended to transform completely to CIM format (Keski-Keturi 2011). A more thorough description of the DMS 600 CIM export feature development is found in the reference Rasi (2009).

The key point in the standards mentioned above is generalizing the interfaces and increase data exchange between different devices and systems. When data is transferred, attention should be paid on the security. The security standard IEC 62351 is developed for handling security in cases related to standards mentioned above.

However, the IEC standards are not the only ones. MultiSpeak is a specification for enterprise application integration and it is evolved to a de facto standard in North America among distribution utilities. It is serving the similar purpose as the CIM model. MultiSpeak defines precise communication protocols and data semantics, as the CIM provides only abstract models. There are tools available for conversion between the CIM model and MultiSpeak but they do not guarantee full compatibility at present. (McNaughton et al. 2008; NRECA 2012)

5.1.2 Existing interfaces

In order to enable the novel system operate efficiently, data exchange between information systems is required. The novel system should be integrated into the existing system ensemble. Therefore it is essential to consider the present state of interfaces.

The main information sources of the novel system concept are SCADA, DMS and MDMS. Even though NIS and DMS are tightly integrated, all information cannot be transferred via shared interface, since the two systems have dedicated databases. Therefore dedicated interfaces may be needed, depending which data is intended to be implemented.

The present system environment with the novel system included in an abstract level is illustrated in figure 5.1. Some changes are expected in the near future and these should be taken into account while planning the integration of the novel system. The interfaces between the novel system and presented system can be either straight between the systems or the data can be delivered via another system. All the interfaces to the novel system are presented separately in the figures in this chapter since it visualizes the required connections the most clearly. Therefore the total number of actual interfaces needed in that matter can be fewer than presented in the figure.

The Customer Information System is used as a work ordering system for contractors. The orders can be made straight from the DMS and therefore a link between the DMS and CIS is required. There is an ongoing implementation project with a new Enterprise Resource Planning (ERP) system. At the first phase, only economy modules are implemented and the work order management remains as it is for the present. However, CIS will be renewed in due course with an ERP-integrated system and this requires the redesign of interfaces in that regard. If everything goes as planned and the new work order management system will be introduced in the near future, the interface to the outgoing work management system can be neglected. The new ERP system is represented with a dashed outline in the figure.

The system ensemble and the interfaces between them form a mesh network presented earlier in figure 3.5(a) as the standards try to steer the development towards 3.5(b). Many of the interfaces are proprietary solutions and do not follow any standards. The system vendors are developing their products to support standard-based

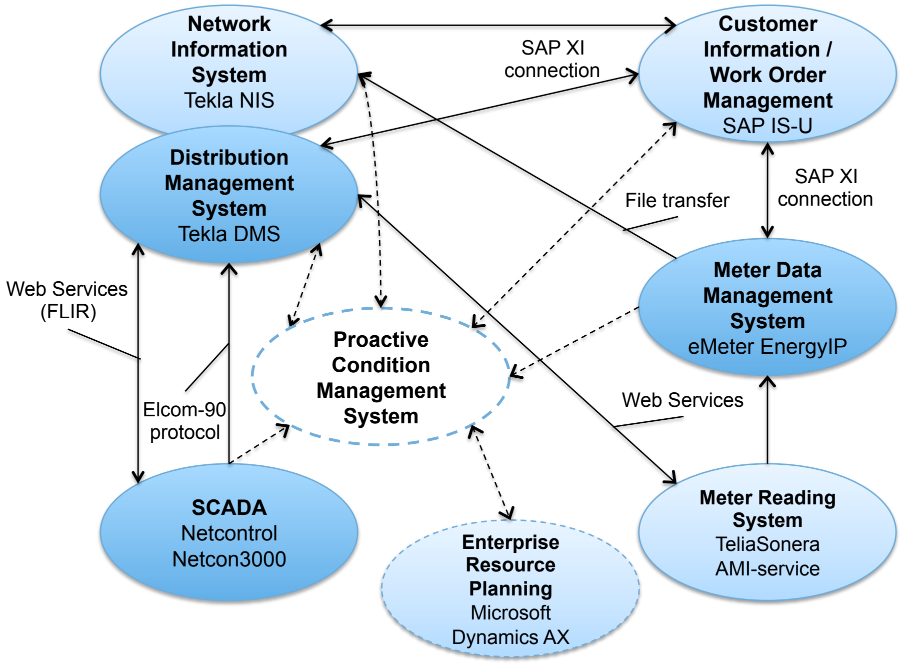


Figure 5.1. *Interfaces in information system environment of Elenia*

interaction but the changes will happen slowly. This complicates the integration of a new system as well as replacing an existing one. In conclusion, it can be stated that integration of the novel system requires a lot of labour work, since many interfaces are needed and there is no standardised bus-type communication available.

5.1.3 Capacity requirements

The capacity requirements of the novel system can be divided to storage capacity and processing capacity. The data transmission capacity of the link between the devices and systems also sets some limitations. However, the data transmission does not directly belong to the novel system and therefore it is not studied further.

The storage capacity requirement depends strongly on the data which is wanted to include in the novel system. Also the way of integration is remarkable. The data can be copied from the source location to the novel system or the novel system could access the source system's storage to fetch the needed data. The former approach increases the storage space requirements significantly. On the other hand, the latter could form a security issue. Technically both approaches would be possible and therefore it is more of a strategic choice to be made. To give some idea of the storage space requirements, a rough estimate is calculated in subsection 6.3.2 for disturance records.

The processing capacity requirement depends significantly on the implemented algorithms and desired time limits for the analysis. Since no mature algorithms exist, the estimation of needed processing capacity is difficult. However, no existing information system has the required capacity available, so some investments would be needed. Some of the discovered new functionalities have strict time requirements but most of the functions are not time-critical. These two types should be evaluated separately.

5.2 Features

This section covers the features of the novel system in general. The main features can be categorized into four: filtering, conversions, processing and transmitting. To complete the process flow, also decision-making based on the gained information and decisions put into action are required. The whole process with the features is presented in figure 5.2. The target is to automate the process gradually as far as possible so that interaction with personnel is minimized. This is illustrated in the figure with a dashed line from the systems to the decisions. The main features are discussed more thoroughly in following and the features are concretised via example cases in section 6.3.

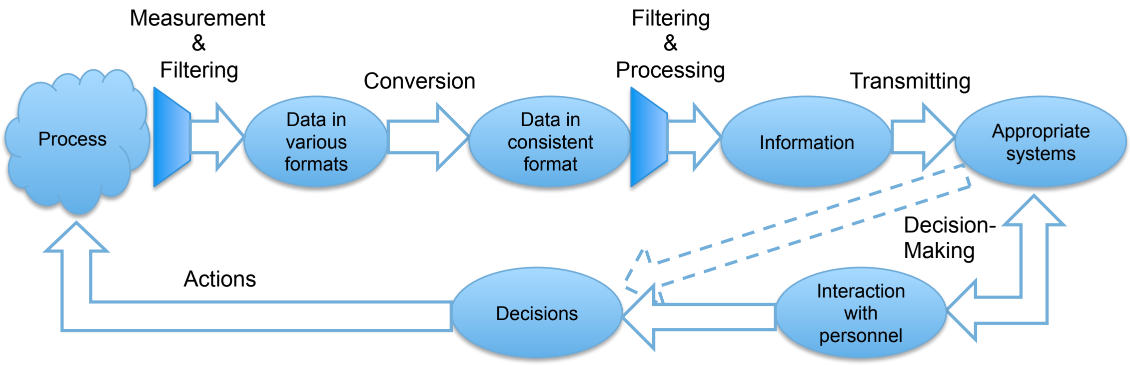


Figure 5.2. *Process flow with features of the novel system*

It should be noted that the process flow figure does not take a stand on the location of each feature. For example, filtering is required to be done in multiple steps and conversions can be carried out in various steps depending on the architecture and topology used.

Another notable factor is the data quality introduced in section 2.5.3. It should be ensured all the way from the measurement up to transmitting the final result to the destination. Especially crucial it is for the conversions and the main processing since they alter the data and a possible error could multiply and distort the result significantly.

5.2.1 Filtering

The filtering of the data collected is required to maintain the process efficiency. In future, an exponential growth of data sources is expected and even though the data transmission systems evolve and processing capacity increases simultaneously, there is a possibility of overloading the system. Therefore attention should be paid to filtering before it forms a problem.

The filtering of the data is required at least in two steps: Which quantities are measured and transferred to upper level systems, and which data is processed further from the foregoing. It should be specified precisely which data is collected in the first place and how it is exploited. Collecting all available data is often justified with economic reasons since it is reasonable to install all possible measurements at the same time. The process should be developed so that even if the measurements are installed in a substation for example, they could be filtered or blocked in the RTU. If the filtered measurements are needed later on, they could be activated remotely with minimal labour costs.

5.2.2 Conversions

The data collected from multiple sources is not often completely consistent. This makes the further analysis complicated and unreliable. The data can be in different format, scaled, compressed or the same quantity can be expressed with different units since the data is originated from devices from different vendors.

The aim of the conversions is to streamline the heterogeneous data so, that it can be compared reliably. To enable the conversions to be applied properly, information about the initial data format is needed and the standard data format should be specified. The format information can be packed up with the payload as metadata or information about the format can be specified in the processing system.

When conversions are made, it should be considered if the original data is needed. Sometimes it would be beneficial to examine the original data instead of converted. In these cases, also the original data should be stored.

5.2.3 Processing

In general, the aim of the data processing is turn data into information. This can be carried out for example by linking and comparing data from different sources, executing calculations and other operations. Processing of the novel system consists of functionalities presented in chapter 4 and are not discussed in detail here.

Processing could also locate in various or multiple places among the process. However, the drawback still remains: Scattering the functionalities around the process makes the management of the system more complicated.

5.2.4 Transmitting

To maintain every user group's work flow as fluent as possible, adding another information system with its own user interface should be avoided. Therefore the produced new information should be delivered to the information systems which are already used by each potential user group. This enables the inclusion of the new information in existent processes and functions in the present system environment.

Specification and creating interfaces between information systems is often a challenge because there are typically several vendors involved and their interests can be different. To take full advantage of the information transferred, also some system development is required for the receiving system. This kind of interconnection is not flexible enough in all situations. Therefore a reporting tool should be included, so that there is a possibility to create reports and queries directly from the system.

5.3 Topologies

This section explores, where in the present system environment the novel system would be the most beneficial to implement. In this study, the system should be considered as a single solution where all the functions were implemented. With this abstract approach it is possible to evaluate clearly the benefits and drawbacks of each option.

Two different approaches can be determined: An extension of an existing system or a dedicated new system. As was determined earlier in the resource analysis, the most important data sources for the novel features are SCADA, DMS and MDMS. These are the main data warehouses and therefore the most interesting from the novel system point of view. While examining which systems could be extended, two alternatives stand out: SCADA and DMS. The extension of MDMS is left out from consideration since it has not as focal role in process data as the two other. However, the link to MDMS cannot be neglected completely and thus it is included in following study as a data source.

Two alternatives can be found also for the dedicated system. The dedicated system could be centralized as the most of the present information systems. On the other hand, the increased processing capacity and the present field communication network would enable a distributed implementation.

The benefits and drawbacks of each four alternatives are evaluated in following. The study includes simplified interface analysis for the main data warehouses mentioned above. More thorough study of interfaces is in section 5.1.2.

In addition to gathering data from various locations and its processing, attention should be paid also for the exploitation of the new information. Two different ways for the exploitation can be found: If the actions based on the new information require actual maintenance work, work order should be created to the appropriate system. In the ideal case, the novel system handles the work order without interaction with personnel. In other case, labour work is not required and the actions can be carried out with information systems or with other remote actions. In this case, the changes can be made in two different ways: The systems can handle it automatically, or a notification should be given to the operator who performs the required actions. In following, the changes in work order management are neglected and work orders are delivered directly to the forthcoming system. The actions are presented as a feedback loop in two different ways: Work orders to the work order management system and immediate actions via information systems.

5.3.1 SCADA extension

One of the main functions of the SCADA system is data storing and analysis. It holds the majority of the data needed for the novel features and therefore it would be justified to implement those features into it. Hence the majority of initial data and the processing would locate in the same system and in this regard data transfer is not needed. If the novel features were implemented as a SCADA extension, the topology would be as illustrated in figure 5.3.

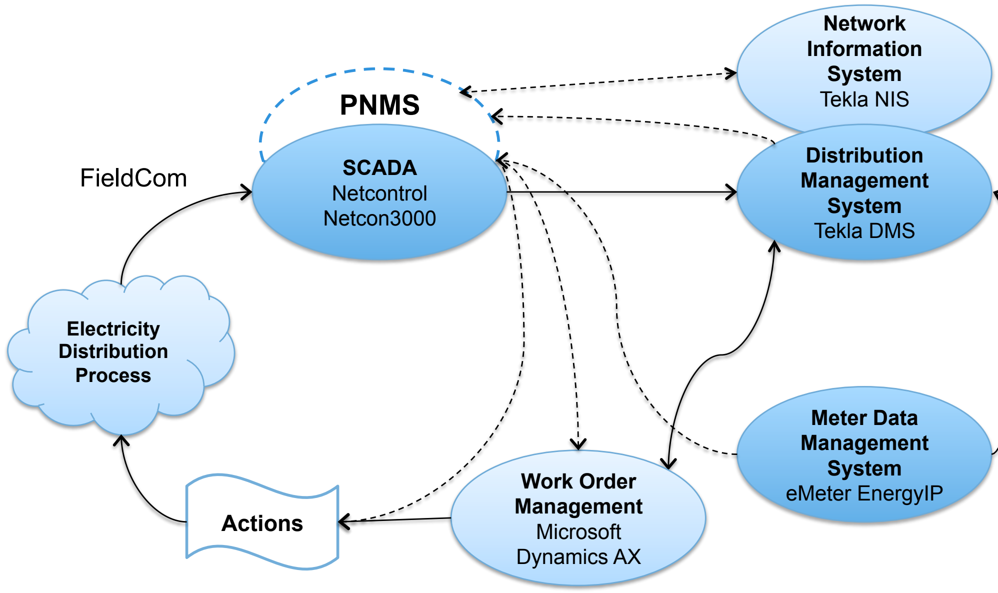


Figure 5.3. *The novel system implemented as a SCADA extension*

In addition to the strong interface to the primary process, SCADA has an existing interface to DMS. At present it is a one-way interface, since no controls or other messages are allowed from DMS to SCADA. It would be possible to extent the interface to the other way also, if the security of the connection was ensured. The existing links between the systems are illustrated as solid lines. There is no existing interfaces to MDMS or to NIS and these should be created. These are illustrated with dashed lines. The process flow after the analysis should be discussed as well. In the figure there is a interface illustrated between the work order management system and the novel extension. Instead of a straight communication between these two systems, the work order could be handled via the DMS and its existing interface to the work order management. However, the present interface between DMS and SCADA is not capable of handling this and should be developed.

The main function of SCADA is to collect and transfer data from all over the network. At present, SCADA includes only relatively simple algorithms and functions due to high performance demand in all occasions and it processes only data gathered by itself. The current SCADA system of Elenia would enable some analysis to be carried out but it is a strategic choice not to implement these since the role of the SCADA has been seen as a process system only delivering data. As determined, more sophisticated processing would also require information from the other systems and this would make the system more complex. These would altogether compromise the performance of the system and therefore it is unlikely to have the novel features implemented in SCADA. The trend for the full integration of DMS and SCADA is another supporting fact for not to implement the features in SCADA. In that integration, DMS would represent the user interface of the system while SCADA provides the data for processing and is left to the background.

5.3.2 DMS extension

DMS has a focal role in network management. The ideology of the DMS is similar to the novel system discussed in this thesis: Collect data from multiple sources and producing this to information with added value. The very same issues with information system integration in electric distribution utility environment were encountered in the development of the DMS. A detailed study may be found in references Verho et al. (1997) and Verho (1997). The similar nature of the DMS can be seen also in existing interfaces between DMS and other systems in figure 5.4. DMS has interfaces to all systems already and therefore it is an attractive alternative for the novel features. In the ideal case, the majority of the initial data required would be available with configuring the existing interfaces presented with solid lines in the figure. Only actions, which could be done without labour work and thus no work order is needed, are considered as a new interface and illustrated with dashed line in the figure.

The role of DMS as a concentrator for data exchange emphasizes its centricity. However, this role has an underlying risk included. It should be carefully considered which features and functions are in the DMS's area of application. Otherwise the DMS may grow uncontrollably as well as the dependency on a single system provider. The risk for the business could be so significant that it alone prevents this type of implementation.

Another strategic aspect regards the DMS's role as an operative system. It is destined for a tool for operators in the network control centre. It is entitled to question, which kind of features are suitable for DMS. Nonetheless, some functions described in chapter 4 would be the most beneficial to implement in DMS.

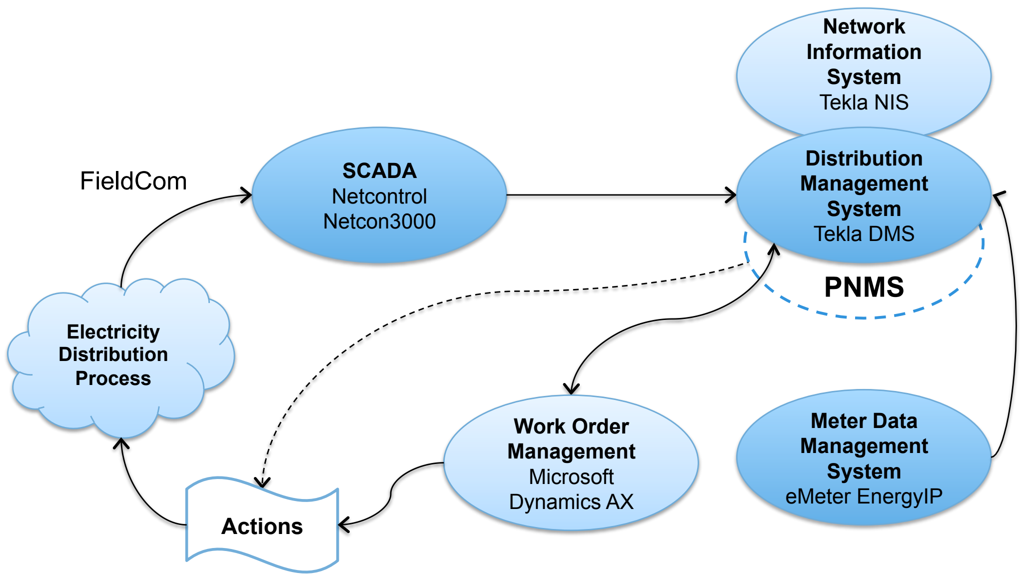


Figure 5.4. *The novel system implemented as a DMS extension*

5.3.3 Decentralized intelligence

In principle, it would be reasonable to process the data as near the source as possible. This approach would minimize the data transfer requirements. Distributing the features to smaller units makes the system more redundant, since a fault in a single unit affects only a small part of the system.

A natural way for distributing the features would be to implement them into substation level, since substations are the main source for the process data. This type of implementation is illustrated in figure 5.5. This approach is also supported by the fact that some processing functions are already included in substation devices. Modern feeder terminals have a function for circuit breaker condition monitoring, for example (ABB 2011; Vamp 2011). There are also products available for substation level data processing and ongoing intensive research on the topic. ABB COM600 enables disturbance and fault record analysis and provides a data storage for process information, for example (ABB 2012).

Although the substations are the main source for data, they are not the only source. Data is available also from the disconnector stations, for example, and it is transferred to SCADA as illustrated. If this data is wanted to include in processing, it should be transferred to substations or processed in another system. It is unlikely to add intelligence to disconnector stations due to the large number of stations and install conditions. The smart meter data from MDMS would also need to be treated in another way. In the figure, actions performed in two ways is emphasized. The actions requiring labour work are handled as earlier. The actions determined by the novel system in substations are handled by automation.

This type of implementation would be beneficial for such functions, which do not benefit from additional data from other sources and the data is not needed

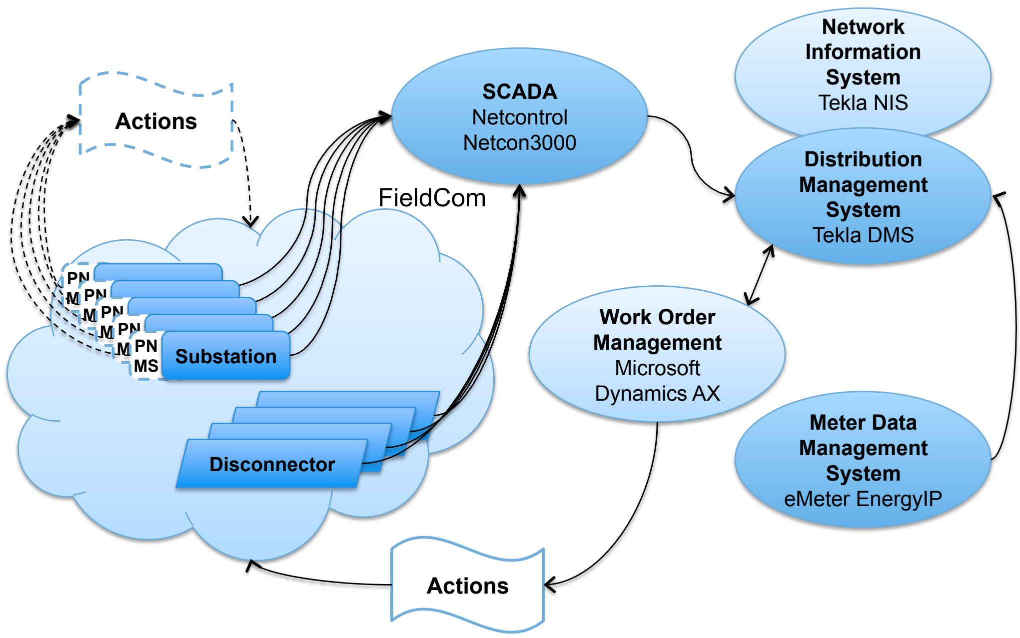


Figure 5.5. *The novel system implemented applying decentralized intelligence*

anywhere else now or possibly in future. Hence, the suitable functions should be considered carefully. Valtari et al. (2010) have considered the location of monitoring and analysis functions among other vital functions for the network operation. In their study, the scope was in the distribution substations but the issue remains in the broader context as well.

The life-cycle of the functions to be implemented should also be considered. As determined by Valtari et al. (2010), the closer to the primary process the device is, the more expensive is its long-term maintenance. The life-cycle costs are related to management of the novel system. There are no well-formulated algorithms for process data analysis yet and the development is expected in the near future. Attention to the management of the distributed system should be paid carefully. For example, updating an algorithm in a feeder terminal is more expensive than updating an algorithm in a centralized management system. Therefore, even if the intelligence was distributed to the substations, the algorithms should be remotely configurable. A comprehensive system for management of process data from other sources should be created as well.

5.3.4 Centralized system

A dedicated centralized system would perhaps be the most obvious solution for functionalities of this kind. There are several reasons standing by this approach. The development trend for a few decades has been the centralization of the functionalities. As a result, a centralized information system environment has been created. The data is collected from multiple locations and processed in a central system. In other words, the existing system ensemble supports this kind of implementation since existing data can be utilised via existing interfaces. The centralized implementation is represented in figure 5.6. Naturally, adding a new information system to the ensemble requiring data from multiple sources, sets a challenge for integration. This can be determined from the number of dashed lines in the figure.

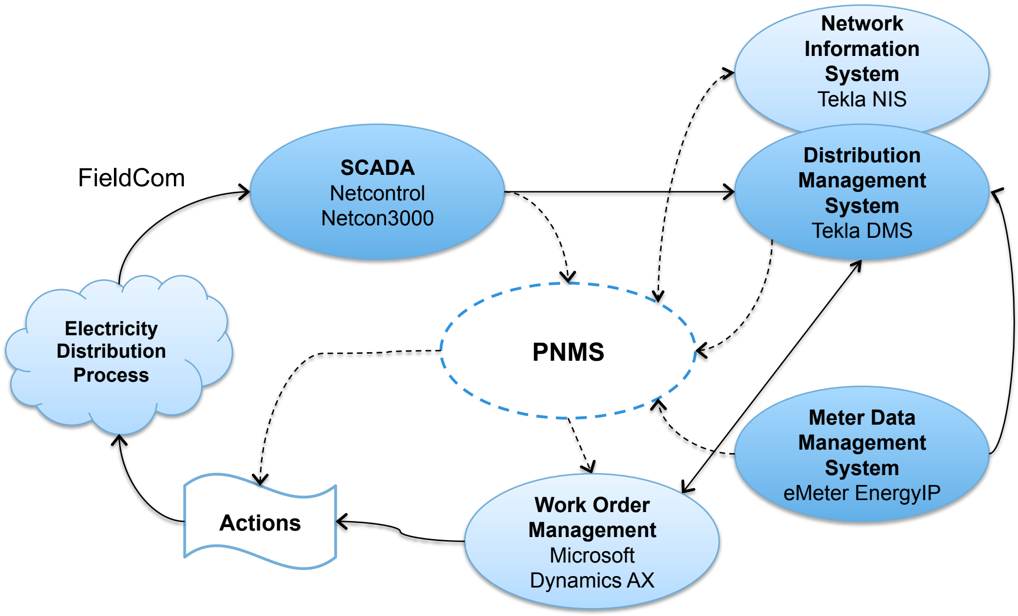


Figure 5.6. *The novel system implemented as a centralized system*

Another supporting fact is that the management of a centralized system is simpler compared with a distributed ensemble. The changes can be made to one system only and this makes the system more agile. At the same time, it is in isolation from the critical functionalities of the primary process. The modifications and maintenance performed to the system do not affect the primary process at all. This is important, since development is expected and new functionalities are applied and tested.

The major difference between a dedicated system and extension of a present system is also related with agility. The present systems are complex entities by themselves at present and adding features presented above would make them even more complex. A new system could be developed in the interests of the novel system only and the development is not limited by the present system vendors' interests or resources.

5.3.5 Hybrid system

All the four previously presented topologies have some benefits over the other. The intention of the hybrid system presented in figure 5.7 is to gather as much of these benefits into the same solution. Only the SCADA extension is neglected due to reasons mentioned earlier.

The preprocessing including filtering and conversions could be implemented in the substation level. This reduces the level of data transfer since only relevant data

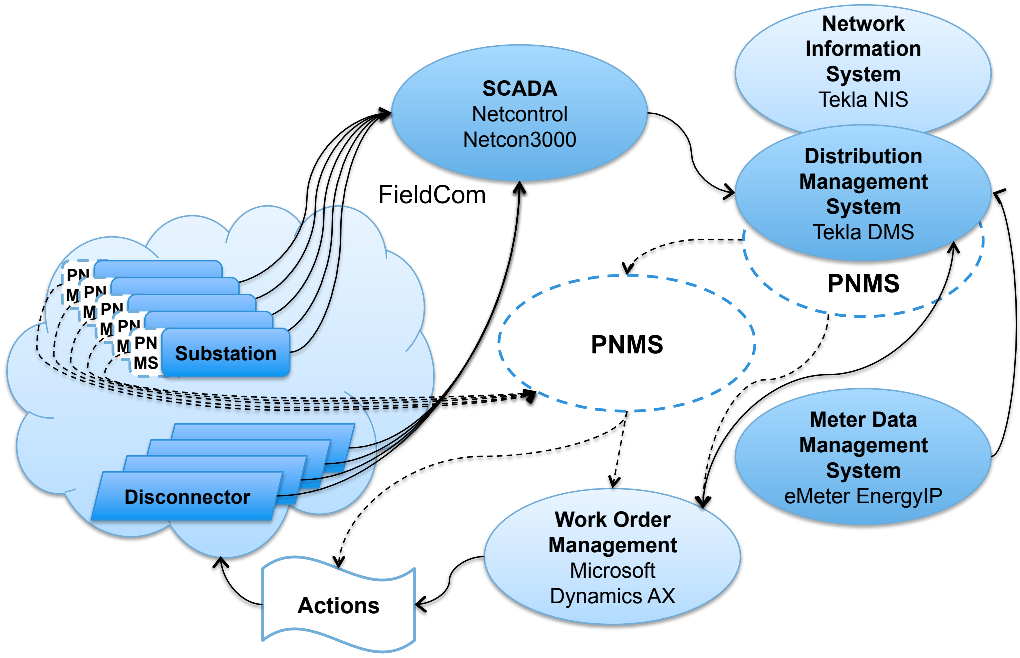


Figure 5.7. *The novel system implemented as a hybrid system*

is delivered further. However, the majority of the processing should be performed in the centralized system. Appropriate interfaces for the novel centralized system should be formed to existing systems by gathering additional data from these and transmitting the processed information to them. The DMS extension represent the development of the DMS since some of the functionalities could be the most beneficial to implement directly to it.

The underlying idea for this topology is that the novel concept should be considered as an entity, not only as a new system nor a single extension for an existing system. The functions of the novel system vary within a wide range and it may not reasonable to implement all of these in a single system. Instead, the location of each function should be considered separately. However, a drawback lies beneath this vision. If the features are scattered all over the information system environment, managing this kind of entity would be challenging. This should be taken into account, so that it is still possible to consider this concept as an entity of network management.

6. DEFINITION OF A NEW CONCEPT

The network equipment of a DSO is derived from several decades and therefore the used technology varies. Naturally, the recent technology offers more possibilities and more data is provided. However, older equipment is renewed within a certain time period and the novel system should be flexible enough to be extended. The technical development continues further and new innovations and tools will become available. The system should be capable of being upgraded with these as well.

The utilization of process data by these means is a relatively new topic. There are no comprehensive analysing methods and algorithms waiting for implementation but the research is going on and testing is needed for new algorithms. To fill these requirements, the novel system cannot be closed and dependent on inflexible traditional software development processes. The novel system should be considered as a platform in which the features are built on. The entity can consist of improvements in existing systems and a new centralized dedicated system.

In this chapter, the different approaches for taking the concept into practice are considered. The section 6.1 considers different approaches to implement the novel functions from the business perspective as well. Section 6.2 discusses the development possibilities and the potential of the present information systems. Finally, section 6.3 describes two of the functions in practice as an example.

6.1 Business perspective

The present system environment is mainly based on self-owned systems and there is no intention of changing it. The systems are run on company-owned servers and partly maintained in-house. The new centralized system mentioned above can be achieved with different ways, instead. The previously favoured traditional IT architecture is still an option. However, the increased network bandwidth and development of business models have created an option, cloud computing. The benefits and the drawbacks of both are discussed here in brief.

The traditional approach to acquiring an information system requires hardware and software to be purchased and labour work to get the system installed and maintained. All of these could be done in-house, or one or more of these can be outsourced. The result of this approach is a self-maintained system with usually a relatively long life time expectation. Scaling the system up or down is often expensive or impossible and time-consuming, at least. The flexibility of the system depends on the software system and its vendor. The main benefit of this approach is the degree of control. The user has an exact knowledge about the security and processes in the system and can set them according to the demands.

Cloud computing has its origin in the idea of providing IT as a service. The resource allocation on demand enables flexibility for both the user and service provider. In the ideal situation, cloud computing reduces costs, releases labour resources and provides the scalability of the system. Reduced costs are a consequence from resources which are paid only when used and there is no need to tie up capital in systems. If the resources are needed only in a certain time period of the day, for example, the service provider could offer the same resources to another user for the rest of the day. The labour resources are freed to the core business from maintaining the hardware and software. The idea of cloud computing enables scalability on demand without long-term commitments. (Walker 2010)

Cloud computing consists of different levels. The levels provide different degrees of control to the system. These levels are illustrated in figure 6.1. Infrastructure is the foundation of any information system including the physical hardware. Infrastructure as a Service (IaaS) is the bottom layer, where the user has the most wide-ranging degree of control. The user does not have access to the physical hardware itself but have control of operating systems, storage, network and such. The IaaS is often considered as virtual machines. (Walker 2010)

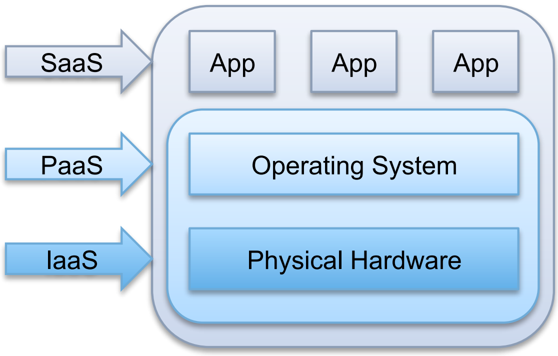


Figure 6.1. *The layers in cloud computing (Walker 2010)*

The middle layer of cloud computing is Platform as a Service (PaaS). This platform allows the user to install applications, a database for example, and develop their own software for the environment. In this case, the operating system is usually maintained by the cloud service provider. The hardware resources scale automatically to match the demand and the user does not have to take care of these. The top level of cloud computing is called Software as a Service (SaaS). It is the most virtualized level and has the least degree of control. At the same time, the user does not have to care about the maintenance of the system. At this level, the provider maintains the software and the user can only access and operate the application. Usually, the user does not have to install anything and the execution of the application does not require any resources from the client computer. (Walker 2010)

However, the distribution of services into layers is not strict and sometimes there are even more layers considered. Storage services can be considered as separate layer and above the application layer can be seen a service layer, for example. The service layer consists of machine-to-machine operations with no interaction of a human. (Kontio 2009)

Clouds can be divided into three types: Private, public and a hybrid of the two. Public clouds are operated over the internet. The service is provided by specific organization who maintains the system and offers it forward. Private clouds are maintained in-house and are not connected with the public internet. In the hybrid type, the management of the system is handled by both the cloud service provider and the customer organization itself. (Walker 2010) A private cloud enables sharing a limited amount of software licenses for a large number of users, for example. This approach is exploited in Elenia for some information systems at present. A private cloud enables also executing applications over the network so that user does not have to install anything on his desktop.

Kontio (2009) highlights some risks to be considered before engaging with the cloud. Some of the issues are similar as in outsourcing in general and taking functionalities out of business. The vendor lock-in can occur if there is no way to export the data from the service. This is more likely in the top-level services where the user has less rights to control the service. If the service is run down for some reason, the data should be exported and a substitutive service sought. Data security should always be considered as should the reliability when outsourcing services. These risks can be minimized with careful selection of the partner. For the security point of view, it should be ensured who has access to the data and which data is wanted to include in the service in the first place.

The service-type system acquiring lowers the risk of misdirected investments. The potential of the new system can be evaluated with acquiring certain parts of it instead of investing in the whole system at once. The flexible model of cloud computing enables the extension of the system if the potential is verified in use. This has a considerable impact in cases which have uncertainty of fulfilling the desired need. The cloud computing is a potential option for such functions which cannot be implemented in the existing systems, like disturbance record analysis.

An example of SaaS application in electric utility environment is PQNet by PowerQ. It is a measurement data management system based on a database, data analyzing tools and a web browser based user interface. Typically, it is used to store disturbance records and measurements from substations and smart meters. (PowerQ 2012)

6.2 Development of the present systems

Some of the functions presented in chapter 4 can be included in the existing information systems with minor system development. On those occasions, it is not reasonable to transfer this data to another location for processing but develop the existing system if the strategic guidelines are not run over. On the other hand, some resources for the functions presented require the development of existing systems. Some development proposals are presented in following.

The SCADA system provides flexible tools for event and alarm prioritization. This prioritization would be carried out with the tools of the centralized end of the SCADA system. In other words, it does not affect the data gathered and transferred from the substation level. At present, the problem is the information overflow on the event list. Therefore, comprehensive guidelines for the prioritization of the events and alarms should be created and implemented. The target is to streamline the prioritization to increase the usability of the SCADA. The guidelines should be evaluated from time to time since the system and devices evolve and more data becomes available.

A study for repetitive reclosing analysis should be made. The target is to find correlation with repetitive reclosings and possibly the following permanent fault. This is studied more thoroughly in subsection 6.3.1.

The interface between SCADA and DMS should be improved. At present, the integration is carried out with two separate protocols as illustrated in figure 5.1. The Elcom-90 protocol handles the process data transmission and Web Services are dedicated to FLIR operation. The current Elcom-90 protocol enables real-time measurement data to be transferred between systems and SCADA is capable to sent it to DMS. (Maksimainen 2012) It should be ensured if the DMS was capable of receiving such data and visualizing it in a usable way. This would provide more information for network operators and switching planning. At the same time it should be considered enabling control signals from DMS to SCADA. All this requires the careful evaluation of information security.

Wide potential exists in the interface between the smart metering infrastructure and the DMS. An analyzing algorithm for smart meter alarms should be developed in DMS. The algorithm requires information about the present topology and the other faults in the network. In case of a MV line fault, the alarms from the smart meters do not usually provide any additional information and therefore should be filtered out, for example. All the data needed is available in DMS already. The power quality logs of the smart meters could be also exploited more efficiently. The frequency of the log download should be considered so that the meter's internal memory is not overwritten before downloading. Secondly, the logs should be available in DMS and NIS.

6.3 Example cases

Some potential functionalities of the novel system were presented briefly earlier. Two of these are discussed next in more detail. The functions selected are purposely different by their nature. The idea is to verify the potential of the novel system concept for a wide range of processes. The function presented in subsection 6.3.1 could be implemented in existing information systems with relatively little labour effort and costs. The ideas presented in subsection 6.3.2 instead require further development work to be done and the present system environment is not capable of handling these.

6.3.1 Repetitive reclosings analysis

The target of the repetitive reclosing analysis (RRA) is to find incipient faults. Certain fault types, tree branches and structural defects for example, usually cause some momentary faults before escalating to a permanent fault. The momentary faults are cleared with a reclosing operation or the fault can disappear spontaneously before the operation of the circuit breaker. The number of the momentary faults in the rural area network is so extensive that it is impossible to carry out the analysis by labour work and therefore a need for a tool exists. As presented earlier, the analysis tool could be implemented in the DMS, since the majority of the data is already available there. The following is based on that approach.

The simplest way to implement a functionality of this kind is to evaluate passed and validated faults registered in DMS. The fault location function of the DMS is triggered with circuit breaker operation and it requires the fault current or the reactance being measured by the feeder terminal. If many faults are located in a small area during a short period, a notification could be shown to the operator who can order a crew patrol to the site. In this simple case, the majority of the decision-making is dependent on the control centre operator. There is not much additional information provided automatically and therefore it is left to the operator to include other inputs in the decision-making or not. However, the notification for repetitive reclosings is valuable itself since it streamlines the process for treating them. This procedure is illustrated in figure 6.2.

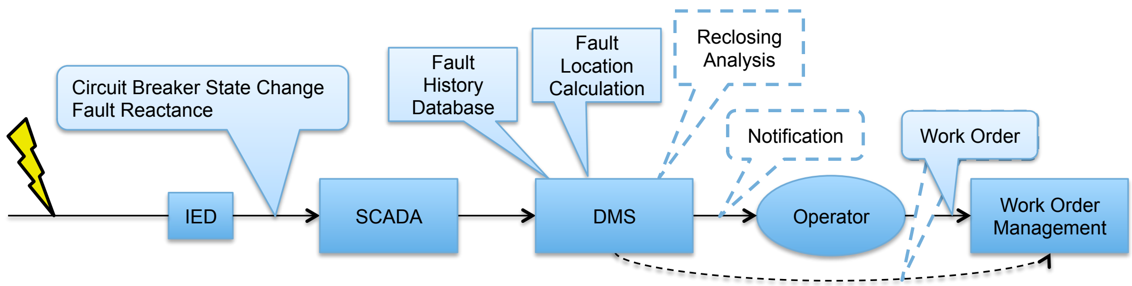


Figure 6.2. *The simple procedure for the repetitive reclosing analysis*

The existing properties of the systems are presented with objects with solid lines as the novel functions to be created are presented with dashed lines. At the first stage, the work order is made by the operator manually as it is done at present but after the analysis is mature enough, certain explicit cases could be handled automatically. This is illustrated with a dashed line in the figure. With this already available data, the analysis could be carried out in DMS and no modifications to the other systems or interfaces are needed. It would be possible to include such a feature in the general development program of the DMS without additional expenses.

The advanced version of the function is presented in figure 6.3. Again, the existing properties of the systems are presented with objects with solid lines as the novel functions to be created are presented with dashed lines. The fault reactance can be measured from the relay pick-ups even if actual tripping does not occur. This value is delivered to SCADA but not to DMS and therefore the fault calculation is not carried out. Including the relay pick-ups in the reclosing analysis would be beneficial since they provide a way to prevent the actual fault from happening and any harm to occur for the customer in that matter. Disturbance records could provide valuable information about the cause of the fault. The utilization of them is discussed in more detail in the next subsection.

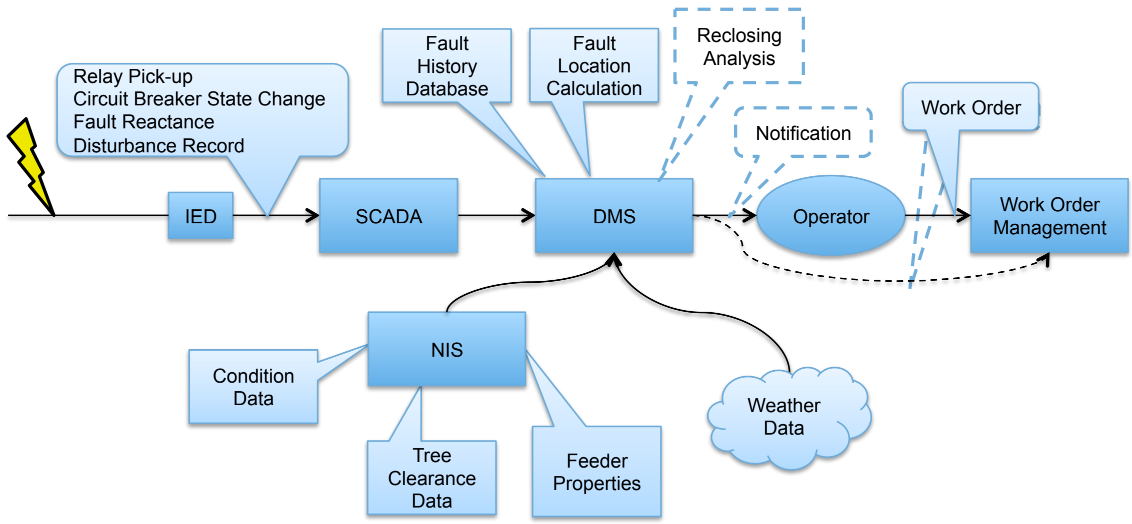


Figure 6.3. *The advanced procedure for the repetitive reclosing analysis*

The comparison of the figures 6.2 and 6.3 shows, that the main frame is similar in both and only some additional data is included in the analysis in the advanced procedure. This allows the development to be made in smaller steps even though the final target is the advanced version. It is also possible to find other additional data for the improvement of the analysis and its inclusion should be possible as well.

At present, there are functions to calculate the location of the two- and three-phased short-circuit faults. Instead, the location of the earth fault is challenging to calculate. The earth-faulted feeder can be recognized but the distance of the fault can not be calculated with present technology. However, the methods are improved continuously and promising results are achieved in field testing for earth-isolated overhead lines (Kostiainen et al. 2012). Without the measured fault reactance or current data, it is considerably more complex to evaluate the location of the fault. The analysis can be improved with the utilization of some other information about the feeder and the prevailing circumstances but in most cases these alone are insufficient for locating the fault precisely and some additional measures are needed.

It is important to pinpoint the exact location but the main question to be answered is the original cause of the fault. In this perspective, the location is only a part in an entity when resolving the cause. If the cause as a whole was known, it could certainly be stated whether there is a correlation between reclosings or not in the first place. The analysis of the disturbance records could enable evaluation of the cause without location data. For example, the correlation between earth faults could be evaluated with disturbance records without the location calculated from the fault reactance. Additional network data near the located area could be used for improving the analysis. At first, it should be considered if the specific part of the feeder is an overhead line, insulated overhead line or underground cable. If the feeder is an overhead line, it should be checked if it is located in a forest, field or such and when the last tree clearing took place. The other condition related data of the network components such as the age of the components and inspection notes should be also included in the analysis.

The most typical fault types and their most common causes are collected in table 6.1. This data is based on tacit knowledge since there is no statistical data available. Therefore no strict conclusions should be made based on this categorization but it gives some picture about the main issues. The fault type can often be deduced with available data. The DMS is capable of identifying the fault type based on fault current and the feeder terminal can separate the earth fault from short circuits.

Table 6.1. *The most typical faults and the causes for reclosings*

	Short circuit		**Line-to-line with**	**Line-to-earth**
	3-phased	2-phased	**earth contact**	
Tree	X	X	X	X
Lightning	X	X	X	X
Animal	-	X	X	X
Surge Arrester	-	-	-	X
Insulator	-	-	-	X
Cable Terminal	-	-	-	X
Conductor Break	-	-	-	X

As the table illustrates, recognizing the fault type with satisfying reliability requires additional data to be applied. Trees and flashing can lead to faults of any kind as well as an earth fault can occur for many variable reasons. Instead, component failures usually start as an earth fault but they can develop into short circuits gradually due to the lowered level of insulation, for example. The fault type caused by an animal may vary as well. The small animals usually cause earth faults as the birds can crash into conductors causing short circuits. The earth faults are the most challenging to process. A misleading conclusion could be made based on the table above, that the majority of the faults in the MV network in rural areas are earth faults. However, this is not necessarily the case since trees and lightning are the most common causes for faults and these can occur in both short circuits and earth faults. There is no statistical data available to study the distribution of fault types. The type of the fault is not stored for reclosings at all and over the half of permanent faults is undefined. Thus conclusions cannot be made due to defective data.

Value could be added to the analysis with weather data. Such weather conditions as heavy snow and wind cause more likely tree branches to bend and touch the line than calm sunny weather, for example. Weather institutes provide lightning location services and this data could assist verifying reclosings caused by lightning. The analysis could highlight the areas where the probability of the lightning is relatively high and measures such as cabling or improving the over-voltage protection can be allocated there. Finnish Meteorological Institute (FMI), for example, provides tailored weather services for electric utilities. The weather data is available in different formats, such as XML or FTP which enables it to be integrated directly to the analysis (FMI 2012).

The algorithm of the RRA is presented in figure 6.4. When the desired critical threshold for reclosings is exceeded in a feeder, the main question to solve is the cause. The evaluation of it starts from recognizing the location and the type of the fault. At first, the automatic analysing should be applied. Depending on the self-evaluated uncertainty, the function could propose either the straight corrective measures to be carried out by a field crew or patrolling to gather more information about the situation. The crew visit may consist only of visual inspections but also some additional measurements can be performed, for example thermal imaging or acoustic partial discharge measurements. In order to enable a work order for a crew patrolling requires, however, some estimation of the fault location and the cause is needed. It is not usually reasonable to order a patrol for the whole feeder without knowing what the crew should look for. In case of lightning, patrolling is not usually needed.

At times, a manual method of iterating the location of an intermittent or a high impedance earth fault is applied. This is based on the rise in the zero sequence voltage of the substation feeding the fault. The configuration of the network is changed so that a certain part of the presumably faulted feeder is switched to another substation. If the rise of the zero sequence voltage is also shifted to that substation, the fault is in the switched part of the network. However, this trivial method can be applied only certain suitable parts of the network since it requires another substation

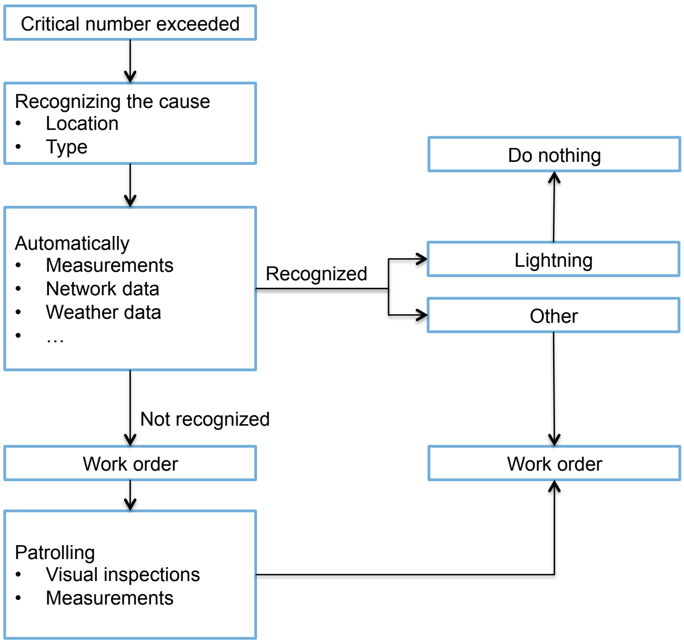


Figure 6.4. *The algorithm of repetitive reclosing analysis function*

and a meshed network topology. For these reasons it is not included in the function presented in figure 6.4. In addition to the zero sequence voltage follow-up, the modern feeder terminals have protection function for recognizing intermittent transient earth faults which could be used for recognizing these incidents (Vamp 2011). The similar switchings could be performed based on the alarms of this function. These methods are challenging to automate but it could be possible that the intermittent earth fault alarms would trigger a switching sequence of the FLIR functionality.

The impact of the major disturbances should be evaluated separately. In major disturbances, there are typically multiple faults within a short range and the cause of the faults is often obvious. Under these circumstances, there are not as much benefits for a tool described. In reverse, the inclusion of the reclosings during a major disturbance to the long-term analysis should be carefully considered. After the fault clearing of the major disturbance, threatening trees might still be left causing reclosings and recognizing these with the function would be beneficial. On the other hand, including these reclosings in the analysis without any indication of the major disturbance might cause misleading results in the long-term analysis.

The way of storing the fault history in a database enables applying data mining methods. If all the information related to the fault is examined, unexpected correlations could be found. The application of data mining requires all the data being available, well formed and accurate enough. Therefore it should be noted if the cause of the fault is based on an educated guess or is it confirmed some how.

Practical case study

Lastly a practical example is studied. The events took place in October 2012 in a rural area MV feeder. The process started from customers reclaiming of power quality. Before the customer reclamations, the network control centre was totally unaware of the problem. More thorough study of SCADA event list revealed eight feeder relay pick-ups for short-circuit within two hour time period. There was no circuit breaker operation since the occurrences lasted so short period at a time. The activated protection functions were the lowest overcurrent level and the undervoltage of the busbar. In five of these, a fault reactance was measured successfully. Based on the measured fault reactance, all the faults had occurred at the same location. Since there was no circuit breaker operation, the fault location calculation of DMS was not started nor was the disturbance recorder of the feeder terminal. The network in which the incidents occurred is presented in figure 6.5

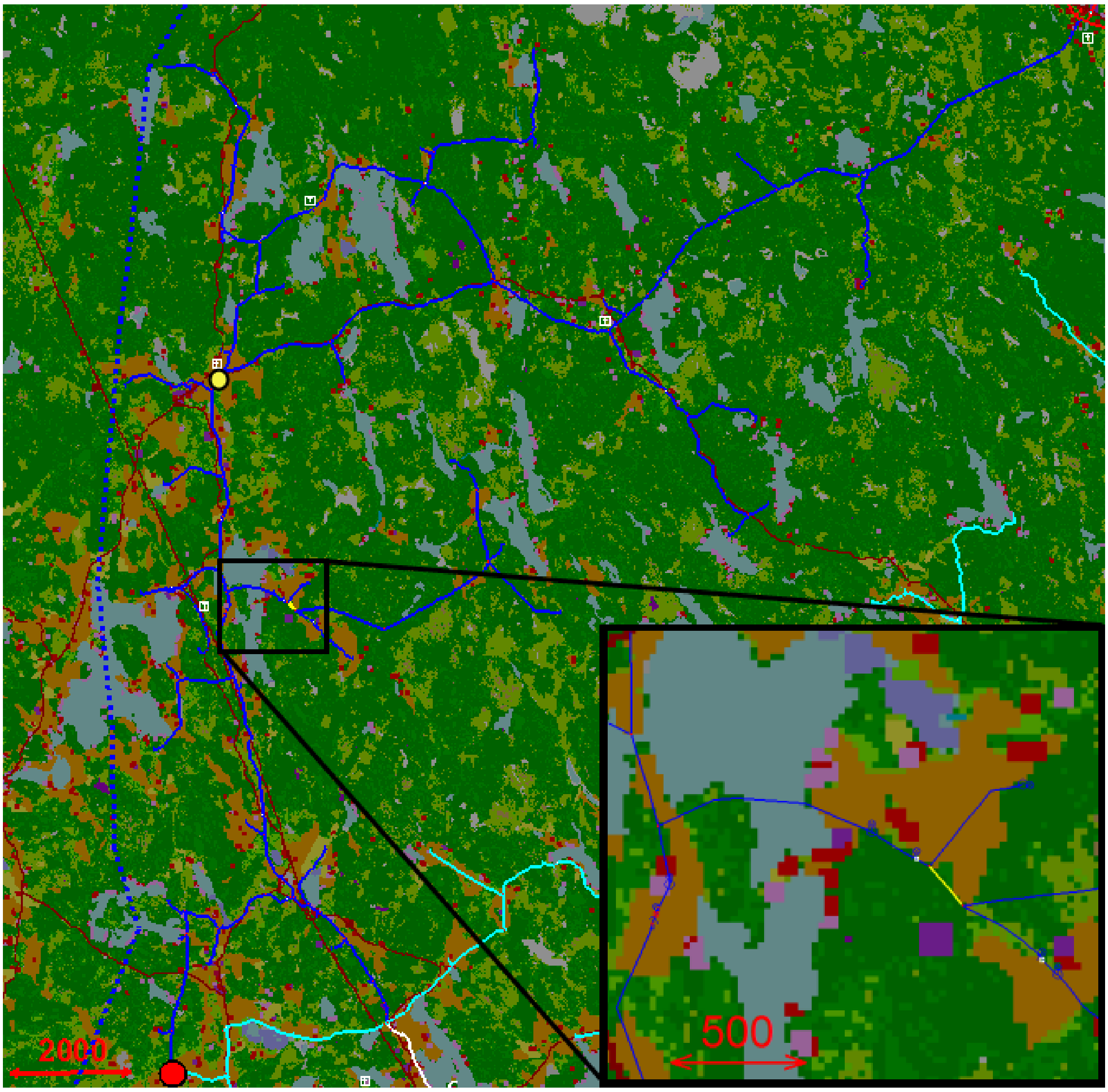


Figure 6.5. *The network of the practical case*

The faulted feeder is presented with a blue line in figure 6.5. The feeder is completely an overhead line with a total length of 82,5 km. The substation is illustrated with a red circle in the figure. There is also a remote recloser in the middle of the feeder and it is illustrated with a yellow circle. There is no Petersen coil for earth fault compensation at the substation, so the network is neutral-isolated. The unit of the scale presented in the figure is a meter.

An estimate of the fault location was made with the short-circuit calculations of NIS. The simulated overcurrent meeting the measured was at an overhead line 11,67 km from the substation and this points to location between the substation and the remote recloser. This part of the feeder is illustrated with a yellow line. The terrain in the estimated location was in the edge of a forest according to Corine Land Cover data represented in the background of the figure. This terrain data is available in NIS and the most recent dataset is from 2006. According to the maintenance data, the tree-clearing had been carried out in December 2010. The actual cause is still unverified but a tree is a promising candidate. The reclosings occurred within a relatively short time period. This supports the conclusions that the reclosings were caused by a tree bending due to wind conditions, for example. Unfortunately, there is no weather history data available from that time to verify the assumption. There were not patrolling or other measures taken since the incident caused only relay pick-ups instead of actual trippings. The cause disappeared also after these mentioned eight occurrences. All this relatively simple analysis had to be carried out manually requiring hours of labour work.

6.3.2 Disturbance records

A disturbance record is rather a resource for various functions than a function itself. Benefits can be seen for various purposes by exploiting disturbance records efficiently and therefore it is discussed here separately.

In general, the disturbance recorder is triggered when an abnormal event takes place in the network. In other words, a disturbance is needed to create data. As stated before, the intention is to turn from repairing the faults to preventing them from happening. Thus a conflict can be seen when paying attention to things that should no longer exist. However, the case is not that simple. The idea is to learn from previous conditions and by these means prevent the same problems from happening again.

The threshold values of the disturbance recorder can be set so that the recorder is triggered also from relay pick-ups, not only actual faults. If these pre-fault recordings were analysed efficiently, it would enable the clearing of the cause before it develops to a permanent fault. According to Yliaho (2008), the threshold should be set so low, that enough data is gained in every situation. On the other hand, this leads to excessive amount of data and it should be preprocessed by filtering to maintain the efficiency of the processing system. The limited storage capacity of the IEDs sets limitations for the disturbance records. With the present configurations of Elenia, a permanent fault with preceding fast and delayed reclosings is recorded in three parts: each operation separately. These three recordings are tightly related together but stored in separate files which makes the analysis unnecessary complicated. Along the original records, a combined file including all related records would ease the visual analysis.

In 2011, a total number of unexpected faults in the MV network of Elenia was 14 018 (Energy Market Authority 2012). The number includes also faults cleared by reclosing operations but it does not include reclosings preceding permanent faults. If the disturbance recorder is triggered also by a relay pick-up or some other abnormal occurrence, the number of the disturbance records would be multiple in comparison with the number of faults. In turn, only about 60 % of the substations of Elenia are equipped with a disturbance recorder at present but the number is continuously increased. Needless to say, there are no resources to study all the passed faults thoroughly by labour work. In many cases, the cause of a fault disappeared during a reclosing operation is left unknown and only educated guesses can be made. The most exceptional disturbances are analysed as comprehensively as possible.

In table 6.2 is examined the amount of disturbance records of a year. In that calculation, it is assumed that the records are made from every fault. Based on the fault history of Elenia, the faults are distributed as follows: Fast reclosings 55 %, delayed reclosings 20 % and permanent faults 25 % of all faults. In general, the number of records related to each fault type are respectively one, two and three. In the most abnormal occurrences, the fault affects not only in the faulted feeder but also the other feeders of the substation and the measurement bay. This leads to the activation of these bays' recorders as well.

In order to estimate the number of records, the average of activating bays is calculated. There are 133 substations with a total of 790 line feeders in Elenia and it is assumed that all of these are equipped with a disturbance recorder. Further it is assumed that all disturbance recorders in a substation are activated in every fault. The busbar feeder and the measurement bay are also equipped with a disturbance recorder and these should be included as well. The activated bays on average are

$$\frac{133 \cdot 2 + 790}{133} = 7,94.$$

With the assumptions mentioned above, the final number of records is as presented in table 6.2.

The required storage capacity of the records can be evaluated with the total number of records. The size of the record depends mainly on the specified sample rate, the number of channels recorded and the length of the record. The size of a record is assumed to be 0,8 MB. If we consider these constant in every fault type, it

Table 6.2. *The number of disturbance records in a year*

Interruption	Number of incidentes	Records / Incident	Records
Fast reclosings (55 %)	7 710	1	61 217
Delayed reclosings (20 %)	2 803	2	44 521
Permanent faults (25 %)	3 505	3	83 477
Total	14 018		189 215

leads the storage space requirement of 0,8 MB · 189 215 = 151372,0 MB = 147,9 GB in a year. If the disturbance recorders were configured so that they are activated also in relay pick-ups, it extends the number of records and the storage space requirement significantly. The result calculated can be held as the worst case scenario due to made assumptions. The target of the calculation was not to give the precise value but some idea of the space required.

Usually, it is informative to study the behaviour of the other feeders in addition to the faulted one and therefore it is desired to have records from these as well. The records can be categorized into four according to their relevance in incident. The most important record is the one from the faulted feeder. This can be considered as a directly related record. The records from the other feeders of a faulted substation are considered as related records. The third category is formed by indirectly related records from other substations than the faulted one but which are however triggered by that particular incident. If a record cannot be linked to any incident, it is considered as a miscellaneous record. A similar approach to the categorization was found by Davidson et al. (2006) but in meshed transmission networks. The main purpose of this categorization is to ease the finding the most important records. It is assumed that the present field communication system of Elenia is capable of transferring the records from the substations to the centralized system. However, some prioritization may be needed for example in case of multiple simultaneous faults. The categorization of the records could be used for prioritizing the transmission if it is carried out in the substation level.

Utilization of the records

The present state of disturbance record utilization is presented in section 4.2.4. The first step towards more efficient utilization would be making the records available in every disturbance or abnormal event occurred. This includes ensuring the fetching of the records from the feeder terminals to SCADA via RTU. A systematic storing for the records should also be arranged which would allow the records to be found and observed afterwards. According to the interviews of the control centre personnel, the record should be available in DMS. In practice this requires improving the SCADA-DMS interface so, that the DMS could fetch the record from SCADA database and show it to the operator on demand. If the threshold of the disturbance recorder was set at a low level, filtering should be applied so that every recorder event is not shown to the operator.

After the records are available for visual analysis in every occasion, the focus should be shifted to the automatic analysis. The data from disturbances is very heterogeneous. This makes it almost impossible to create comprehensive rules for analysis and a different approach should be considered. In following, the exploitation of disturbance records in fault analysis is discussed. A possible technique for the automated analysis of the cause of a fault is presented in general.

Case-Based Reasoning (CBR) is a form of artificial intelligence. The main idea is to exploit knowledge gathered with previously solved problems, cases. It has proven its potential especially in applications which could be difficult to generalize with models or rules, and where the reasoning is based mainly on tacit or experimental knowledge. (Montani & Jain 2010)

Aamodt & Plaza (1994) introduced a CBR cycle with four steps which describes the procedure of the CBR: When a new problem occurs, it is solved by retrieving one or more previously solved cases with similar properties, reusing the case and its solution, revising the solution based on knowledge gained from the previous case, and retaining the experiences from the new case by adding it to the case-base. The process is illustrated in figure 6.6.

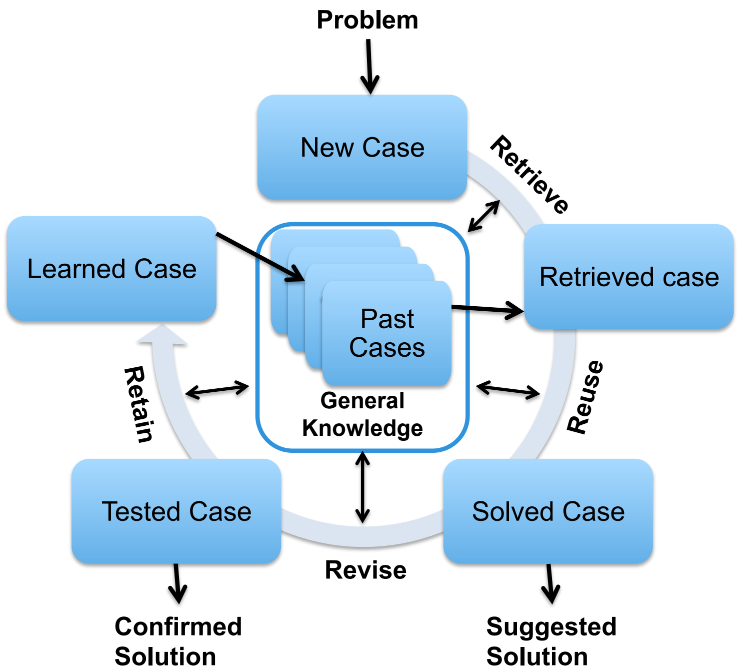


Figure 6.6. *The cycle of CBR (Aamodt & Plaza 1994)*

The CBR-based analysis has been exploited in various applications in manufacturing industry, for example. Bengtsson et al. (2004) have carried out a case study for CBR-based analysis for the end-testing of industrial robots. The main idea is to diagnose mechanical faults with sound analysis. The sound of operation is recorded with a microphone and the record is compared with the previous ones. The similarity of the new record and the previous ones is evaluated with the nearest neighbour algorithm which is not the most accurate but adequate for the application. Even though applications can be found from various industries, there are no applications for disturbance record analysis in electric utilities.

The major challenge of utilizing CBR is handling the similarities of the cases. A wide range of methods have been applied in academic research as well as in practical implementations. All these have a different approach for handling the uncertainties in the comparison. The nearest neighbour mentioned above is one of the most commonly used due to its simplicity. Also methodologies such as induction, fuzzy logic and bayesian methods have been successfully applied. (Myllymäki & Tirri 1993; Watson 1999) It should be carefully considered which is the most appropriate approach to the desired application.

In order to create and maintain the case base in electric utility industry, labour work is required for the analysis of the disturbance records. In practice this means solving the cause of the fault triggering the disturbance recorder and documenting the cause and the solution to a system with the record. As the number of solved cases in the case base increases, the requirement for the labour work decreases respectively. A great benefit for the system based on CBR is continuous learning. The changes in the distribution network and its technology are taken into account automatically since the new cases are continuously solved and the case base is updated.

A general challenge for the technique presented above is related to the execution time of the processing. If the function was desired to be usable in the network control centre, the execution time should be not more than minutes. The time includes fetching the record from the substation until the result is shown to the operator. Naturally, the function is useful also in secondary fault analysis carried out afterwards for unexceptional faults and for this the execution time limits are not as strict.

Even though applying the CBR does not require comprehensive rules for the analysis, some evaluation of the records should be carried out. The circumstances which have effect on the recording values should be known in general and these should be measured as well. In case of manufacturing industry, it is straightforward to standardize or measure the circumstances. In electric utility industry, it is more complex. The prevailing circumstances, the climate for example, have considerable effect on the behaviour of the quantities measured. In the worst case, two similar occurrences in the network could result in totally different disturbance records if the surrounding circumstances vary. Without knowing these affecting circumstances, the analysis is incapable of analysing the incident properly. Altogether, the effect of each factor should be studied separately so that the variables with the most significant effect will be found.

The CBR algorithm focuses on studying the cause of the fault. If the cause was known, it is possible to evaluate if the protection has operated as it should. This requires data from multiple sources: Setting values from feeder terminals, SCADA events related to the protection operation and fault location calculation results from the DMS. If the comparison shows that the feeder terminal has operated incorrectly, it should be taken into closer evaluation.

In figure 6.7, the CBR cycle presented above is applied to disturbance records. The input to the analysis is the record and the analysis is triggered by the SCADA event indicating the operation of the disturbance recorder. The new record is compared with the previously solved ones and if similarities are found, the previously found cause is evaluated. The foundation for the analysis is the assumption that the different incidents, for example trees bending slowly due to snow load or incipient cable insulation faults have a unique fingerprint for disturbance records. The evaluation includes also the analysis of the prevailing circumstances such as the climatic quantities or the loading of the network during the incident. All these are represented by the other information in the figure. If the surrounding circumstances differ remarkably, the correlation of the records could be questioned. If the correlation exists after the analysis of the circumstances, the previous record and the information related to it could be exploited.

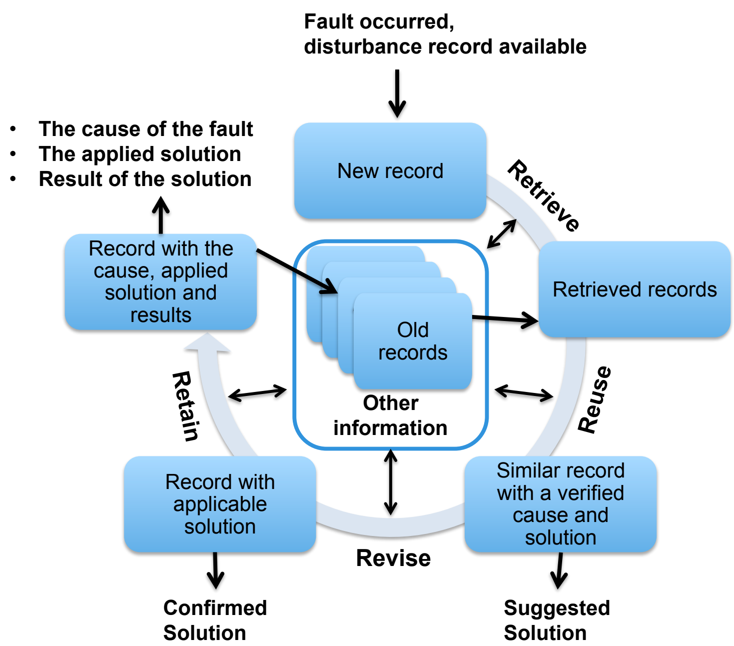


Figure 6.7. *The CBR-based analysis of disturbance records*

The previously solved record is stored with the information about the applied solution and its effects. If the solution was effective, it could be applied again. After the measures are carried out, the effects should be stored for further analysis. Altogether, the outputs of the procedure are the cause of the fault, the solution applied to remove the problem and the effectiveness of the solution.

The implementation of a CBR-based system should be carried out as follows. When the process of gathering the disturbance records is ensured, the records should be linked with the DMS fault data. DMS enables storing detailed data concerning the cause of the fault and prevailing circumstances. However, this feature is not fully exploited at present, even if the cause was resolved. Storing the fault data and linking the related disturbance records to it represent building the case base. After some data collecting, a study should be made to verify the potential of the cause analysis. This could be carried out by taking similar incidents from the fault history and comparing the related records. If the correlation was found, the analysis could be automated. By this approach, remarkable changes in present systems are avoided and the potential of the analysis is ensured before investing in new information systems.

The CBR would improve mainly the fault analysis. In addition to the improved fault analysis, other benefits can be found for the disturbance record analysis and these should not be neglected. The target for applying the CBR-based algorithms is not to replace other calculations which could be carried out for the records but supplement the utilization methods of the records. Therefore, the records should be made available also for calculations of different kinds. Some examples for more of a traditional analysis are presented next.

The estimation of the condition of a circuit breaker requires such quantities calculated as the times of the switching event, the simultaneity of the operations in different phases, cumulative currents and energy being switched and the number of switchings. The time related to the switching operation can be divided into time delay caused by the relay, mechanical operation time of the breaker and following arcing time. The algorithm should be capable of separate these times automatically. The change in these times could indicate the wearing. The wearing of the circuit breaker is studied relatively thoroughly. More specific algorithms and formulas are presented in the literature. (Peltola 2007)

As there are traditional calculation algorithms for the application presented above, the CBR-based method could be applied there as well. The wearing of the circuit breaker has effect on the behaviour of the quantities measured with the disturbance records and incipient faults could be recognized with CBR. However, this analysis should be separated from the CBR-enhanced fault analysis even if the algorithm was similar by its ideology.

The disturbance records could be used for replacement of periodical relay testing. An actual operation of the circuit breaker represents a relay testing with actual primary values. The idea is to compare the measured values as a disturbance record with the relay setting values. The comparison shows whether the protection has operated as desired or not. The replacement of the periodical testing also requires a systematic procedure which should be described in the maintenance program. A more detailed review to the topic is carried out by Vuorinen (2012, p. 37-40)

The economic benefits for the comprehensive disturbance records analysis are difficult to evaluate in general. As stated before, the disturbance records are a resource for functions of different kinds. They should be seen as part of a bigger solution for network management. The real benefits are gained from the functions and how they enable the enhancement of the actions and cost reductions in that manner. With the functionalities presented above, the benefits would consist of savings due to the optimized service interval of the primary equipment and avoidance of the faults.

7. CONCLUSIONS

This thesis concentrated on studying the process data and its utilization in the second largest electric utility in Finland. The process data studied in this thesis is provided by distribution automation and it was reviewed in a general level together with the present system of Elenia in order to gain understanding about the present state. The studied data sources were substations, automated disconnector stations, remote reclosers and smart meters. The study revealed that there is a wide range of data available and it is about to increase in the future due to the renovation of distribution automation devices.

At present, half of the substations of Elenia have modern IED-based feeder terminals installed. One third of the 147 substations and switching stations are equipped with previous generation numerical relays. The remaining substations are mainly based on older technology and these are being renovated in the near future. Over 80 % of the substations are capable of creating disturbance records in case of a fault. If all the substations were capable of disturbance recording, the annual number of records would be about 200 000. This sets a challenge for processing but also for storing and transferring the records. In addition to substations, there are approximately 3 000 automated disconnector stations and 130 remote reclosers providing process data. In practice, all the 408 000 customers of Elenia a have remote readable smart meter installed in their premises.

Understanding about the present state and the needs for improved process data utilization were gathered also by interviews of the personnel of Elenia. The interviews strengthened the idea about the underlying potential of gathered process data. The visions gathered from the interviews were refined into functions which lay the foundation of the Proactive Network Management System concept. In that sense, this thesis sets a guideline for the system-driven development of proactive network management in Elenia.

The original idea for the concept definition was that all the processing would be implemented in a single system. However, the functions discovered were so different by nature that it is not reasonable to implement them into the same system. Some of the functions would be more beneficial to implement in the existing systems as the other do not have a suitable spot in the present system environment. Thus a need for a novel system was verified and the general requirements for the system were examined. Furthermore, it was determined that the PNMS concept does not consist of a single system but a wide range of functionalities implemented in different systems. This led to the introduction of the hybrid topology which combines the benefits of different approaches. Nevertheless, scattering the functionalities around the system environment brings up the issue of management of the entity.

Two of the discovered functions were defined specifically. The repetitive reclosing analysis could be implemented in the DMS with relatively little effort. The function would ease the work of the control centre personnel and diminish the customer interruptions since the incipient faults could be recognized efficiently. The disturbance records would enable multiple profitable functions to be developed. The focus for the disturbance record analysis in this thesis was the improved fault analysis. A case-based reasoning algorithm for the analysis of disturbance records was presented but it requires more research to be done to verify its feasibility.

The main target for this thesis was to define a system concept for process data utilization. There was no precise specification made but the potential functionalities of the system were evaluated together with some general requirements of the system. The separate evaluation of different functionalities was found more reasonable than specifying an information system in the lack of knowledge about the actual usage. The functionalities can be divided into the functions of a novel information system and to the development of the existing systems. By these means, targets for the development of existing systems were found and another target set for this thesis was fulfilled. The initial assumption was that process data could provide valuable information for various levels of network management. This assumption was verified as well.

7.1 Further study and future work

Even this thesis raised up several new functionalities, only two of them were evaluated in detail. Despite the detailed analysis of the two, some questions remain with these as well. For the analysis of repetitive reclosings, the economic benefits should be evaluated. If the function was seen beneficial enough, a more detailed specification should be made together with the software vendor.

In order to enable the automatic analysis of the disturbance records, the effect of the prevailing circumstances on the records should be evaluated thoroughly. Instead of rushing into software development with an inadequate specification, some evaluation of the potential should be carried out. In case of the improved fault analysis, the disturbance records should be linked with the DMS fault data. The fault data should be stored in more detail as well. As the amount of data increases, the correlation between disturbance records could be evaluated. The evaluation of economic benefits should be carried also for the other functionalities based on disturbance records such as primary equipment condition monitoring and replacing the periodical relay testings.

The other discovered functionalities should be further studied to gain better understanding about the practical benefits, possibilities and requirements of each. At least the condition monitoring of disconnector stations can be improved with relatively simple effort since the data is already available. Also the possibilities of the integrated condition monitoring functions of the substation equipment should be studied.

The smart metering was included in this thesis as a data source to supplement the entity but the analysis of it was consciously left shallow. As the new generations of meters would provide more accurate measurements, the smart meters' potential for condition management will increase enormously.

Great potential lies beneath the previously mentioned off-line inspection data. The contractors should be encouraged to report the findings to the NIS and a systematic procedure should be created for the handling and verification of this data.

It would be interesting to see whether the recent data mining algorithms could find unexpected relations in data. This would require the data being well organized and available for the analysis of a novel system.

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Interviews

The interviewees are personnel of Elenia Verkko Oy unless otherwise mentioned.

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