CODEN:LUTEDX/(TEIE-5382)/1-87/(2016)

Industrial Electrical Engineering and Automation

Internet-of-Things in Low Voltage Electricity Grids

- Distributed Intelligence using 6LoWPAN and embedded Linux

Henrik Palmlund Wahlgren

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Internet-of-Things in Low Voltage Electricity Grids

Distrubuted Intelligence using 6LoWPAN and embedded Linux

ABSTRACT

When evaluating future technologies for smart metering and automatic meter reading (AMR) E.ON Elnät Sverige AB has set up a pilot to test a communication technology supplied by Connode AB. Connode have developed a mesh radio solution based on 6LoWPAN, IPv6 over Low Powered Wireless Personal Area Network. By using this technology the communication unit on every meter is acting as both receiver and sender of IP-based communication packets. The meters are aware of the other meters around them and automatically set up the best way to send a message. If two meters do not have a direct communication path to each other the message will be relayed via other meters until it reaches its destination. These meters will create a wireless network that covers a large area of the E.ON test site Hyllie in Malmö.

Connode has also developed a radio card that makes it possible to connect an embedded Linux platform, Intel Edsion, to the mesh network. By having this computer connected to the wireless network from the meters, this will enable a range of use cases within smart grid technologies taking advantage of using distributed computing in the low voltage grid.

This thesis has investigated what use cases this technology can be used for. Some of the use cases defined were also implemented by developing two demonstration boxes. The demonstration boxes made it possible to implement the use cases without having an actual grid to test on. The demonstration boxes represent a facility and a substation. In each box there is an embedded computer with a mesh radio communication module. The embedded computer has all grid information via the I/O from the demonstration boxes to be used in the use cases.

The use cases that were defined were among others, anti-islanding protection, prioritized automatic disconnection, substation controller and demand response controller. Of these the ones clearly implemented were the anti-islanding protection, prioritized automatic disconnection and the substation controller.

The following was performed during the thesis.

- Interviewing E.ON employees
- Defining use cases
- Design of simulation platform for use cases
- Construction of simulation platform
- Development of software for simulation platform
- Evaluation of 6LoWPAN and Connode's implementation for usage in smart grid applications.

Using distributed computing in smart grid applications is clearly a very promising way to handle the future complexity of the modern grid. But it is still the communication technology that will be the crucial part of the solutions since some use cases will depend

on high data throughput and transport integrity. This can somewhat be overcome by optimising the architecture of such solutions but still for larger deployments the communication is the limiting factor.

The Connode solution seems very promising, but there are a few issues that are in the way when planning to use the technology for a larger implementation of smart grid. It needs to be stressed that the Connode solution of connecting embedded computers is just for development use and not for production, but some other factors are still in the way. One major issue is the separate IP address that the computer gets that is separated for the meters IP addresses. This makes the solution server unaware of the computer and separate systems must be implemented to be able to use the computer in distributed intelligence architecture. It is also needed to implement all the security features that is already implemented in the metering solution, the embedded computers are not able to use the same features from the Connode server. Also it is not possible for the distributed computers to talk directly to the meters as they must go via the Connode server. At last it was seen that for many use cases a full embedded Linux distribution might be somewhat excessive.

SAMMANFATTNING

Vid utvärdering av framtida tekniker för smarta elmätare och automatisk mätaravläsning (AMR) har E.ON Elnät Sverige AB startat en pilot för att testa en kommunikationsteknologi som tillhandahålls av Connode AB. Connode har utvecklat en mesh-radio-lösning baserad på 6LoWPAN, IPv6 over Low Powered Wireless Personal Area Network. Genom att använda denna kommunikationsteknik på varje mätare fungerar de både som mottagare och sändare av IP-baserade kommunikationspaket. Mätarna är medvetna om de andra mätarna kring sig och sätter automatiskt upp det bästa sättet att skicka ett meddelande. Om två mätare inte har en direkt kommunikationsväg till varandra kommer meddelandet att vidarebefordras via andra mätare tills den når sin destination. Dessa mätare kommer att skapa ett trådlöst nätverk som täcker ett stort område av E.ON:s mätplats Hyllie i Malmö.

Connode har också utvecklat ett radiokort som gör det möjligt att ansluta en inbyggd Linux-plattform, Intel Edison, till mesh-nätverket. Genom att ansluta inbyggda system till det nätverk som mätarna skapar möjliggör för en rad användningsfall inom smarta nät som drar fördel av att använda distribuerad databehandling i lågspänningsnätet. Detta examensarbete har undersökt vilka användningsfall denna teknik kan användas för. Några av de användningsfall som anges testades även genom att utveckla två demonstrationslådor. Demonstrationslådorna gjorde det möjligt att genomföra de användningsfall utan att ha ett verkligt nät att testa på. Demonstrationslådorna representerar en anläggning och en transformatorstation. I varje låda finns en inbäddad dator med en radiokommunikationsmodul. Den inbyggda datorn har all information från nätet via I/O från demonstrationslådorna.

De användningsfall som definierats var bland annat anti-ödrifts-skydd, prioriterad automatisk avstängning, nätstations-controller och laststyrning-controller. Av dessa implementerades bland annat anti-ödrifts-skydd, prioriterad automatisk avstängning och nätstations-controller.

Följande moment genomförders under examensarbetet.

- Intervjuer med E.ON-anställda
- Framtagande av användarfall
- Design av simuleringsplatform
- Konstruktion av simuleringsplatform
- Utveckling av mjukvara för simuleringsplatform
- Utvärdering av 6LoWPAN och Connode's implementation för användning i smart grid applikationer.

Att använda distribuerad intelligensen i det smart nätet är helt klart ett mycket lovande sätt att hantera den framtida komplexiteten i det moderna elnätet. Men det är

fortfarande kommunikationstekniken som kommer att vara den avgörande delen i lösningarna, eftersom vissa användningsfall kommer att bero på hög datagenomströmning och dataintegritet. Detta kan övervinnas något genom att optimera arkitekturen i sådana lösningar, men fortfarande för större utbyggnad är kommunikationen den begränsande faktorn.

Connodes lösning verkar mycket lovande, men det finns några frågor som är hindrande när man planerar att använda tekniken för en större tillämpning i smarta elnät. Det måste betonas att Connode lösning för att ansluta inbäddade datorer är bara för utvecklingsändamål och inte för produktion, men några andra faktorer är fortfarande i vägen. Ett stort problem är den separata IP-adress som datorn blir tilldelad i förhållande till den IP adress som kommunikationskortet och mätarna har. Detta gör Conodes server omedveten om datorn och separata system måste implementeras för att kunna använda datorn i en arkitektur för distribuerad intelligens. Det behövs också extra utveckling för att för att införa alla de säkerhetsfunktioner som redan används av Connode-servern då den inbäddade datorn inte kan använda samma funktioner från Connode-servern. Det är inte heller möjligt för de distribuerade datorer att kommunicera direkt med mätarna utan de måste gå via en Connode server. Till slut har det framgått att för många användningsfall är en fullständig Linux-plattform något överdriven.

CONTENT

1. Introduction 7
1.1 background 7
1.2 Purpose And Goals 7
1.3 About E.ON and E.ON Elnät Sverige AB 8
2. Smart Grid 9
2.1 Overview 9
2.2 Smart Grid Architecture Model 10
2.3 Smart Grids At E.ON 14
2.3.1 Hyllie, Smart city project 14
2.3.2. Local Energy System 14
2.3.3. 100Koll 14
2.4 Smart Metering 15
3. Real Time Measurement and Smart Metering Project 17
3.1 Overview 17
3.2 Technology 17
3.2.1 OVerview 17
3.2.2 6LoWPAN 18
3.2.3. COAP 20
3.2.4 Connode product 20
3.2.5 Intel Edison 22
4. Use Cases 25
4.1 Methodology 25
4.2 Prioritized Automatic Disconnection 26
4.2.1 Overview 26
4.2.2 Value added 26
4.2.3 Requirements for implementation 26
4.2.4 Evaluation 27
4.2.5 SGAM Mapping 28
4.3 High resolution logging 30
4.3.1 Overview 30
4.3.2 Value Added 30
4.3.3 Requirements for implementation 30
4.3.4 Evaluation 30
4.4 Substation Controller / Surveillance System 31
4.4.1 Overview 31
4.4.2 Value Added 32
4.4.3 Requirements for implementation 32
4.4.4 Evaluation 32
4.5 Demand Response Controller/Enabler 33
4.5.1 Overview 33
4.5.2 Value Added 36
4.5.3 Requirements for implementation 36
4.5.4 Evaluation 36

4.6 Protocol bridge 37
4.6.1 Overview 37
4.6.2 Value Added 37
4.6.3 Requirements for implementation 37
4.6.4 Evaluation 37
4.7 Increased size of solar PV installation in strong and weak grid 38
4.7.1 Overview 38
4.7.2 Value Added 39
4.7.3 Requirements for implementation 39
4.7.4 Evaluation 39
4.7.5 SGAM Mapping 40
4.8 Anti-Islanding protection 42
4.8.1 Overview 42
4.8.2 Value Added 43
4.8.3 Requirements for implementation 43
4.8.4 Evaluation 43
4.9 Phase-shifter for single-phase production 44
4.9.1 Overview 44
4.9.2 Value Added 44
4.9.3 Requirements for implementation 44
4.9.4 Evaluation 45
4.9.5 SGAM Mapping 45
4.10 Distributed load analysis 47
4.10.1 Overview 47
4.10.2 Value Added 47
4.10.3 Requirements for implementation 48
4.10.4 Evaluation 48
5. Implementation of use-cases 49
5.1 Overview 49
5.2. Facility Platform 50
5.3. Substation Platform 52
5.4. Inside the boxes 54
5.5 Software 56
5.5.1. Local 56
5.5.2. Server 58
6. Results 59
7. Discussion 69
7.1 Smart Grid applications 69
7.2 Demonstration Platform 71
7.3. Mesh radio solution by Connode AB 71
7.3.1. The hardware platform, Intel Edison 71
7.3.2. Connode Agent 72
7.3.3. Connection to Internet over Connode 6lowpan mesh 72
7.3.4. Review of radio performance 73
7.3.5. Possible IMPROVEMENTS 74

7.4 Smart Grid integrated in Smart Metering 75
8. Future work 77
8.1 Connode Solution 77
8.2 Demonstration Platform 78
8.3 Smart Grid 79
8.4 Smart Metering 80
8.5 New areas of interest 80
9. Conclusion 81
References 82

1. INTRODUCTION

1.1 BACKGROUND

E.ON Elnät Sverige AB is evaluating an IPv6-based mesh-radio communication technology (6LoWPAN) from Connode AB at E.ON's smart city test site Hyllie, Malmö, Sweden. This technology enables E.ON to collect meter values from electricity meters via radio, having all meters relay messages from other meters to enable the messages to reach the Internet. Since the communications is using 868 MHz the range of the radio is long and when fitting all electricity meters with this technology it will create a mesh network that will span all of Hyllie. E.ON Elnät wants to evaluate if this mesh network could be used for other applications than automatic meter readings (AMRs).

Connode's hardware on the electricity meters is microprocessor based but to be able to use their technology in smart grid evaluation projects they have developed a hardware shield that fits the Intel Edison platform with Arduino breakout board. Instead of using their microcontroller solution, the program to control the communication stack is run in the embedded Linux environment that Intel Edison is using. Since there is a full embedded Linux environment it is possible to extend the functionality of the Intel Edison with our own programs handling smart grid applications. Using small, embedded devices where communication to every device is possible using IP is commonly known as the Internet-of-Things.

1.2 PURPOSE AND GOALS

The purpose of this master thesis is to help E.ON Elnät get a firmer knowledge of the possibilities with more access to more information from their low voltage electricity grid. It will also increase E.ON Elnät technological knowledge in Internet-of-Things, Smart Grid and Smart Metering and how the technologies can work together to form valuable solutions for both the grid operator and the customer.

The Intel Edison together with Connode mesh radio solution is quite new and untested and this thesis will also evaluate the functionalities for this technology in Smart Grid applications.

The goals of the master thesis are to define and evaluate use cases for Smart Grid applications using small embedded devices for distributed intelligence and design a demonstration of those use cases that seem the most promising. It was decided that the Connode mesh radio solution and the Intel Edison should be used in the demonstration.

1.3 ABOUT E.ON AND E.ON ELNÄT SVERIGE AB

EON Group is one of the world's largest private energy company with over 30 million customers, primarily in the electricity, gas and heat.

The E.ON Group includes 50 sub-groups and subsidiaries in Europe and the United States. E.ON headquarters is in Essen, Germany,

E.ON Sweden is working with electricity, natural gas, LPG, heat, cooling and energy from waste. The subsidiaries of E.ON Sweden form, together with a number of group management features, a complete energy group. Head office is located in Malmö.

One of these subsidiaries is E.ON Elnät Sverige AB, which is responsible for distributing electricity to around one million end customers in Sweden.

2. SMART GRID

2.1 OVERVIEW

Smart grid is considered a very wide concept where it could refer to an adaptable electricity grid and its components or services based on the information exchange between systems and users.

Oxford dictionary defines Smart Grid as:

"An electricity supply network that uses digital communications technology to detect and react to local changes in usage"

Whilst the European Regulators' Group for Electricity and Gas (ERGEG) has defined it like:

"An electricity network that cost efficiently can integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both - in order to ensure a sustainable power system with low losses and high levels of quality, security of supply and safety."

The differences of these two definitions are that they take into account different aspects of what smart grids are. It also shows that there is still a debate of what exactly smart grid means. It could on one hand, close to the current way of power distribution, be a grid-centric and production focused way of thinking, using communication to optimize the grids function and operation. On the other hand it could be considered a more user-centric and consumption focused way of thinking.

In a grid-centric view, a smart grid could be seen as the distribution operator trying to optimize all aspects of their grid, with their own recourses. But the user-centric smart grid goes beyond the distribution system operators' (DSO) facilities and components to make use of the things that are actually consuming the energy, the end users are more involved in their energy consumption and the grid operator creates possibilities for controlling the users' consumption or production. This could either be done with a tariff that makes the users want to consume or produce at the right times or the grid operators could be directly connected to the end users' facilities and components and control them automatically within agreed limits.

In Sweden the Swedish Energy Market Inspectorate (EI) has issued a report on smart grids and what needs to be solved in the conversion of the Swedish electricity grid (Swedish Energy Market Inspectorate, 2010). EI wants Smart Grids to:

- Ease the introduction of renewable electricity production.
- Improve incentives to more efficient energy usage

- Contribute to power reduction at peak load.
- Create better conditions for active electricity customers.

2.2 SMART GRID ARCHITECTURE MODEL

The use if the Smart Grid Architecture Model (SGAM) and its methodology have been developed to assist in the design of Smart Grid use cases in an architectural and conceptual way but still being solution and technology neutral (CEN-CENELEC, 2012).

At the base of the SGAM is the Smart Grid plane, see figure 1. It represents the physical domains and of the electrical energy conversion chain and the hierarchal zones of the management of the electrical process. The domains and zones are described in more detail in table 1 and table 2.

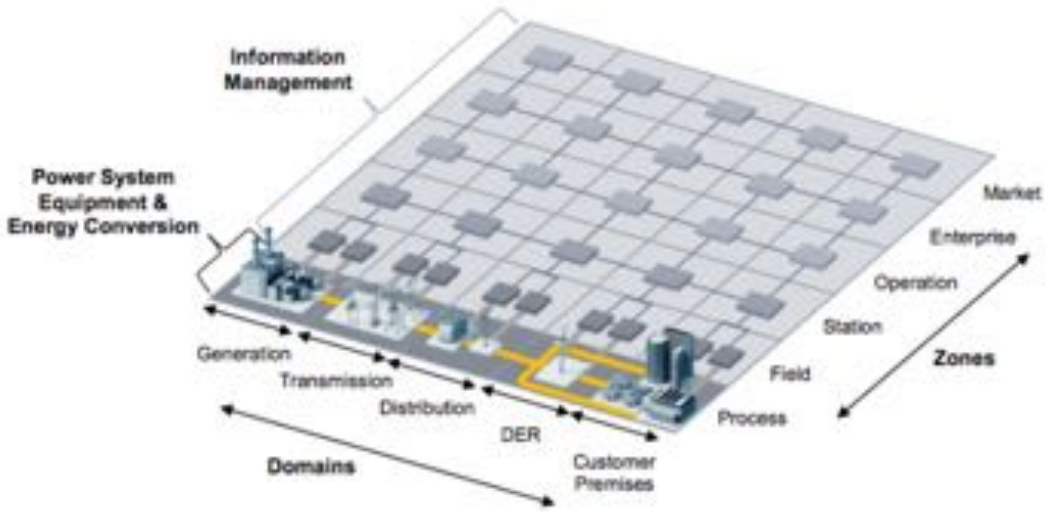

Figure 1, SGAM Plane, ***Source: CEN-CENELC-ETSI Smart Coordination Group***

Table 1, SGAM Domains

Domain	Description
Generation	The generation domain represents generation of large amounts of electrical energy. Typically by fossil, nuclear and hydro power plants, off-shore wind farms, large scale photovoltaic (PV) power. These are usually connected to the transmission system

Transmission	The transmission domain is representing the infrastructure and organization, which transports electricity over long distances.
Distribution	The distribution domain represents the infrastructure and organization, which traditionally distributes electricity to customers.
DER	The distributed electrical resources (DER) domain represents electrical resources, directly connected to the public distribution grid, using small-scale power generation and storage technologies. These distributed electrical resources could be directly controlled by the distribution system operator (DSO)
Customer Premises	The customer premise domain is hosting both users of electricity but also producers of electricity. The premises include industrial, commercial and residential facilities. Generation in form of e.g. photovoltaic generation, electric vehicles storage, batteries, micro turbines are hosted here.

Table 2, SGAM Zones

Zone	Description
Process	The process zone contains primary equipment of the power system (e.g. generators, transformers, circuit breakers, overhead lines, cables, electrical loads ...), as well as physical energy conversion (electricity, solar, heat, water, wind).
Station	The station zone represents the aggregation level for the fields, e.g. for data concentration, substation automation etc.
Operation	The operation zone is containting the power system control operation in the respective domain, e.g. distribution management systems (DMS), energy management systems (EMS) in generation and transmission systems, microgrid management systems, virtual power plant management systems (aggregating several DER), electric vehicle (EV) fleet charging management systems.

Enterprise	The enterprise zone includes commercial and organizational processes, services and infrastructures for enterprises (utilities, service providers, energy traders), e.g. asset management, staff training, customer relation management, billing and procurement.
Market	The market zone reflects the market operations possible along the energy conversion chain, e.g. energy trading, mass market, retail market, etc.

To be able to have a clear presentation and a simpler handing of the model, interoperability aspects are gathered into five abstract interoperability layers. In figure 2 they are visualized and in table 3 the different layers are described.

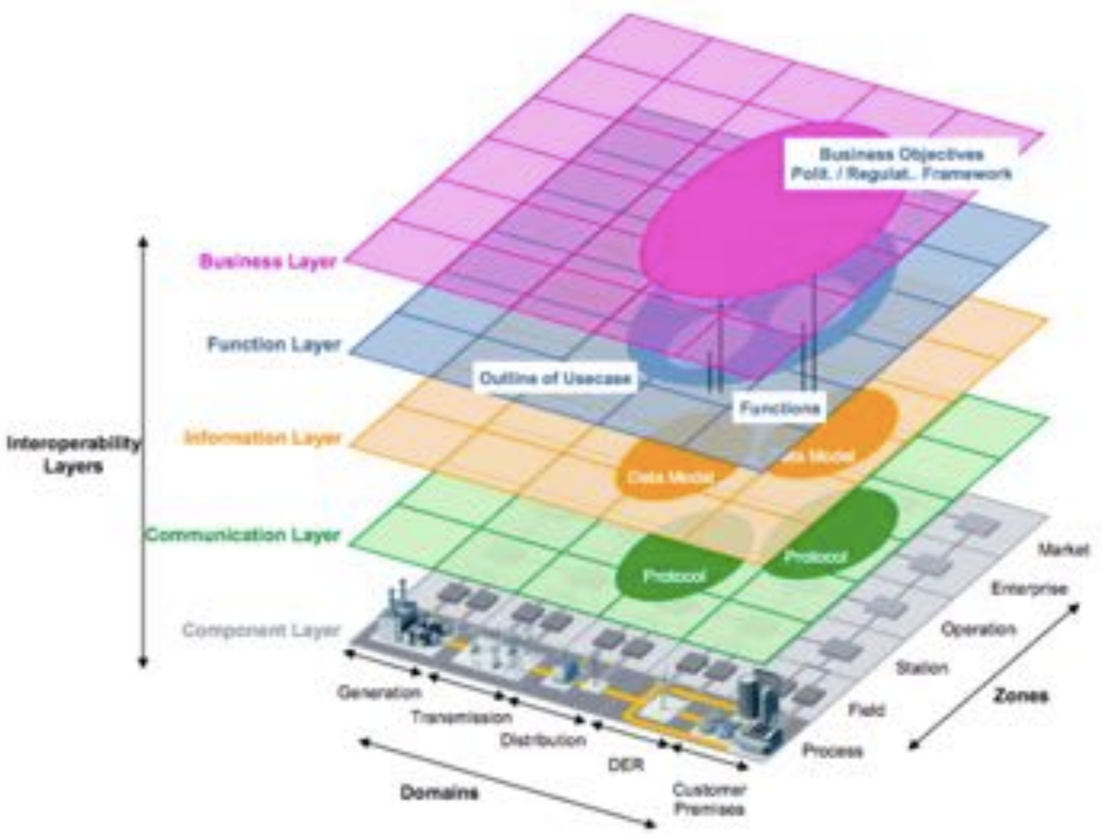

Figure 2, SGAM with interoperability layers, ***Source: CEN-CENELC-ETSI Smart Coordination Group***

Table 3, SGAM Layers

Layer	Description
Component Layer	The component layer is the physical distribution of all participating components in the smart grid model. This includes actors, applications, power system equipment (typically located at process and field level), protection and telecontrol devices, network infrastructure (wired/wireless communication connections, routers, switches, servers), and any kind of computers.
Communication Layer	The communication layer is to describe protocols and mechanisms for the interoperable exchange of information between components in the context of the underlying use case, function or service and related information objects or data models.
Information Layer	The information layer describes the information that is being used and exchanged between functions, services, and components. It contains information objects and the underlying canonical data models. These information objects and data models represent the common semantics for functions and services in order to allow an interoperable information exchange.
Function Layer	The function layer describes functions and services including their relationships from an architectural viewpoint. The functions are represented independent from actors and physical implementations in applications, systems, and components. The functions are derived by extracting the use case functionalities and are independent from actors.
Business Layer	The business layer represents the business view on the information exchange related to smart grids. SGAM can be used to map regulatory and economic (market) structures and policies, business models, business portfolios (products & services) of market parties involved. Also business capabilities and business processes can be represented in this layer.

2.3 SMART GRIDS AT E.ON

2.3.1 HYLLIE, SMART CITY PROJECT

In 2011 E.ON, the City of Malmö and VA Syd signed a Climate Contract for Malmö's largest development area, Hyllie. Cooperating they plan on making Hyllie the most climate-smart city district in the Öresund region. By 2020, Hyllie is supposed to be supplied by 100 % renewable or recycled energy. To reach this goal there is need for developing smart grids that will contribute to more efficient energy use. With this technology, people will actively be able to measure, control and influence their own energy consumption, and to become energy producers themselves.

It is the smart city project E.ON have been looking into new smart metering technologies and possibilities for smart grid solutions in low voltage grids that is the background to this thesis.

2.3.2. LOCAL ENERGY SYSTEM

E.ON Elnät is planning a project in Local Energy Systems (LES) in Sweden. The LES is a system that with the help of smart grid technology integrates renewable energy sources and creates a self sufficient supply of electricity within a limited area of the main grid. It will be possible to isolate the area from the central electricity grid but also possible to use the stability of the central grid if needed. The components that will be integrated are solar power, wind power, energy storage and a controllable generator.

The project will be in small scale, around 100 kW – 1 MW. The purpose of the project is to answer the questions about if LES is a valid alternative to the central grid, now and in the future, and how all parties can benefit from it

2.3.3. 100KOLL

The sales company within E.ON is running a project called 100Koll, meaning something like a hundred percent awareness (E.ON Sverige AB, 2015). It is about connecting a small device to your electricity meter that sends real time consumption data to E.ON servers. E.ON then provides an app to the customer so that they can monitor their energy usage. E.ON also provides so called SmartPlugs. The SmartPlugs are controllable switches plugged directly into an electricity socket. Via the 100Koll app it is possible to schedule the on and off of these switches and it is also possible to control the actions directly. This project is to help customers get aware of their electricity usage and help them reduce it.

2.4 SMART METERING

What smart meter means is, as smart grids, not completely defined. The main concept is that it is possible to communicate with the meter remotely so that the meter does not have to be read locally by a person. Then the smart meters differ in functionality as in communication methods. Some smart meters only enables the grid operator to communicate with them and other also enables the end customer to get its consumption online or on an in-house display. Some also differentiate between Automatic Meter Reading (AMR) and Smart Metering, where the AMR is just collection of data remotely and the Smart Metering refers to extra functions such as power outages notifications and power quality monitoring.

In Sweden the first roll-out of smart meters started by the legislation that by 1 June 2009 all customers should be billed their actual consumption with hourly metering for large customers and monthly metering for household customers. This was decided so that the customers could get a better understanding of their energy consumption (Swedish Energy Market Inspectorate, 2007). Since 2012 it is also possible for household customers to have their consumption measured per hour without any extra cost for the customer (Swedish Energy Market Inspectorate, 2014). E.ON have already started projects in this using the meters that have already been rolled out to the customers.

The next step is to roll out new electricity meters with new functionalities (Swedish Energy Market Inspectorate, 2015). E.ON is investigating what other functionalities the meters should have and is preparing for the roll out of the next generation of electricity meters. It is from this work, evaluating technologies for new smart meters that this master thesis has sprung.

3. REAL TIME MEASUREMENT AND SMART METERING PROJECT

3.1 OVERVIEW

E.ON is right now evaluating IP based communication to smart meters. The technology provider is Connode AB that has developed a system for mesh radio communication that will be used to connect meters in Hyllie, Malmö. The purpose of this project is to test this technology and evaluate the possibilities it could create for Advanced Meter Infrastructure (AMI) applications and smart grid applications. In the beginning of the project around a hundred meters and communication nodes will be installed in Hyllie. The plan is to extend this to a maximum of 1000 nodes if the preliminary tests go well. One mission is to be able to convert the dedicated electricity meter standard, DLMS/COSEM, that is used by the meter to represent its different values to CIM (Common Information Model) standard to ease the communication with upstream information systems, since CIM is widely adopted by transmission system operators (TSOs). For the communication there will be extensive connectivity tests when the meters are deployed. To be able to evaluate the mesh functionality some meters will be installed in boxes that can be moved around Hyllie. Also the rate of data collection will be varied to investigate how the radio network acts under high load and if it is possible to use the technology for real time measurements of the meters. It has been tested that it is possible to get an on-demand reading in a few seconds but the effect of having a large amount of meters sending values continuously needs to be investigated.

Connode AB has also developed a solution that makes it possible to connect other devices than the meters to the mesh network and thereby accessing the Internet via IP communication. This thesis is focusing on the smart grid applications that connecting devices to the Internet-of-Things could aspire. It will also investigate the possibilities of distributing intelligent systems and computing power in the low voltage grid. In the thesis, the solution from Connode AB will be used as a development platform.

3.2 TECHNOLOGY

3.2.1 OVERVIEW

The Internet of Things or IoT is difficult to define precisely. It is a concept of having machines, vehicles and a large range of different devices that are connected to the Internet using different forms of IP communication. The devices are embedded with electronics, sensors, actuators, software and network connectivity that enables the device to collect and exchange data.

When a device can represent itself digitally it becomes something greater than just the device by itself. The device doesn't just relate to its user, but it is now connected to surrounding devices and all the data found on the Internet. By using many devices in conjunction, with or without an overlaying system, advanced functionalities can be accomplished.

3.2.2 6LOWPAN

6LoWPAN , IPv6 over Low-Power Wireless Personal Area Networks , is a networking technology that enables IPv6 packets to be carried within small link layer defined in IEEE 802.15.4 (Internet Engineering Task Force (IETF), 2011). IEEE 802.15.4 is a standard that defines the physical layer for low-power wireless networks. 6LoWPAN enables the usage of end-to-end IP communication that can utilize the infrastructure of the Internet.

6LoWPAN supports meshed network structures. A mesh network is a network where multiple wireless nodes can route messages to other nodes that is out of range of the sender. In figure 3 a network structure is shown with a 6LoWPAN edge router acting as the gate from the radio network and the normal Internet. There is always need for an edge router to all 6LoWPAN clusters. It is possible to use multiple edge routers in a cluster to increase the efficiency and limit the numbers of hops a message has to do before it reaches the normal Internet. The edge router could also assist in getting IPv6 to work on IPv4 networks by encapsulating IPv6 traffic in IPv4 packets.

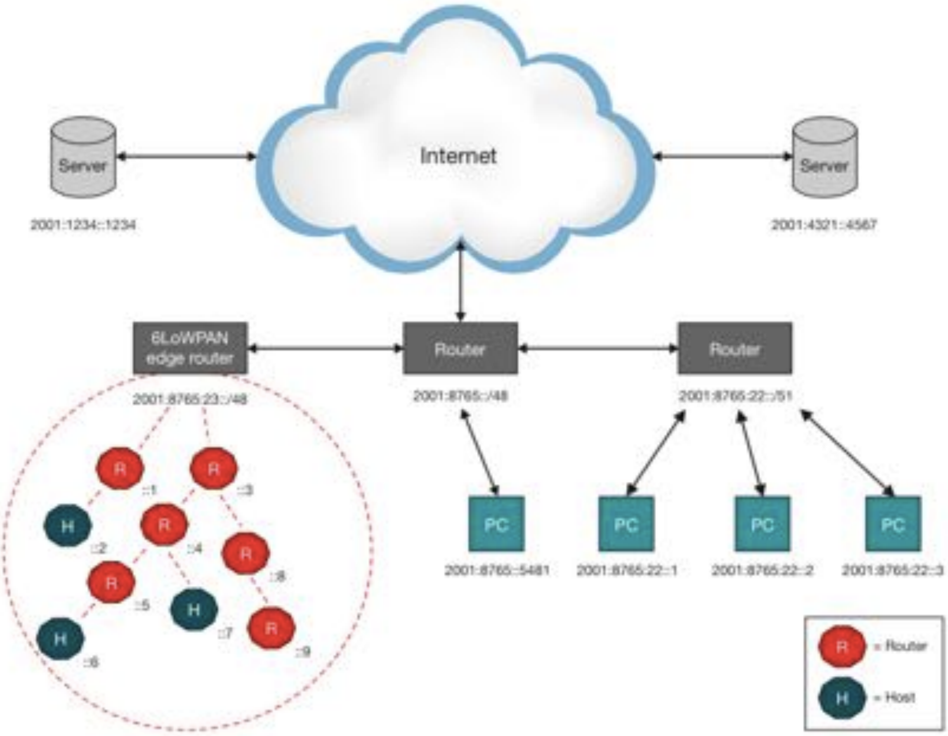

Figure 3, 6LoWPAN network structure, ***Source: Texas Instrument: 6LoWPAN Demystified***

The nodes in a 6LoWPAN can be divided into two categories. Routers and hosts, or end devices. The routers are able to route messages across the network and end devices cannot. The routers are usually always on since they are supposed to route the traffic. If one goes down or the radio conditions change the routers will rewrite its routing tables and having routers always go in and out in the network creates too much traffic on the network. To get around this problem there are end devices. These devices do not route any traffic and if one of these devices goes down no rerouting will be done. This is good for very small, embedded systems that have limited computational capacity and power supply, like battery-powered units. In a smart grid architecture the nodes and routers would be distributed energy resources like, solar inverters, meters, heat pumps etc.

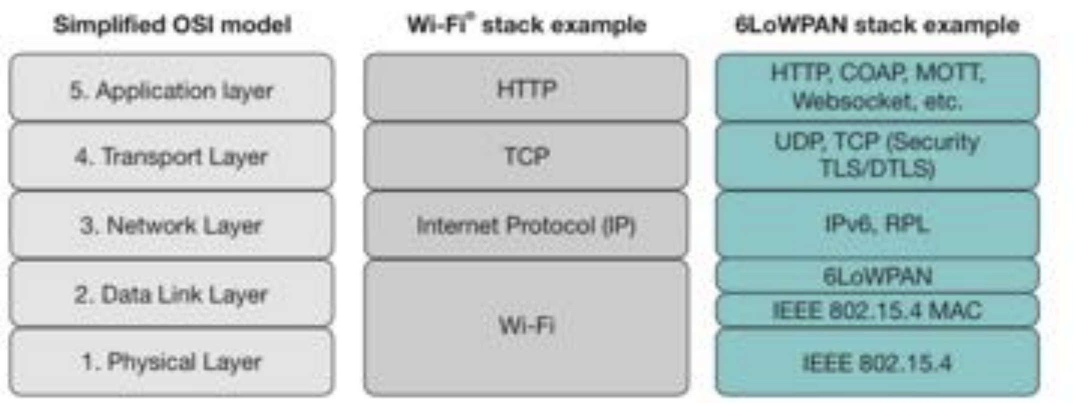

Figure 4, Visualization of the 6LoWPAN stack., ***Source: Texas Instrument: 6LoWPAN Demystified***

The 6LoWPAN stack supports all normal IP-applications standards, see figure 4. But when using meshed networks it is usually common to only use UDP (User Datagram Protocol) instead of TCP (Transmission Control Protocol). The problem with TCP is that it is a connection-based protocol and to set up a connection several handshake messages will be sent and this would create a lot of traffic in the radio network and create problems for all other units trying to send data. UDP is not connection based which is better for the network but introduces other problems for applications. One of them is that there is no guarantee of that a message is transferred properly.

TCP also has a large overhead data that would be unwanted to send over a constrained wireless networks. But if an application is using UDP instead there is no guarantee that the message arrives. Having a large message will introduce fragmentation of the message so that it can fit in the 127 byte long message frame of 6LoWPAN. If a UDP message is split into several messages and there is no guarantee that any of those messages arrive the probability for that the full message arrives intact and in correct order is decreased. Therefore it is desirable to have all messages on in the 6LoWPAN network to conform to the 127 byte message frame.

When using IPv6 the IP header of the message is even larger than in IPv4 and will take up a large amount of the available frame length of 6LoWPAN. To work around this problem header compression is used. Header compression uses that fact that the IPv6 structure is hierarchical. This means that all devices under an edge router will have a part of the edge router's IP-address in their own IP-address. Since all traffic goes through the edge router there is no need to use that part of the IP-address within the wireless radio network. All incoming traffic gets stripped of the unnecessary parts of the IP-address and all outgoing traffic gets the full IP-address added to it.

3.2.3. COAP

TCP is the most common protocol on the Internet today and HTTP (HyperText Transfer Protocol) is commonly used as application layer protocol. TCP and HTTP create large overheads and are not suitable for use in constrained environments. To get similar functionality as HTTP over TCP for UDP traffic CoAP, Constrained Application Protocol, was created

CoAP runs over UDP and features REST (Representational State Transfer) access to recourses over the Internet on constrained devices with support for URI (Unique Resource Identifier) on formats like "coap://www.someurl.com/sensor/temperature". To further reduce the overhead it is common to use predefined recourse identifier so that the URI would be on the format "coap://www.someurl.com/3/12".

CoAP also supports discovery of resources to predefined CoAP services, subscription to recourse, generation of push notifications, caching of values for sleeping nodes and confirmable messages. The confirmable messages handle the UDP problem of that the messages are not guaranteed to reach its destination. CoAP also supports mapping to HTTP so that proxies between CoAP and HTTP can be built, making it easier for devices to communicate with services based on TCP. CoAP can be secured with DTLS (Datagram Transport Layer Security), the equivalent of TLS (Transport Layer Security) for TCP providing very secure communication.

3.2.4 CONNODE PRODUCT

Connode AB offers a complete system, Connode 4, for communication based on 6LoWPAN, see figure 5. They have their agent embedded in smart meters and are able to collect values via CoAP to their service server. Through the server all nodes can be controlled, read on demand and get their software updated. The Connode Server also controls all the networking and supplies all mesh clusters with their IPv6 address and can also tunnel traffic over IPv4 if for example the cellular connection of a mesh gateway doesn't support IPv6. To secure the transmission DTLS is used and there is also encryption applied to the radio communication itself.

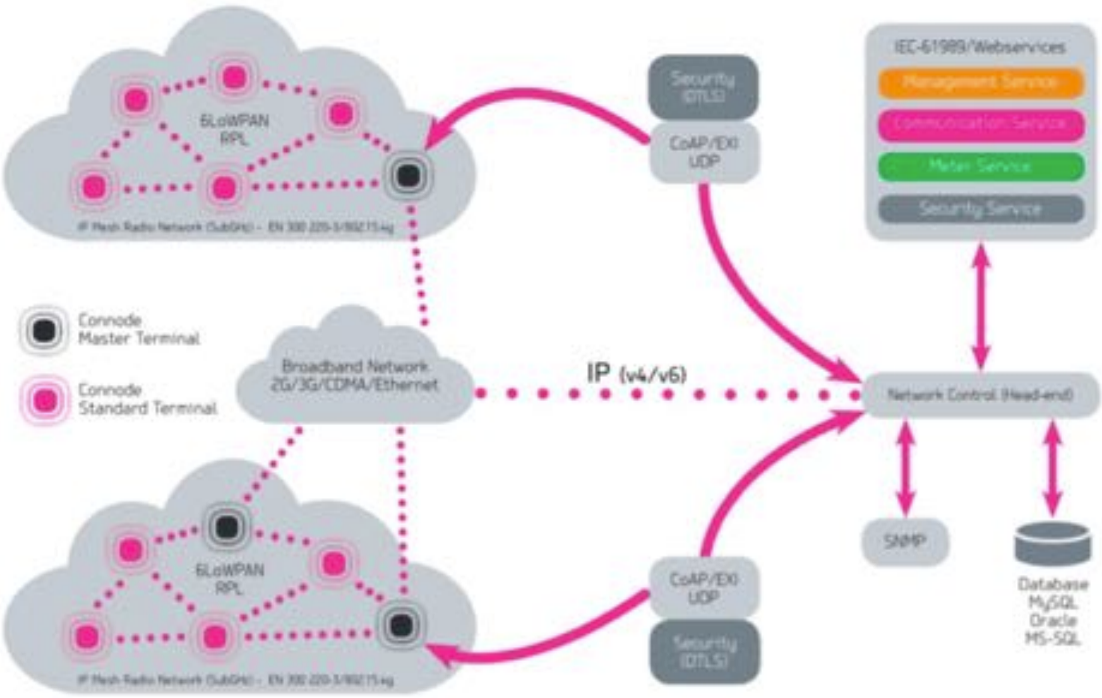

Figure 5, Connode system architecture, *Source: Connode AB*

The Connode 4 solution differs somewhat from the standards in that the maximum frame length is 254 bytes instead of 127. Also the Connode 4 solution does not support sleeping nodes.

Connode also has developed a hardware card to fit the Arduino Breakout board of Intel Edison, see figure 6. The hardware has the radio components to be able to communication via IEEE 805.15.4 and the Intel Edison is running the software to handle the networking of 6LoWPAN. In the Connode solution for Intel Edison the Agent software is coupled to the Connode server and the communication between the server and agent is secured the same way as between smart meters and the server. The difference is that the agent then gives the Intel Edison a new IPv6-adress and enables it to use this for UDP communication. The Intel Edison and the Connode Radio Shield is meant to be a testing platform for the Internet-of-Things.

Figure 6, Intel Edison with Connode radio module mounted

3.2.5 INTEL EDISON

The Intel Edison is a system-on-chip (SoC) product that features a dual-core, 500 MHz x86 Intel Atom CPU, see figure 7. It also has a microcontroller that in this moment is not supported to use. But this could be used for real time applications. The Intel Edison has 1 GB of RAM and 4 GB of internal flash storage and also has integrated WIFI and Bluethooth. The chip also has a 70-pin connector that breaks out all the different I/O:s of the board.

Intel Edison ships with Yocto Linux, a lightweight Linux distribution for embedded systems, which enables it to run a multitude of different programming language and functions and the ability to make use of a lot of already developed and free software for Linux. It is also possible to use the Arduino IDE to program the Intel Edison for simpler functions.

Figure 7, Intel Edison SOC (35 x 25 mm) and the larger Arduino Breakout board, (125 x 70 mm)

To be able to make use of the I/Os of the Intel Edsion there is need to break out the 70-pin connector into physical contacts and interfaces. This can be done with the Arduino breakout board which breaks out the pins of an Arduino Uno and adds the following interfaces:

- 20 digital input/output pins including 4 pins as PWM outputs
- 6 analog inputs
- 1 UART (RX/TX)
- 1 I2C
- 1 ICSP 6-pin header (SPI)
- Micro USB device connector OR (via mechanical switch) dedicated standard size USB host Type-A connector
- Micro USB device (connected to UART)
- SD Card connector
- DC power jack (7V – 15V DC input @ 500mA)

By using the Arduino breakout board test setups of hardware and software are made much easier. However, it is not a solution that should be used in a commercial product.

4. USE CASES

4.1 METHODOLOGY

The defining of the use cases was done in conjunction with personnel at E.ON Elnät. By interviewing personnel from different departments and presenting the concept of Internet-of-Things and distributed computing a discussion was made around the possibilities of using these kinds of systems in E.ON Elnät low voltage power grid. Based on what the employees on E.ON Elnät said that they would benefit from a series of use cases were defined. The employees where from the following functions within E.ON Elnät:

- Product development, smart products
- Micro grids and local energy systems
- Grid automation
- Grid supervision
- Network planning
- Protective relay planning and testing

The main functions of the Internet-of-Things and distributed computing and intelligence that were presented to the E.ON Elnät employees were:

- Monitor a value and react to it autonomously
- Update setting to system automatically or on demand for optimizations
- Send information to system or devices
- Read information from systems or devices
- Interface with a large range of sensors.
- Automation and Control

For some use cases a simple SGAM-mapping was preformed on one possible implementation of the use case. The mapping disregarded business layer logic and detailed functional description and focused on showing how the different technologies and components could be represented in the SGAM model to visually represent smart grid use cases.

Here follows a list and explanations for the use cases that were defined after the interviews. The order of the listed use cases has no meaning to the priority of the use case.

4.2 PRIORITIZED AUTOMATIC DISCONNECTION

4.2.1 OVERVIEW

Placed in E.ONs grid there are under-frequency relays that will, via breakers, disconnect radials of the grid if the frequency deviates too much below a certain value. The purpose of this is to save the rest of the distribution grid and in the end the transmission grid from the frequency change. Along with the automatic circuit breakers there are also remotely operated breakers that can be operated from the grid operation centre. Furthermore, if the national capacity is not enough it is upon the DSO to be able to disconnect 50 % of its power consumption within 15 minutes (Svenska Kraftnät, 2012). Also the Swedish Civil Contingencies Agency (MSB) wants the DSO to have a priority when they disconnect so functions that are important for the society are kept intact (FOI, 2013).

By using connected smart meters with a breaker built in to each of them, it would be possible to disconnect just the customers that are not prioritized by sending a disconnect signal to the meter. This would ensure that prioritized consumers are protected from black-outs in the event of power shortage. The priority of loads could then be done by using a predefined list and with consideration of customer contracts at E.ON Elnät and when a disconnection command would come from the TSO, E.ON could automatically disconnect the right end users. It would also be possible to read the meter in real time and know how much power that is disconnected and in that way optimize the disconnection sequence. Also if the meters have local intelligence connected to them they could monitor frequency on large loads and if the frequency became too low disconnect the load via the meter. This system, if it were reliable enough, could replace the automatic frequency dependant breakers.

4.2.2 VALUE ADDED

- Controlled disconnections where vulnerable consumers will be excluded.
- Less equipment in the grid
- Implement advanced functions for less costs
- Only disconnect as much as is needed.

4.2.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to measure frequency
- Ability to send frequency to control system/unit.
- System that can receive frequency data and handle the different priorities and dispatch disconnection signals.
- Databases for priorities from different instances.

- Policy to put together a total priority disconnection order.
- Local intelligence to disconnect if severe faults are detected and if the control system is not responding.
- Ability to receive disconnection signal and issue the disconnection

4.2.4 EVALUATION

By using the smart electricity meters, the frequency could be obtained from their measurement registers. The signal path is achieved from the IPv6 mesh radio that the energy meters use. Depending on how fast the disconnection must be the mesh radio could be a good option. When the need of fast disconnection (seconds) is present there should be local intelligence that can read the meter directly, i.e. not via mesh radio, and decide if it needs to disconnect using the meter. For a controlled and prioritized disconnection procedure that has a longer time span the mesh radio is a viable option.

The disconnection place may not be where the meter is so a signal path is needed. This could be solved with cable communication with, for example, Modbus to I/O-modules that can handle the disconnection. It is also possible when speed is not critical to have a device connected to the mesh radio network that can receive the disconnect signal.

Building a system to detect the need for disconnection is a matter of software and connection to different databases and meters within E.ON. This should not be a limiting factor in the implementation.

4.2.5 SGAM MAPPING

In figure 8-11 the SGAM layers for the use case "Prioritized Automatis Disconnection" are modelled.

Figure 8, SGAM Function Layer

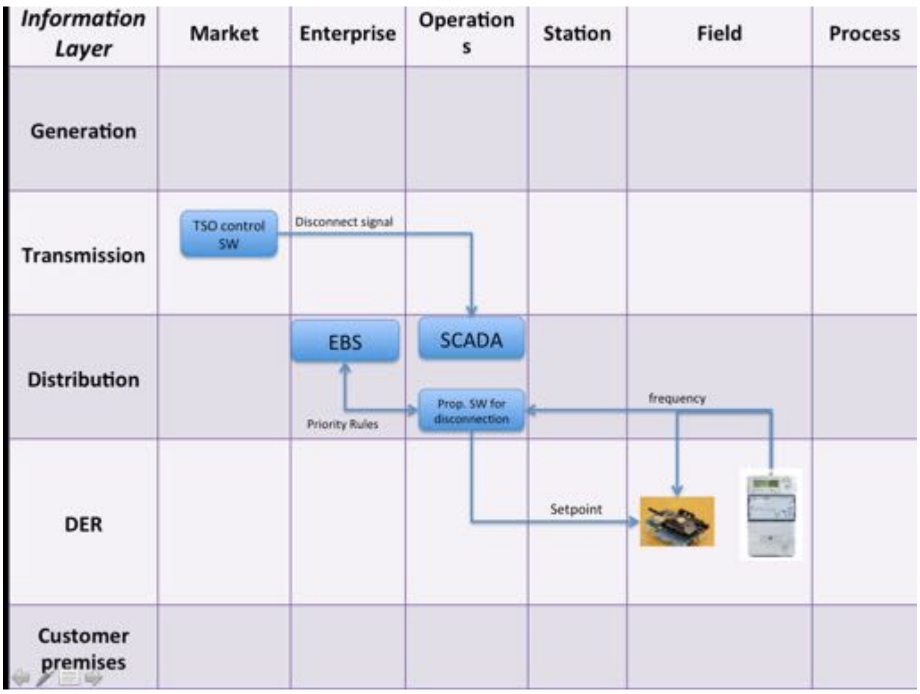

Figure 9, SGAM Information Layer, EBS = Enterprise Business System, SCADA = Supervisory Control and Data Acquisition.

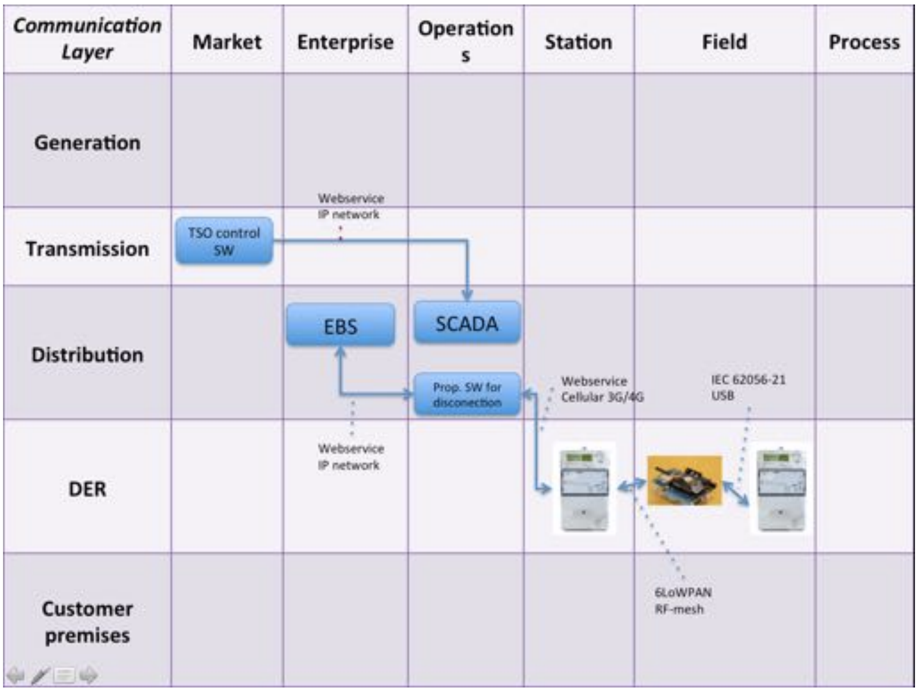

Figure 11, SGAM Communication Layer

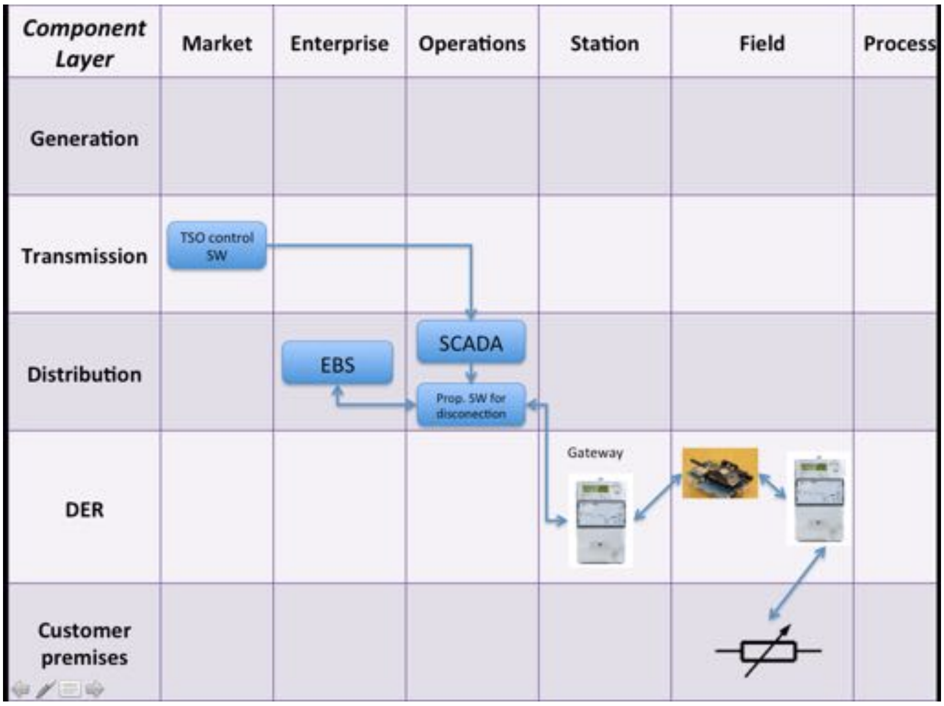

Figure 10, SGAM Component Layer

4.3 HIGH RESOLUTION LOGGING

4.3.1 OVERVIEW

In some cases it is interesting to log large amounts of detailed data from a meter during a long time. Usually these measurements are not conducted using the meter since the meter data acquisition system is based on monthly readings and the bandwidth would be filled if a meter wanted to send very detailed data. Important applications for this are power quality analysis and network analysis of different installations on industries or in domestic environments, for example to log data from an area with a high penetration of solar PV panels to study their effect on the grid. The logger could also function as an event recorder that only starts logging at a certain event or signal from supervisory system.

4.3.2 VALUE ADDED

- Detailed data for studies
- Good basis for decisions
- Cost efficient logging capabilities

4.3.3 REQUIREMENTS FOR IMPLEMENTATION

- Method to extract detailed data from meter
- Storage medium for collected data.
- Possible ability to retrieve aggregated data files remotely
- Method to set up logging device so that the correct values and correct sample intervals are used. Possibly remotely so that it is possible to change what data that is being logged.

4.3.4 EVALUATION

To extract the detailed data from the meter, the optical port could be read using the standard IEC 62056-21 with an optical reader. Using an embedded computer, for the small footprint, it is then possible to interpret the data and save the data to a logfile. It could be possible to connect an external storage device, for example a USB-stick or an SD-card to get extra space for logs that run over extended periods of time. If the embedded computer is connected to the mesh radio network from the meter it should be possible to both get aggregated log files, though possibly at a very poor data transfer rate, and to set up the logging parameters or change them remotely. With the connection it would also be possible to start an event recording. If larger amount of data is to be gathered and sent to servers it is also possible to connect the embedded computer with a cellular modem

4.4 SUBSTATION CONTROLLER / SURVEILLANCE SYSTEM

4.4.1 OVERVIEW

While primary substations are quite well monitored and visible to operators in the control room, the monitoring of the many more secondary substations is very limited today. With the access to low cost embedded computers and low cost sensor it would be possible to construct a low cost substation controller and/or monitoring system. Possible sensors could be:

- Temperature sensor
- Humidity sensor
- Presence or door sensor
- Arc detection sensor with photodiodes
- Sound analysis for discharge detection and noise detection
- Gas detection, Ozone etc.
- Weather station
- Transformer status, temperature, oil quality etc.
- Power Quality Sensor
- Reading of substation meter values
- Capacitive voltage sensors

If low cost sensors are used they might not have as high accuracy as more industrial sensors. But this might not be a problem if the main goal is to get an overview of the status of the substation. If the substation controller is connected to a supervisory system where the grid operation can access the data it could help speeding up the fault isolation process or the maintenance operation could get indications on where to direct their preventive maintenance efforts. It should also be possible to connect the controllers to actuators to directly act on certain condition in the substation.

If the substation controller is connected to a supervisory system, there will be possibilities to remotely acknowledge alarms and also being able to set the alarm limits remotely.

Today outages in the low voltage grid are not supervised. E.ON Elnät is relying on the customer to call and report an outage. If there were voltage sensors on the correct places in the substation these could be used to immediately detect an outage and even be used to identify the problem, for example using one voltage sensor above and below a fuse and if the upper has voltage and the lower doesn't the fuse has burned. This information could immediately be sent to the operation centre and they could dispatch a service technician to the correct place with the correct spare fuse before the customers even have reacted to the outage.

Another function of the substation controller could be to sum up all the meter values below the substation and compare to the substation meter. If there is a large deviation it could signal that there might be a power thief connected to the low voltage grid below the substation.

4.4.2 VALUE ADDED

- Better knowledge of substation status
- Fault detection, identification and isolation
- Remote access to substation data
- Help for maintenance operation
- Personal security with presence sensors.
- Alarms
- Faster action to outages

4.4.3 REQUIREMENTS FOR IMPLEMENTATION

- Embedded computer
- Sensors
- Connectivity for remote access and alarms
- Software to handle the substation controller and the different sensors
- Integration to grid operation center.
- Communication to and knowledge of meters below the substation.

4.4.4 EVALUATION

If the embedded computer handling the substation controller is connected to the smart meters mesh radio network it is possible to access it remotely. Via remote access it should be possible to configure the alarm limits and other important aspects of the controller. The communication also provides a way to connect the substation controller to the grid operation centre.

Connecting the sensors and actuators to the controller shouldn't be a problem. It might require additional hardware for signal conditioning and being able to communicate with sensors, but if there could be agreed on a standard interface for sensors, for example 4-20 mA or Modbus communication it would simplify the installation and software development to handle all sensors. To get values from the electric grid the substation meter could be used with optical IEC 62056-21 serial read out.

To integrate the substation controller with the grid operation centre shoudn't technically be a challenge, but the security demands on systems that integrates with the grid operation system might be very high and it could take a lot of work effort to achieve the proper security. In the beginning maybe a stand-alone system is easier to test.

If collecting values from meters below the substation and comparing to the substation meter the substation controller would need to know which meter that is below it and which IP addresses they have. To handle this there should be a central system that keeps track of where in the grid topology the meters are connected. If that information were well defined and the topology of the grid was known it would be possible for a substation controller to query its own location and then the system would return all meters that are below that substation.

4.5 DEMAND RESPONSE CONTROLLER/ENABLER

4.5.1 OVERVIEW

Demand response (DR) is defined as:

"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." (Balijepalli & Pradhan, 2011)

In these use cases the end user provides the grid operator with flexibility control. But it is done at the expense of affecting the operation of the end users' equipment. For such a system to work there is need for incentives to the end users to allow the grid operator to utilize the flexibility options in the grid. For example could the charging of e-vehicles be at a lower cost when the user lets the grid operator delay the charging. In some cases it is not possible for the DSO to give any financial incentives since they have to stick to the tariff. To overcome this problem it would be possible to use an aggregator company. The aggregator is introduced to be a broker between the DSO and the end user for DR function and actions and how they are compensated. The use of the aggregator enables other compensation models than just the electricity tariffs.

This use case is focused on automatically controlling loads and generation to benefit both the end user and the grid. The demand response actions that have been identified are:

4.5.1.1 CENTRALISED BATTERY STORAGE MANAGEMENT.

If an end user has local generation, for example PV, and energy storage it would be possible to control their energy storage utilization to benefit the grid and the end user. If for example the power output would be limited due to too much generation it would be more beneficial for the customer to store the energy that cannot be used. When the generation is decreased it would be possible to feed the energy from the battery out to the grid. It would also be possible for the grid operator to hold the battery discharge if that would be beneficial for the grid.

If the end user has battery storage it would be possible to send information about the coming day's electricity price. By using models for solar or wind generation and weather forecasts the system could calculate how the battery would operate that day and if there is financial gain load the storage with energy from the grid to be used later when the electricity price is higher. It could also make this energy buffer accessible to the grid operator for DR-operations.

If the end user does not consume the energy generated during the day it would be safe to say that if the end user has battery storage they would probably want to store the energy so that it could be used for their own consumption at a later time. This must be taken into consideration when controlling the battery usage. With use of statistics of the end users' power usage it would be possible to determine the most beneficial operation of the battery storage with the customers' interests and the grid operator interests. There is also a possibility to have multiple battery storage units at several end users in close proximity to each other to cooperate to benefit the customer and the grid.

It would be possible for the grid operator to supply a service to store end users local generation at a centralised battery storage system. To benefit the customer with the possibility to store their produced energy and get the possibility to use the storage for demand response. The storage of the end users energy could be "virtual" and only be a service that is handled by an aggregator, but the revenue that it generates could finance the physical installation of battery storage systems that can be used for demand response actions to benefit the grid.

4.5.1.2 LOAD CONTROL.

With the possibility to control loads in end user facilities, another dimension of demand response is reached. At sites with local production of energy it would be possible to turn on consumption when the feed out power limit is reached to still make use of the energy that is produced. This would allow for larger installations of renewable energy sorces, installations that are technically too large for the grid to handle. But since the installations are constructed and calculated at peak generation and peak generation is only achieved a small portion of the year having a larger installation would result in more renewable energy output to the grid (Leisse, 2011). Also if the maximum allowed generation is reached extra loads could be turned on to make sure the extra energy is not disruptive to the grid. It would also be possible to control the end users' facility so that it favours the own production of energy and firstly uses up the produced energy within the facility before feeding it to the grid.

Loads that could be interesting to control are thermal generation loads, due to the possibility to store energy longer in thermal storage systems. It could also be possible to use the slow time constant of buildings to store heat or cold in them. Resistive heating, heat pumps, air conditioning and cooling equipment are possible loads to control. Since in some cases the storage of energy is not needed, just the consumption of energy, the loads could be fans or pumps, but this would probably need a more in depth integration with and analysis of the end users' facility. A simpler approach for smaller direct loads would be to supply the end user with the possibility to choose what loads he would like connected to the system, via sockets or power plugs.

The solutions that have been mentioned so far has been in facilities that both have generation and consumption but there should also be possibilities to interface with pure consumptions facilities as district heating plants, larger buildings and industries to make use of the same kind of loads but with a larger result on the grid performance. All of this using distributed embedded computing and communications resources.

4.5.1.3 ENERGY/POWER CAPACITY ESTIMATION AND ENERGY STORAGE MANAGEMENT.

Using thermal storage and systems with large time constants there is a need to know how much power the system can receive and for how long it can receive the energy. By interfacing with the consumer systems this can be determined and this can be the basis for the decision making of the demand response actions in the grid. It should also be possible to interface with energy storage that can feed in energy into the grid, for example battery storage or hydrogen based electric generation systems.

4.5.1.4 E-MOBILITY MANAGEMENT.

By interacting with e-mobility vehicle users it would be possible to make use of the charging load of the vehicles batteries. This interaction and exchange of functionality could be done in different ways. One way is to inform users that there is a demand for load in certain areas during certain times and that the grid operator decreased the cost of charging at these charging station in these areas. It could also be that the user informs the grid operator that they are plugged in at a certain charging station and needs the vehicle to be charge at a certain time. This gives the grid operator the possibility to delay the charging of the vehicle until the latest possible time that the charging need to be started for the user to have the charging level it desires at the time the user needs the vehicle. During the time the grid operator is able to delay the charging it is possible to use the charging as a variable load for demand response usage.

4.5.2 VALUE ADDED

- Enabling end users to install more and larger RES and generate more energy
- Enabling end users to utilize more of their generated energy
- Control reactive power in the grid, by use of the power electronics in the EV-chargers and solar inverters
- Gain more stable feed in power from distributed generation
- Gain the possibility to use end users equipment to control loads in the grid to optimize grid operation.
- Better flexibility in grid
- More stable grid

4.5.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to control PV inverter and other generation with respect to total power output and reactive power draw.
- Ability to measure voltage and energy flow at end user.
- Ability to send signal or give signal to start or stop loads. Communication to smarter systems or just digital outputs to start direct load.
- Ability to communicate with supervisory system.
- Ability to calculate the energy capacity of an energy storage system.
- System with ability to make demand response decisions and make use of the best equipment to optimize grid performance.
- Ability to communicate to users of e-vehicles on where to charge vehicles.
- Ability to register information from e-vehicle users on when they need their vehicle charged.

4.5.4 EVALUATION

To use an embedded computer with Internet connection would be a good alternative for the hardware to implement the different demand response controllers and enablers. It would also be possible to use the mesh-radio network from the energy meter to achieve the Internet connection.

To be able to communicate with systems for the purpose of demand response an embedded computer would be a good platform that easily could be altered to fit many different systems. More simple communication like reading and writing digital outputs and analog values could be done with industrial I/O and communication to Modbus. If the system is a building automation system or a RES-system shouldn't make a difference.

The message should tell what DR action is needed and the embedded computer chooses the best way to do it depending on which system it is connected to.

The most challenging part would be the system that handles the DR-actions. The system could be centralized, decentralized or a mix of both. A mix of both might be the best solution since there is computing power distributed with the embedded computers. The computers could take local decisions within certain limits and these limits and larger DR actions could be handled by the central system. The use of flexibility at the end user is a large research area and is one of the largest areas within the smart grid research community so finding the best way to do this is out of the scope of this thesis.

Handling e-mobility vehicles could be made through an app or equipping the charging stations with a user interface.

4.6 PROTOCOL BRIDGE

4.6.1 OVERVIEW

By distributing embedded computers in the grid there is need to communicate with legacy systems that all might have different communication protocols. To be able to make Smart Grid applications easily implementable there is need for being able to use the same kind of application protocol to control all devices and functions in the smart grid. To be able to use the application protocol and control devices that run different communication protocols like Modbus, M-bus, 1101, 1104, IEC62056-21, BacNet, KNX, Zigbee etc. there is need for a bridge or interpreter between these protocols.

4.6.2 VALUE ADDED

- Ability to connect legacy systems to smart grid applications
- Lower cost of smart grid applications since equipment doesn't need to be changed.
- Possibility to get a larger multitude of commonly available devices accessible for smart grid applications

4.6.3 REQUIREMENTS FOR IMPLEMENTATION

- Hardware to support protocols of choice
- Software to be able to support protocols of choice

4.6.4 EVALUATION

To be able to bridge the protocols is just a question of hardware and software. But what might be the problematic is that the application protocol for smart grid application or

DR-application is too abstract to be used directly with the communication protocols. There might be need for local software the can interpret the application protocol and make decisions on what to read or send via the other protocols. It may even be necessary to send or read data over several communication protocols and to different devices to be able to preform the desired task.

4.7 INCREASED SIZE OF SOLAR PV INSTALLATION IN STRONG AND WEAK GRID

4.7.1 OVERVIEW

It is possible to control the output of PV inverters by sending control commands to them. By controlling PV inverters it would be possible to have larger PV installations than normally would be allowed by the grid owner. By using the maximum power line rating of the facility the inverters could be controlled so that they never exceed this output to the grid. The inverters should be allowed to produce more power if it is not fed to the grid. By putting a cap on production fed to the grid it would be possible to have larger installation that at peak production exceeds the power line ratings. The installation rules today only take into account the peak production and that peak production is not reached that often is not considered (Svensk Energi, 2014). Having a larger PV installation would make the production that is below maximum allowed production larger but at very sunny days some production would be lost due to the limit in production. But seen over a longer period it would still produce more renewable energy. Similar theory has been used when considering wind power by using larger wind turbines and limiting them when the production became too high for the grid to handle (Leisse, 2011).

The above example is assuming a strong grid with a low feed-in impedance but the controlling of PV output could also be applied when the PV is installed in a weaker grid. The DSO is mandated to allow PV installations up to the rating of the end user's meter fuse. But they are also mandated to make sure that a PV installation does not give a voltage increase of more than 5 % in the end users facility and 3 % in the connection point (Svensk Energi, 2014). If the end user is connected to a weak grid the PV installation will create a larger voltage difference than if it was installed in a strong grid. This is due to the feed-in impedance of the line connecting the end user and if the feed-in impedance is too large to make it possible for the rated size of PV installation the DSO have to reinforce the grid to that end user.

This could come at a high cost for the DSO and without that much gain for the end users since the hours of the year that their PV installations would generate so much power that it would affect the voltage might not be that many. To the DSO it would be desirable to only allow the end users to output that much power that the limits of voltage and line ratings are met. By setting an upper limit of the generation the line rating will be enforced and by controlling the voltage in the end users facility the instantaneous power output could be controlled with the use of the PV inverters. In this scenario it would also be possible to further increase the voltage limit since the legal obligation of voltage difference in an end users facility is 10%. It would also be possible to control the reactive power to control the voltage.

One issue that the DSO has to deal with is how to compensate the end users for limiting their output power to a lower value than the DSO are obligated to deal with. One possible solution to this problem could be to offer the end user a battery unit to store the energy that is produced over the power limit. This solution could be more financially beneficial to the DSO since they don't have to reinforce the grid and more financially beneficial to the end user since they might be able to cover more of their internal energy need.

4.7.2 VALUE ADDED

- More generation from RES in the grid
- DSO doesn't need to reinforce grid for just a few customers

4.7.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to measure voltage in end user facility
- Ability to control end user's PV installation
- Ability to set limits of controller depending on end users facility

4.7.4 EVALUATION

Interfaces and methods of controlling inverters are implemented in many inverters on the market. If the inverter conforms to SunSpec it has Modbus protocols to set and read a variety of values in the inverter, maximum power output and reactive power output included (SunSpec Alliance, 2015).

Getting voltage readings on each phase could be done via local readout of IEC 62056-21 of the facility's electricity meter. If the meter also was connected via mesh radio it would be possible to read values from the server, but since it is continuously controlled it might be not as stable using an UDP stream of values for the control. Also the radio network could be cluttered if it was used to a lot of real time measurements. An embedded computer could then control the inverters by using the values from the electricity meter.

Having the meter connected to Internet could still be a good thing. It could simplify the setup of the controller and could be done remotely. It would also be possible to connect the inverters to DR-actions from the DSO.

4.7.5 SGAM MAPPING

In figure 12-15 the SGAM layers for the use case ”Increased size of solar PV installations in strong and weak grid” are modelled.

Figure 12, SGAM Component layer for the use case " Increased size of solar PV installation in strong and weak grid "

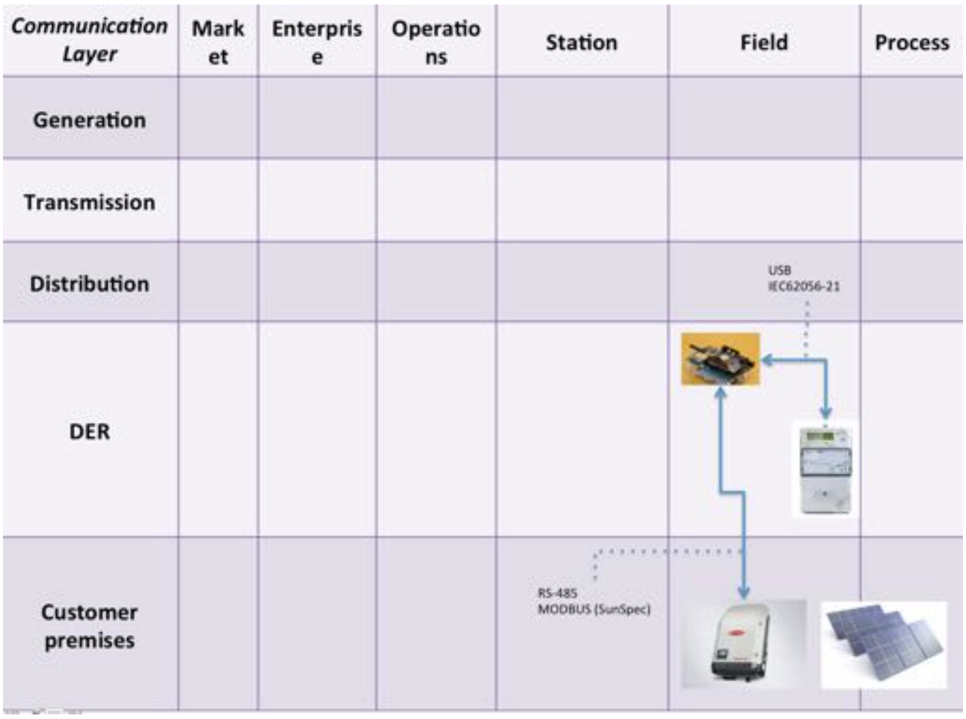

Figure 13, SGAM Communication layer for the use case " Increased size of solar PV installation in strong and weak grid "

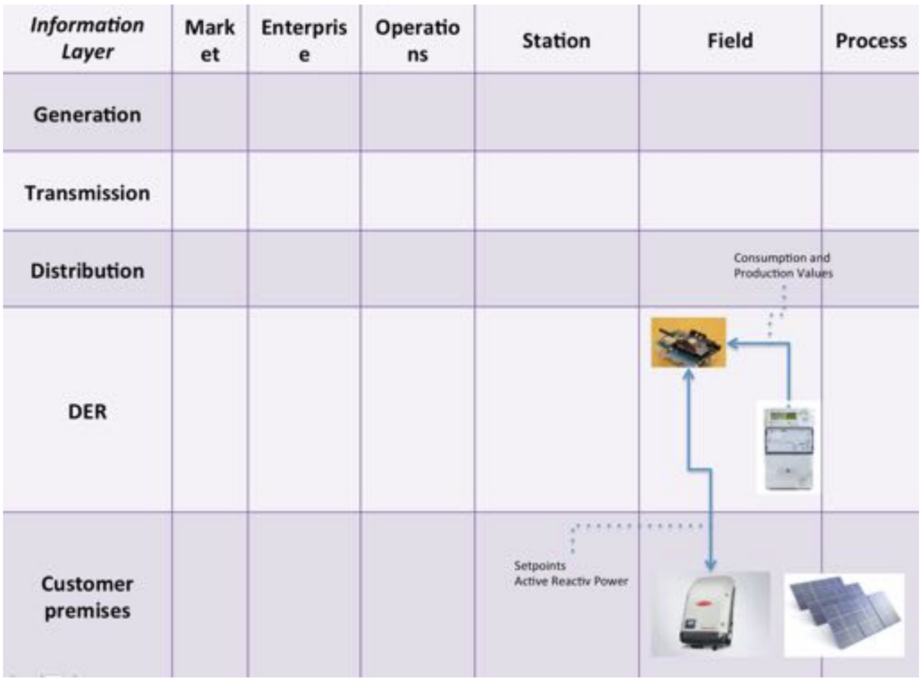

Figure 14, SGAM Information layer for the use case " Increased size of solar PV installation in strong and weak grid "

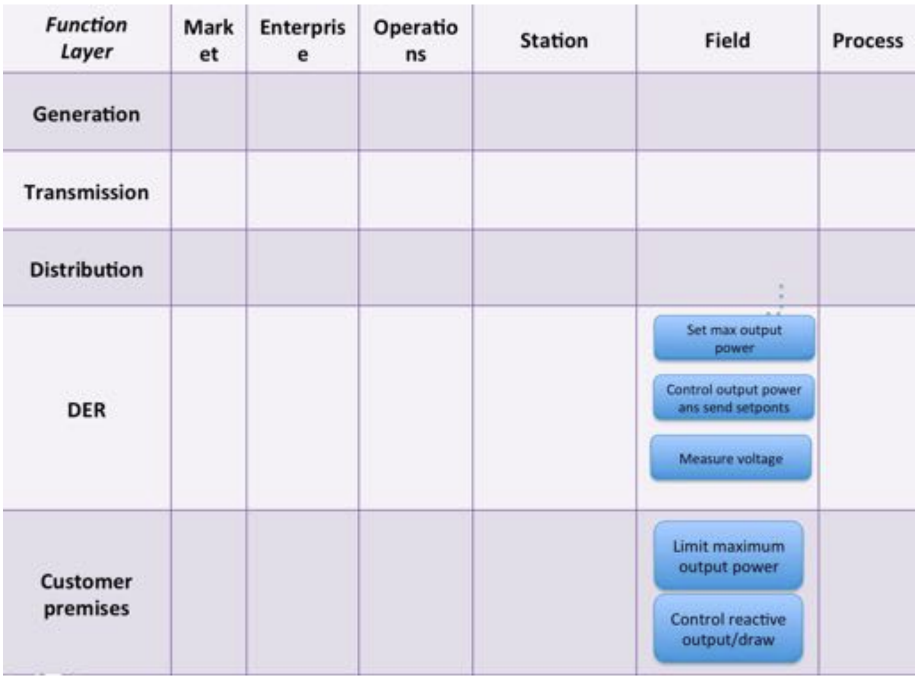

Figure 15, SGAM Function layer for the use case " Increased size of solar PV installation in strong and weak grid "

4.8 ANTI-ISLANDING PROTECTION

4.8.1 OVERVIEW

On the 10kV medium voltage grid connection to substations earth fault detection is implemented and if an earth fault is detected the system will disconnect the line with the fault. If there is local production on the 400 V side this imposes a security risk by energizing the grid when it is supposed to be de-energized. If the production facilities feed into the grid it could travers the transformer and make the disconnected line ends of the line with earth fault live. It would also be a safety risks in the 400 V grid if someone thinks it is de-energized but local production is still feeding into it.

What is needed is a way to recognize the abnormal situation and then a way to disconnect all local production under the substation until the earth fault is removed and it is safe to start everything again. It should also be possible to send messages to the grid operation centre. Since it is a protection it should be possible to test the equipment without actually tripping the protection.

By using a residual voltage protection it is possible to measure if there is anything feeding out of the low voltage grid. If voltage would be fed from the 400 V side the 10 kV side with an earth fault the voltage of the phase with the earth fault would be pulled down to zero and the voltages of the other phases to this phase would change. It would introduce a current in the zero sequence. When this fault is detected a message should be sent to all local production downstream of the substation to turn off their production.

4.8.2 VALUE ADDED

- Added safety
- Cheaper implementation of protection

4.8.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to register the change residual voltage on the 10 kV side.
- Ability to send messages to all facilities below the substation.
- Ability to disconnect and reconnect the local production at the end user
- Substation controller must know of all the local production downstream.

4.8.4 EVALUATION

To detect the residual voltage dedicated hardware could be used or signal from the grid operation system that has registered the earth fault sends an automatic message. Dedicated hardware could be made with an embedded system and capacitive sensors on each phase. This embedded system could then be the handler of the anti-islanding protection too or it could provide a signal to a substation controller that handles the anti-islanding protection functionality. If the embedded system or the substation controller is connected to the Internet, for example using mesh radio it would be possible to send signals to all facilities that have production.

There is need for some equipment in the facility that can disconnect the production. This could be a separate unit or it might be possible to use the meter to disconnect the facility from the grid. The equipment needs to be connected to Internet so that messages can reach it. This could be done with the mesh radio solution.

To have knowledge of the meters below the substation there is need of a system that can handle the designation of equipment to the right substation. If a system has a layout of the topology of the grid it would be possible to only add the disconnecting equipment to the topology and when the substation is added to the topology it can calculate which equipment that is below it. It could also be so that the substation sends a message to the system that has the topology and that system in turn sends the disconnection signals to the correct equipment.

4.9 PHASE-SHIFTER FOR SINGLE-PHASE PRODUCTION

4.9.1 OVERVIEW

If there were devices that could control which phase a single-phase production unit is connected to it would be possible to optimize the utilization of the produced energy for the end user. If the end users consumption per phase could be measured, the phase with the highest consumption would be the phase that it would be most beneficial to connect the single-phase production to. The reason for this is that it is assumed that covering your own consumption is better than selling to the grid. It is also the best for the grid operator since if the production will be added to one of the phases and connecting it to the phase with the highest consumption would make the difference in load to the other phases the smallest.

In areas with a lot of single phase production it would be possible to analyse the difference of the three phases at the substation and if the devices controlling the phase connection is connected to the Internet, for example via mesh radio, it would be possible to send commands to end users facilities. By suggesting the devices to connect the production to other phases than the phase that is most beneficial for the end user the overall load on the grid could be equalized. There would have to be some form of compensation to the end user if the grid makes his production unit less profitable for him.

4.9.2 VALUE ADDED

- Better utilization of single phase local production for end user
- Better balance between phases
- Less strain on grid

4.9.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to measure consumption per phase in end user facility
- Ability to switch connected phase of inverter
- Ability to receive messages from substation
- Substation needs to know which single phase production units that are downstream of it.

4.9.4 EVALUATION

It would be possible to use relays or power electronics to disconnect a phase from the inverter and connect the inverter to another. Standard functions of inverters are that it senses if it is connected to a grid and if disconnected will stop injecting power. When the inverter has stopped it is then possible to connect it to the other phase. The inverter will connect to that phase and start operating as normal. The small stops in production will give a decrease in total amount produced energy but hopefully it will not be such a problem that it won't be financially viable to do so. It is also possible to introduce a hysteresis so that switching phase won't happen too often.

It is possible to get the consumption by reading the electricity meter via IEC62056-21 and get values of voltages and currents and active and reactive consumption. Using mesh radio would be one way to get Internet connection using an embedded device it would be possible to calculate the best phase to connect the production on. It would then take into account both the end user and the grid operator's wishes.

For the substation to be able to know which devices to send messages to it would be possible to implement a topology-based system that keeps track of devices and functions as mentioned earlier in other use cases.

The same electronics to switch phase could be use as the anti-islanding protection mentioned earlier.

4.9.5 SGAM MAPPING

In figure 16-19 the SGAM layers for the use case " Phase-shifter for single-phase production" are modelled

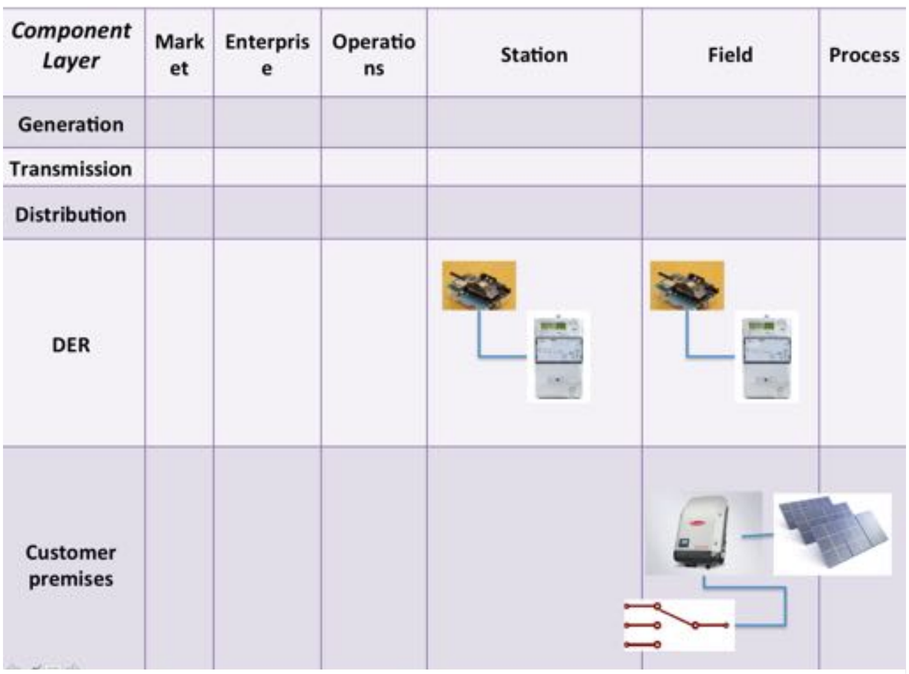

Figure 16, SGAM Component layer for the use case " Phase-shifter for single-phase production"

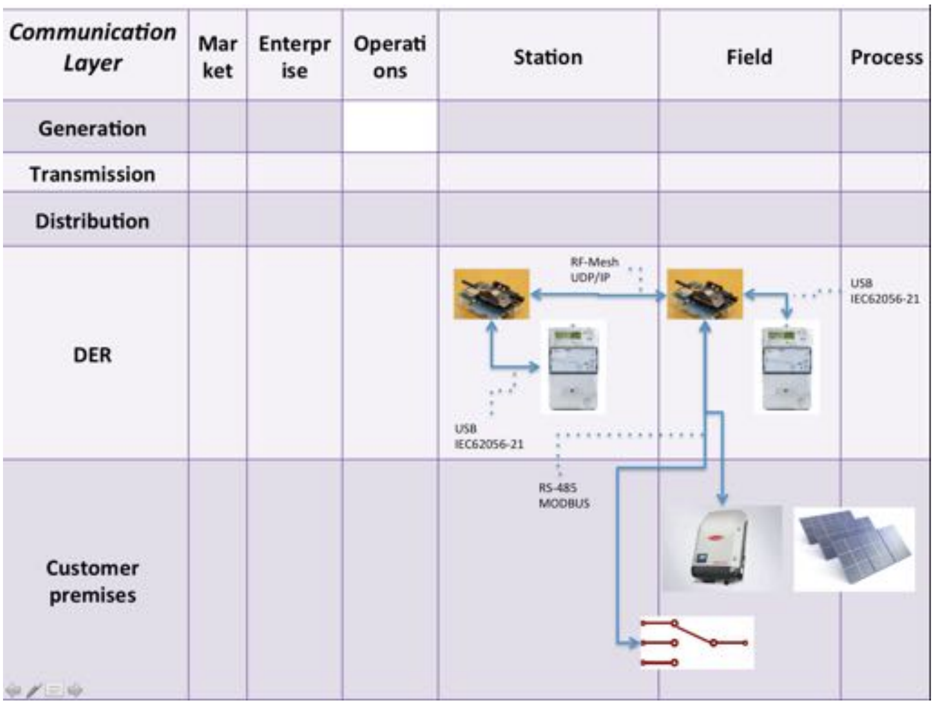

Figure 17, SGAM Communicatoin layer for the use case " Phase-shifter for single-phase production"

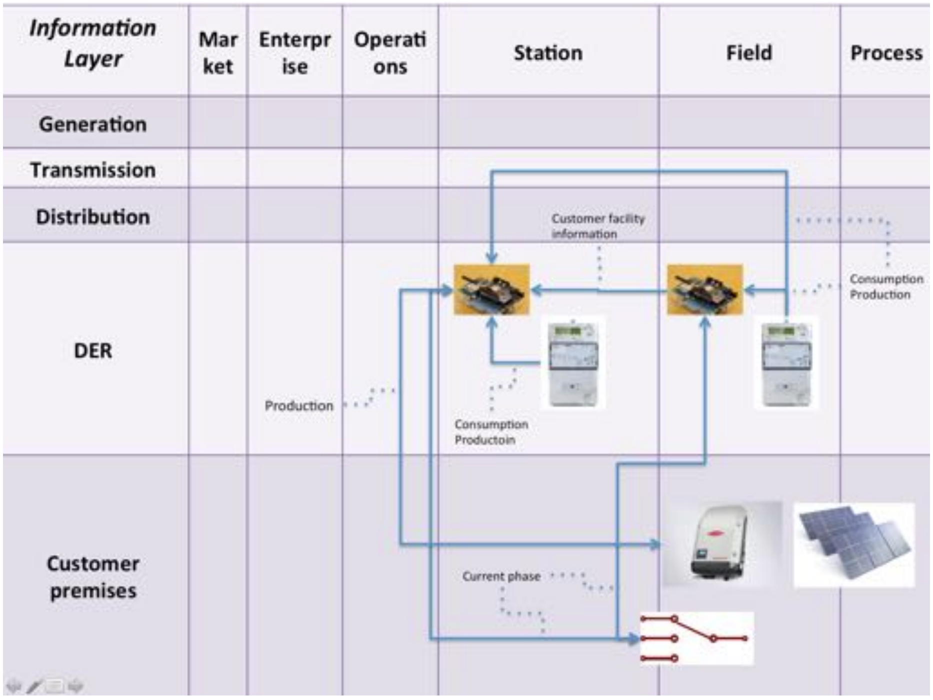

Figure 18 , SGAM Information layer for the use case " Phase-shifter for single-phase production"

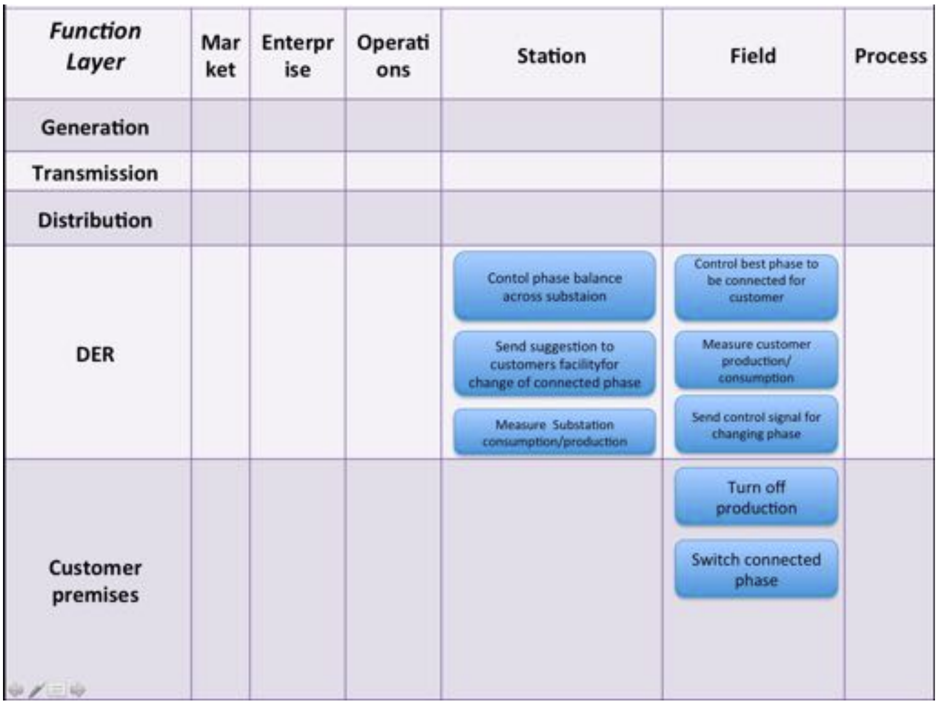

Figure 19, SGAM Function Layer for the use case "Phase-shifter for single phase production"

4.10 DISTRIBUTED LOAD ANALYSIS

4.10.1 OVERVIEW

By having local computing power in substations and end users' facilities it would be possible to make statistical analysis on load profiles to find errors or weaknesses in the grid performance. Daily, weekly, weekend, night profiles could be calculated and amongst other statistical operations for example the variance from a standard load profile could be calculated locally and the aggregated result of the analysis could be sent to the grid operations centre. Also other technologies in fault identification and prediction such as principal component analysis and neural networks could be applied to the distributed computing.

4.10.2 VALUE ADDED

- Advanced analysis distributed in the grid
- Only aggregated data would be collected, easier to compare.

4.10.3 REQUIREMENTS FOR IMPLEMENTATION

- Ability to read information from the grid
- Computing power and data storage to perform analysis
- Connectivity to send aggregated results to main system

4.10.4 EVALUATION

By using embedded computers it would be possible to do the analysis. If those computers then were connected to the Internet, via for example mesh radio, it would be possible to send aggregated data.

It is the ability to read information from the grid that limits the function. It is possible to read electricity meters for information, but only every 2-6 second depending on how much information is wanted. This will be enough for a lot of statistical operation on for example load profiles, but if analysis of wave form and other fast processes is wanted a better hardware that can sample much faster is needed.

5. IMPLEMENTATION OF USE-CASES

5.1 OVERVIEW

To be able to properly test all use cases there would be needed a significant amount of different equipment and access to grid functionality. The demands on physical equipment and facilities to be able to properly test use cases on were seen as a problem. It would be very costly and very time consuming to test all use cases in the actual grid. Functions that operate during abnormal situations are even more difficult to test.

The decision to build a demonstration platform was taken. This demonstration platform should be able to reproduce all the grid functionality and components such as consumption loads and production units. Also sensors and fault detection should be incorporated in the platform.

The platform was divided up into two main platform components, a facility platform, representing all different equipment and functionality at the end user and a substation platform that would collect the data from facilities for certain use cases and also to handle local data from the substation to use in use cases. Since E.ON Elnät wished for a demonstration platform that was more hands-on and easy to demonstrate to others it was decided to make it a more hardware based platform than a software based platform. To control variable values potentiometers were used and discrete values were selected with switches. To be able to show information LCD displays were used. All the equipment was mounted in boxes that easily could be moved around for demonstration purposes. The boxes were made so that it would be possible to implement demonstrations of all use cases mentioned in this thesis.

Most use cases depended on using values from the electricity meter in the control and automation of the facilities and substation. To ascertain the functionality of retrieving local data read out of the electricity meters a Python program implementing IEC 62056-21 was developed. To interface with the meter a USB-version of the standard optical eye for IEC 62056-21 was used. It was seen that due to the protocol it was possible to get a faster readout by reprogramming the meter to report all values at request and sorting out the ones of importance than requesting single values that were interesting for the control and automation. On the boxes that contain the hardware a meter was placed, but since the boxes are only emulating the grid the meter offers no function, it only sits there to emphasize that it is the meter that all grid information is coming from.

5.2. FACILITY PLATFORM

The facility box is divided in seven sections: Production, Consumption, Energy Storage, Demand Response Load, Notifications, Facility Options and Grid Connection, see figure 20.

Figure 20, Facility platform box

- The **production section** features an LCD display, a potentiometer and two switches. Connected to the production is also three LED:s that indicates if and on which phases energy is flowing through. The two switches are to enable the production and to choose between single-phase or three-phase production. The potentiometers are used to control how much power is produced. If three-phase is chosen the power is split on each phase. On the LCD the current production is shown and if the production is enabled.

- The **consumption section** features one LCD and three potentiometers. The potentiometers are used to control the current power consumption on each phase. On the LCD the current power consumption of each phase is shown. The LCD has two empty rows to allow implementation of more information on each phase.

- The **energy storage** section features one LCD and two switches. One switch to enable the energy storage and one to choose if it is connected in three-phase or single-phase. On the LCD the status of the storage solution, charging or discharging information and current level of charging is supposed to be displayed. To the energy storage there are three LED:s that indicate which phases that are transferring energy. This section is not implemented fully in the program and now only has the label "Disabled" written out on the LCD. The reason it is not implemented was that to make it a proper function a more detailed model for operation was needed to be made and where was no time left in the thesis for this.

- The **demand response load section** is made up by two switches, one for enabling the demand response load and one to choose if it is a three-phase or single-phase load. Connected to the demand response load section are three LED:s that indicate which phases are passing current.

- The **notification section** is to indicate if remote commands like anti islanding protection or disconnect has been issued. The commands are indicated with LED:s.

- In the **facility options section** several switches are used to set different operational options for the facility. The "Phase balancing" switch will enable single phase production to be connected to the best phase. Right now it only handles the production but it would be possible to extend it to also take into account the energy storage and the demand response load but that requires that financial rules for the simulations are defined. The "Prioritized Facility" switch is to indicate that this facility shouldn't be disconnected if the DSO needs to disconnect load in the grid. The "Controlled Power-On" switch is to indicate if this facility is to be included in a controlled power on schedule after a black out. The "Grid Type" switch is to indicate if the facility is connected to a weak or strong grid. This has no particular function right now since voltage simulation in the facility is not implemented. But if it was the facility could be using a pre set network impedance to use for calculation of the facility's impact on the voltage on the point of connection.

- The **grid connection section** is the LCD on the bottom that indicates the power drawn from or injected to the grid. By summing up the powers on each phase from production, consumption, energy storage and demand response the total power on each phase is displayed.

5.3. SUBSTATION PLATFORM

The substation is firstly divided in the high voltage side and the low voltage side. In between is the transformer section. The substation controller section represents the automation and sensors in the substation. There is also a simulation control section to activate faults and send commands in the grid. See figure 21.

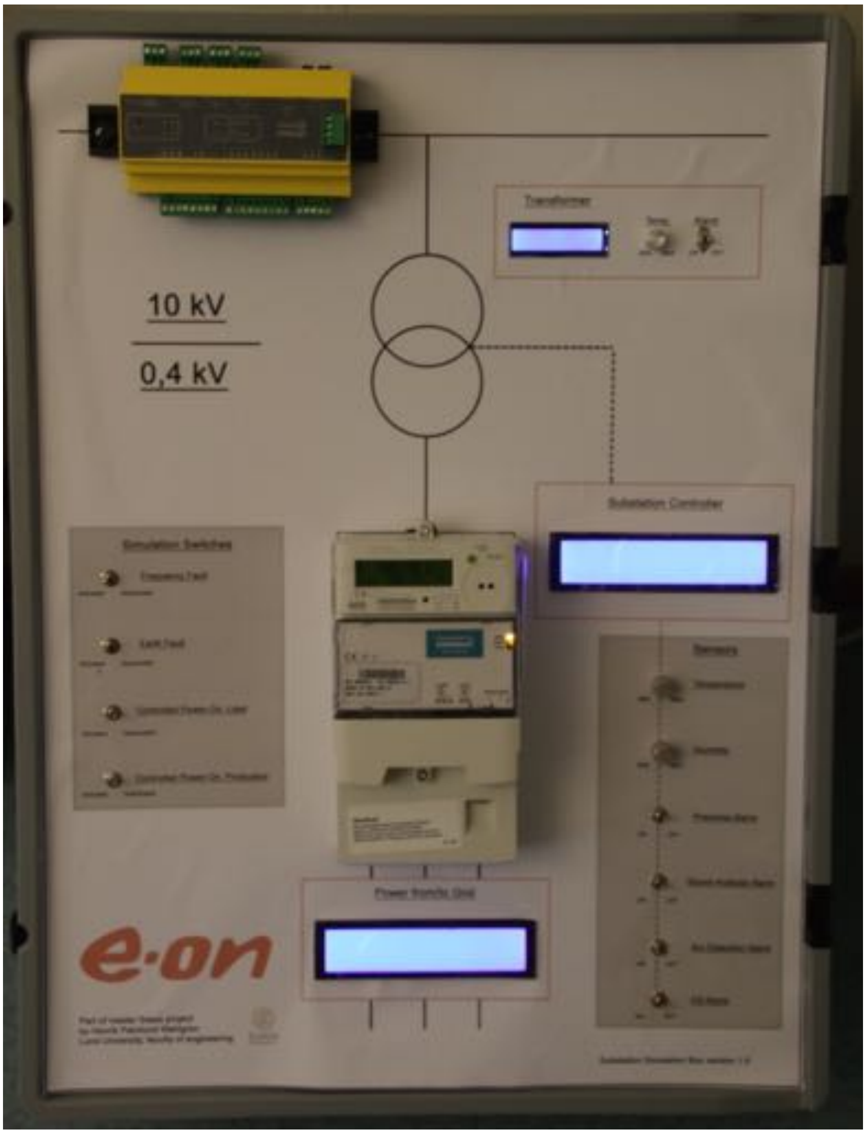

Figure 21, Substation platform box

- On the **high voltage side** is a representation of the high voltage grid supplying the substation. Mounted on the box on the high voltage side is an earth fault detection unit from Protrol AB. This is not connected to anything and is there to show an example of equipment that can aid in the detection and handling of faults.
- The **transformer section** has an LCD that indicates the status and temperature of the transformer. The temperature of the transformer is adjusted with a potentiometer and there is also a switch to emulate a fault on the transformer, for example high pressure fault.

- On the **low voltage side** there is an electricity meter mounted to show that the values used in the substation controller are taken directly from the substation meter. On the bottom of the substation box there is an LCD showing the information of each phase that leaves the substation. This value is the summed up value from all facility boxes.

- The **simulation control section** consists of four switches. The "Frequency Fault" switch induces a low frequency signal in the demonstration environment and this will have the substation controller send messages to facilities to disconnect their load. If a facility is prioritized this command will be ignored. The "Earth Fault" switch till induce an earth fault on the high voltage side of the transformer. The substation controller is then supposed to activate the anti-islanding protection and send messages to all facilities that have production to disconnect their production. The last two switches, "Controlled Power-On Load" and Controlled Power-On Production" is for sending messages to the facilities to turn on their load and production again.

- The **substation controller section** consists of a large 40x4 LCD displaying information about the substation controller, two potentiometers and four switches to represent different sensors in the substation. The two potentiometers control the temperature and humidity in the substation. The "Presence alarm" switch is to indicate if someone has opened a door to the substation. The "Sound Analysis Alarm" is to represent an alarm from a sound analysis unit in the substation the monitors noise levels and other important sounds that might occur in a substation. The "Arc Detection Alarm" switch represents an arc detection sensor and the "O3 Alarm" switch represents an ozone sensor that has registered too high levels of ozone in the substation.

5.4. INSIDE THE BOXES

The demonstration boxes consist of a plastic box with lid of the dimensions 800x600 mm. The main components are Intel Edison embedded Linux platform for controlling the box and demonstration environment and remote connection. To the Edison one Arduino Mega is connected via USB to handle I/O. The Arduino Mega is connected via flat cables to an I/O unit with screw terminals and all switches, potentiometer and LEDs that are mounted in the box lid are connected to this I/O unit. The Arduino Mega continuously reads all inputs and the Intel Edison can request the current values of the inputs via the USB connection. The Edison can also write the preferred output state of all outputs on the Arduino Mega via the same USB connection. The I/O unit has 20 digital inputs, 20 digital outputs and 16 analog inputs. Not all of the inputs and outputs are used but having the large number of I/O:s give the possibility to extend the platform in the future, see figure 22.

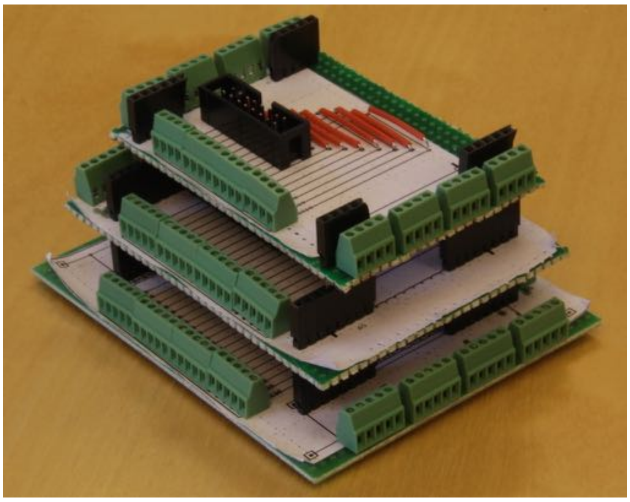

Figure 22, I/O module, (90 x 80 x 50 mm)

Also connected over USB is an Arduino Uno. This Arduino controls all the LCD:s mounted in the lid of the box. The LCD controller is capable of connecting 8 LCD:s in each box. To handle the addressing and connection of each LCD to the controller a LCD interface card is used, see figure 23. There are two versions of this card, one for the 40x4 LCD:s and one for the 16x2 LCD:s. The interface cards and controller are connected via a flat cable.

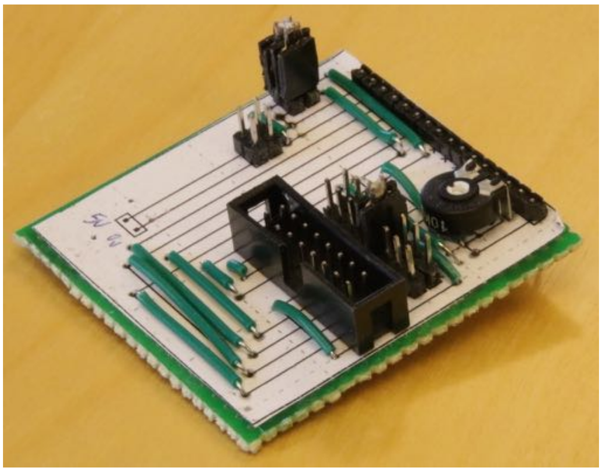

Figure 23, LCD interface card, single LCD version (60 x 55 ı) mm)

In the facility box there is a small HDMI screen with touch capabilities to represent an end user interface.

The Intel Edison only has one USB-host connector so a powered USB-hub is used to provide more connectors and power to the Arduinos. On all LCD interface cards there is the possibility to connect external power supply to the backlighting of the LCD. Also on each box there is a meter installed. This does not provide any function to the platform; it is only there to show that in an actual implementation the values used would come from the meter. In the box an electric cabinet with fuses and earth fault breaker is installed for a safer power distribution within the box. The power distribution to each component is then done via a simple extension lead, see figure 24. All control components are mounted in the lid from behind and the signal cables soldered to the potentiometers, switches and LED:s and then connected to the I/O unit, see figure 25.

Figure 24, internal hardware setup

Figure 25, hardware mounted in boxlid

5.5 SOFTWARE

5.5.1. LOCAL

The local software running on the Intel Edison is a multithreaded Python program. By using a threaded architecture several subroutines of the same process are running concurrently. On single core processors executing multiple threads is done with time splitting of the processor, Intel Edison is a multi-core processor so it would be possible to divided the threads among the cores. Unfortunately due to the Python GIL (Grand Interpreter Lock) Python running on the C-based python interpreter, CPython, is limited to one core. It could be solved by, for example, splitting the program into several processes but that level of functionality was deemed unnecessary for the implementation of the software.

The program consists of the main thread that handles the communication to the application server, the automation thread that performs all automation and control tasks, LCD updater thread that handles what information that is supposed to be written to the LCD:s and the peripherals thread that handles communication with the external I/O unit. These threads works around three main thread-safe objects representing the facility and the current I/O configuration and handling the incoming and outgoing messages stacks, see figure 26.

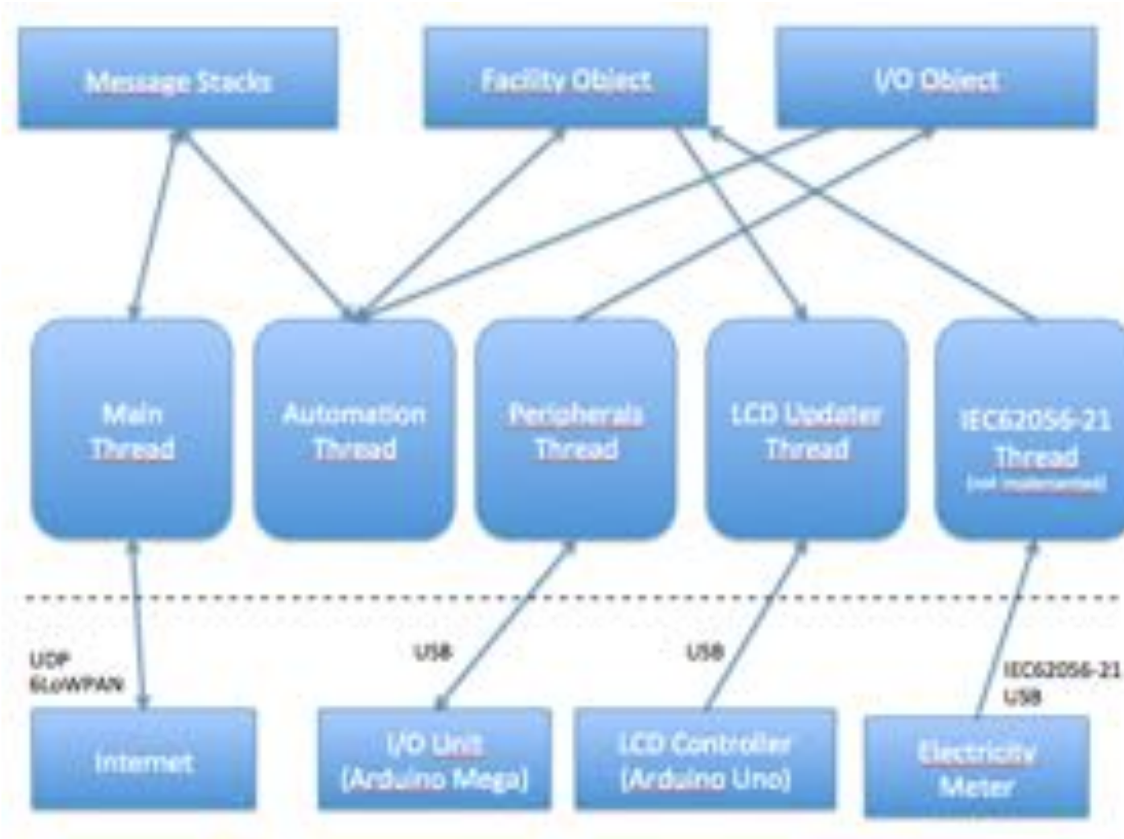

Figure 26, Multi-threaded Python program

The **peripherals thread** is continuously requesting values from the I/O unit that is built on an Arduino Mega via USB. The request message is short and the response is in a proprietary format. The response is then saved in the thread-safe I/O object representing the current state of the I/O:s. If the digital output configuration has changed the peripherals thread will send the digital output state to the I/O unit via the same proprietary protocol.

The **automation thread** is continuously reading the I/O object and the incoming message stack and writes the information the I/O represents to the thread-safe facility object. Then all automation tasks and calculations are performed and where applicable the values are written to the facility object. In the end of the automation sequence the status for the digital outputs are compared to the status of the last iteration. If there is a difference the status is written to the I/O object to be sent to the I/O unit by the peripherals thread. If there is information to be sent over the Internet the information is written to the outgoing message stack.

The **LCD updater thread** is continuously reading the values from the facility object and compiling the correct information and sending it to the LCD controller based on the Arduino Uno via USB and yet another proprietary protocol.

The **main thread** reads the outgoing message stack if there is anything to send and if there is anything to receive it writes that to the incoming message stack.

The **IEC62056-21 thread** was not implemented in the Intel Edison, but needed in a grid-tied application to read the electricity meter. This would be placed in a separate thread and store the returned values in the facility object. The protocol has been implemented in a separate Python program but was never incorporated in the demonstration environment since reading a electricity meter that is not connected to any load would not give any useful data.

In the **Arduino Mega** the software is very simple. All the inputs pins are read continuously and updating arrays that contain the last read value. The outputs pins are written to the state that is said in the pin array representing the output pins value. There is also a function that listens to the serial port for messages and if a request of data is received the status of the inputs are sent back over the serial interface and if a write command is sent along with data it is saved in the output pins array.

In the **Arduino Uno** the software is able to support eight LCD:s since this is the limit of the hardware. The LCD:s are initialized and in the Arduino functions have been implemented to receive text via serial interface and write that text to the LCD:s.

5.5.2. SERVER

It was meant to have a Ruby on Rails application running on the server to be able to set up the facility information and to get an overview of the status from each box via a web interface. But there was no time to develop this properly so the server application is only relaying messages between the facility box and the substation box, see figure 27.

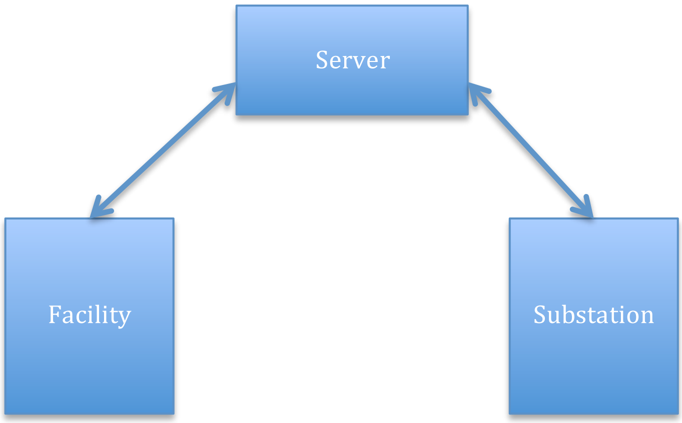

Figure 27, Proxy server program architecture

The implementation of the Connode Agent on the Intel Edison gives the Intel Edison an IP-address but this IP-address is unknown to the Connode server and other systems. Hence there is need to register which IP each demonstration box has. A small server application was written to accommodate this function. It can receive a message from a box, register the IP-adress to that box and then use that IP-adress to forward all messages intended for it. So to send a message from the substation to the facility the message needs to state where it is intended and the server will relay it to the correct IP-address. This is accommodated via a very simple proprietary protocol.

6. RESULTS

The result section will show proof of the functions implemented from the use cases.

- Variable consumption
- Variable production
- Impact on grid
- Transfer of grid state between facility and substation
- Load balancing with single-phase production
- Transfer of anti islanding protection signal and response in facility
- Transfer of disconnect signal and response in facility
- Substation controller function
- Transformer surveillance function

Variable consumption, figure 28 and 29 shows how adjusting the potentiometers can change the consumption in each phase.

Figure 28, Consumption section of facility platform.

Figure 29, Consumption section of facility platform

Variable production, figure 30 , 31, 32 and 33 shows how the production can be varied and that it is possible to switch from single-phase to three-phase production. The connected phases are indicated with red LEDs.

Figure 31, Production section of facility platform. State = Off

Figure 30, Production section if facility platform. State = On. 28 kW single phase

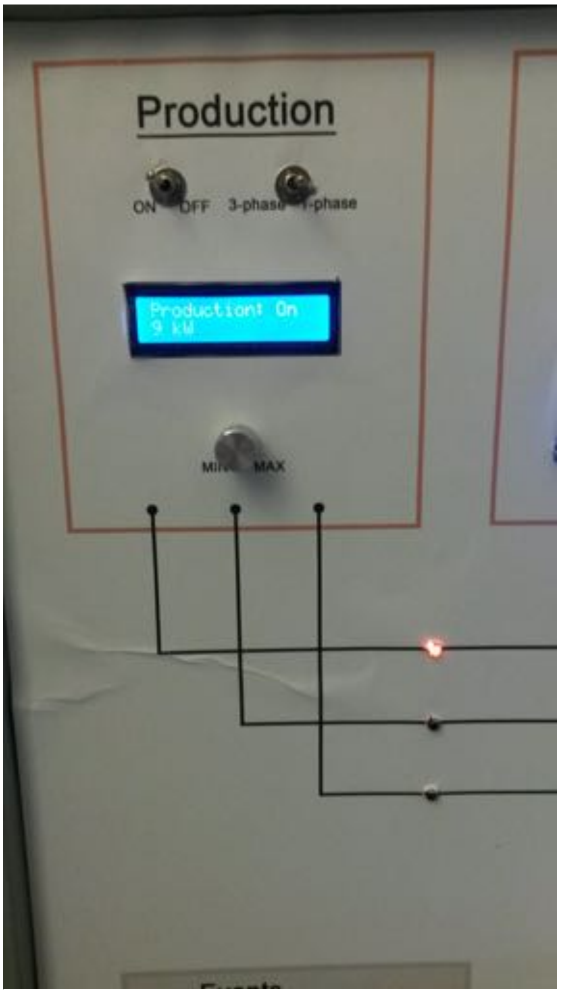

Figure 32, Production section if facility platform. State = On. 9 kW single phase

Figure 33, Production section if facility platform. State = On. 9 kW three-phase

Impact on grid, figure 34 and 35 shows
how the consumption and production adds up to the total impact on the grid.

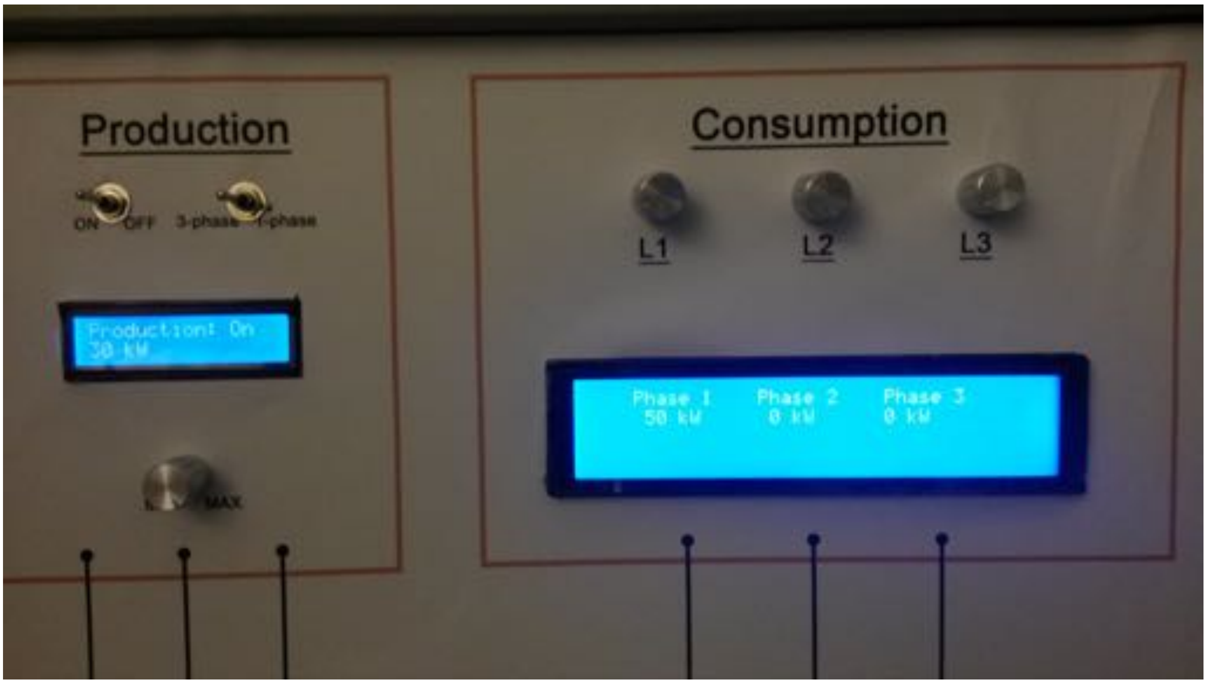

Figure 34, Consumption and three-phase production

Figure 35, resulting impact on grid.

Transfer of grid state between facility and substation, in figure 36 the phase values of the facility from figure 35 have been sent to the substation box.

Figure 36, Grid information in substation platform

Load balancing with single-phase production, in figure 37, 38 and 39 the load balancing function where the single-phase production is switched between phases is shown. The LED shows which phase the production is connected to.

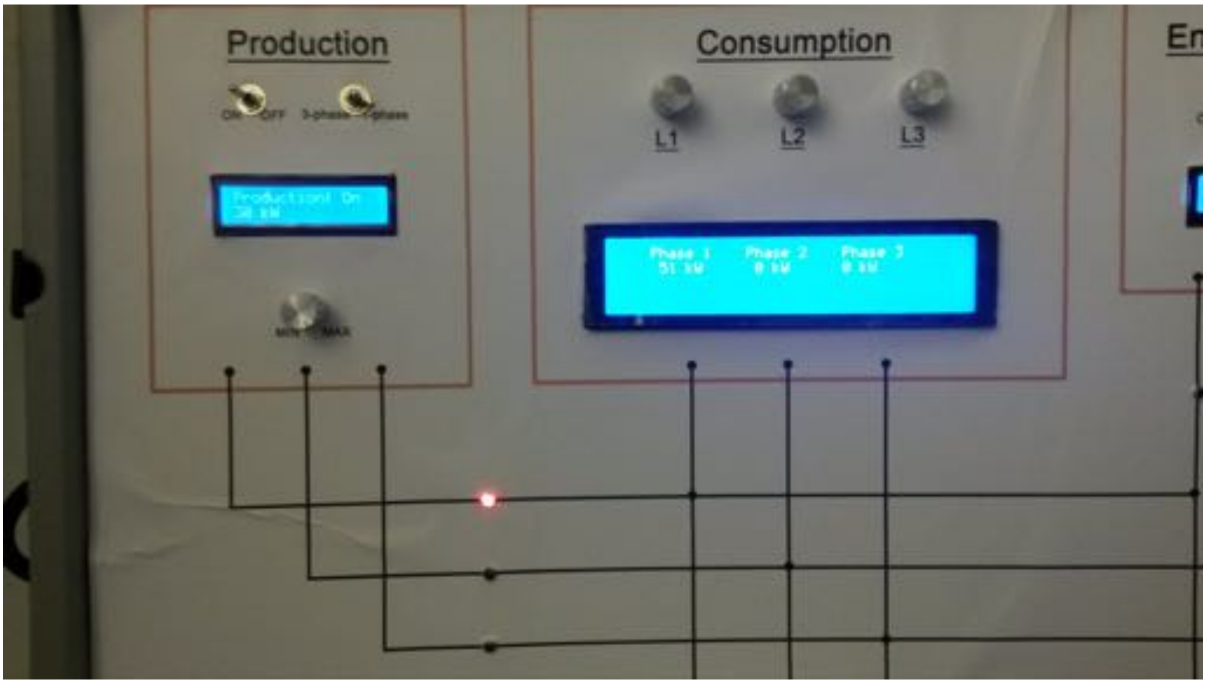

Figure 37, Facility platorm, production connected to phase 1

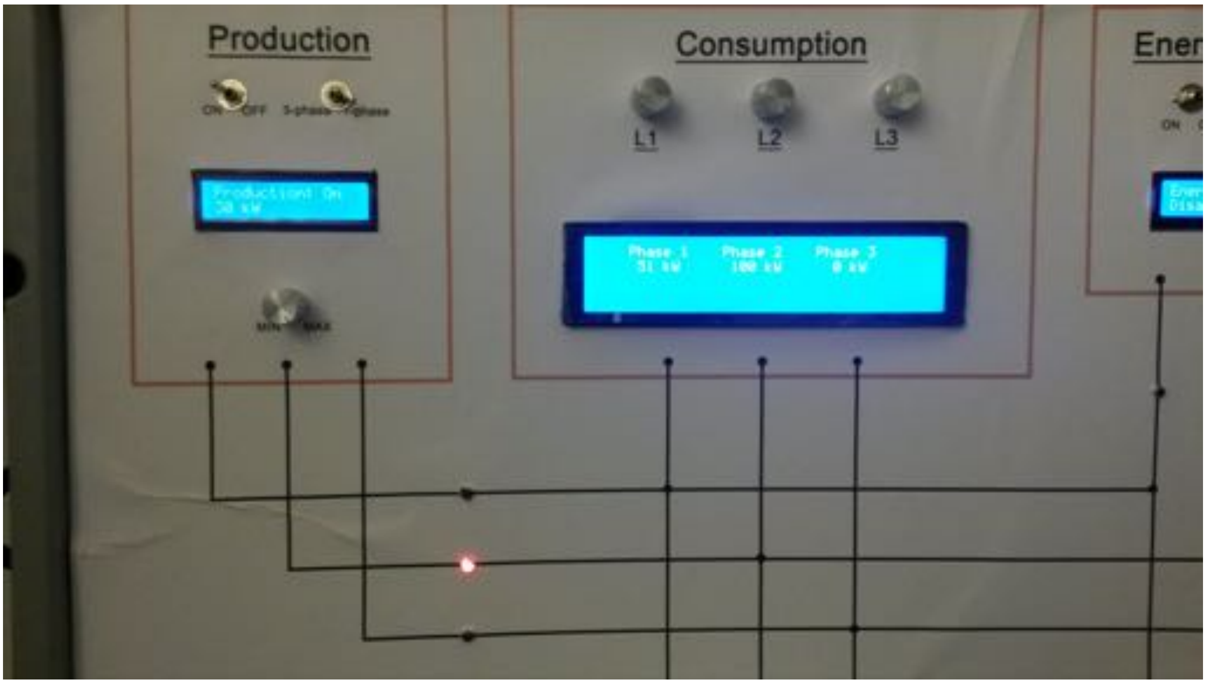

Figure 38, Facility platform, production connected to phase 2

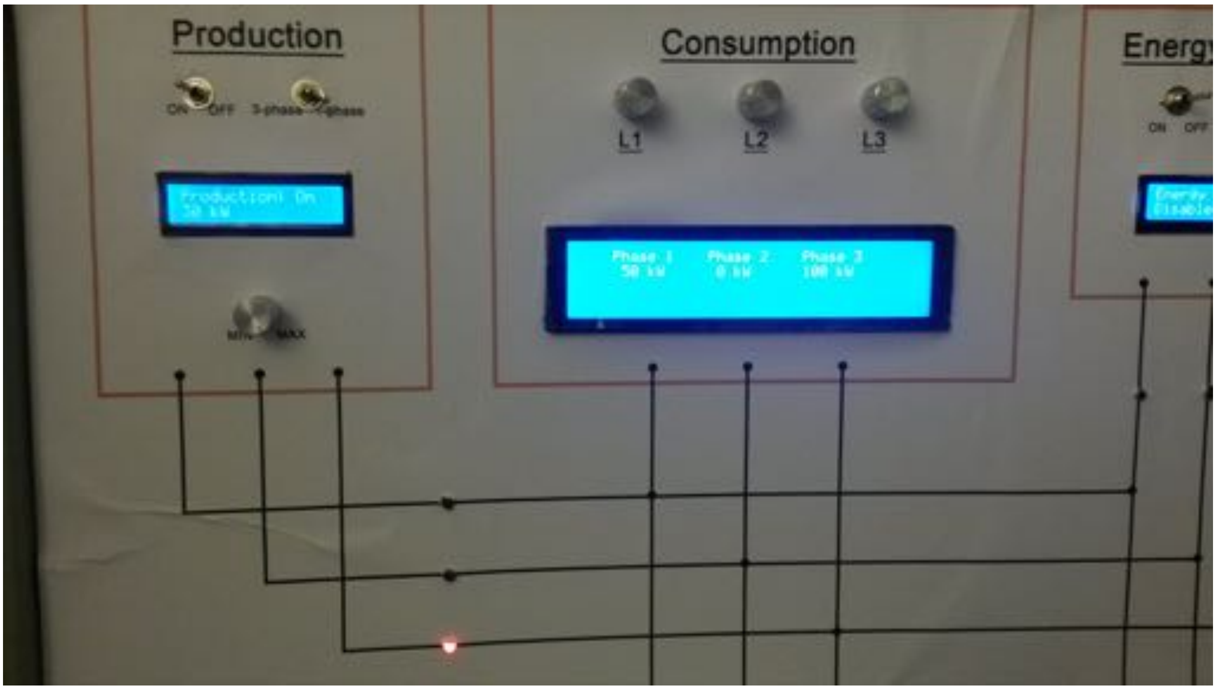

Figure 39, Faciliity platform, production connected to phase 3

Transfer of anti islanding protection signal and response in facility, in figure 40 and 41 the result of setting a frequency fault in the substation is shown.

Figure 40, Anti islanding protection signal recieved

Figure 41, Stopped production

Transfer of disconnect signal and response in facility, in figure 42 and 43 the response of sending a disconnect signal from the substation to the facility is shown.

Figure 42, Disconnect command recieved

Figure 43, Consumption to zero to indicate that the meter has switched off.

Substation controller function, in figure 44 and 45 the result of altering the state of the substation's controllers potentiometers and switches is shown.

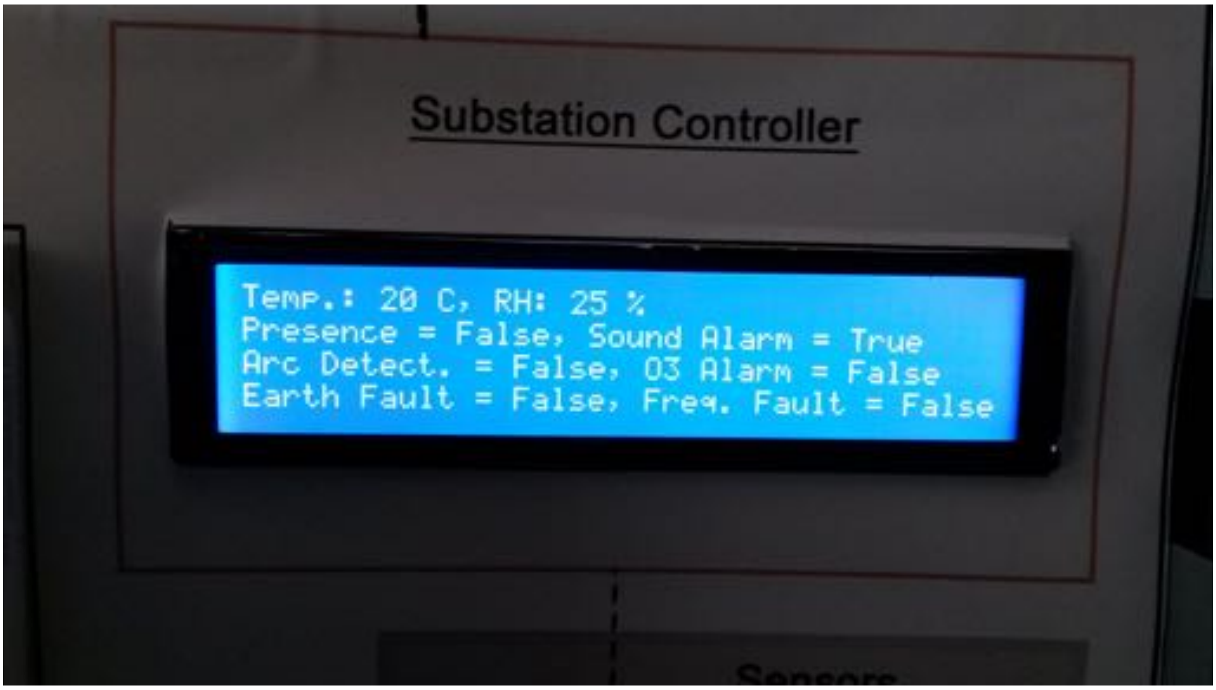

Figure 44, State of substation controller

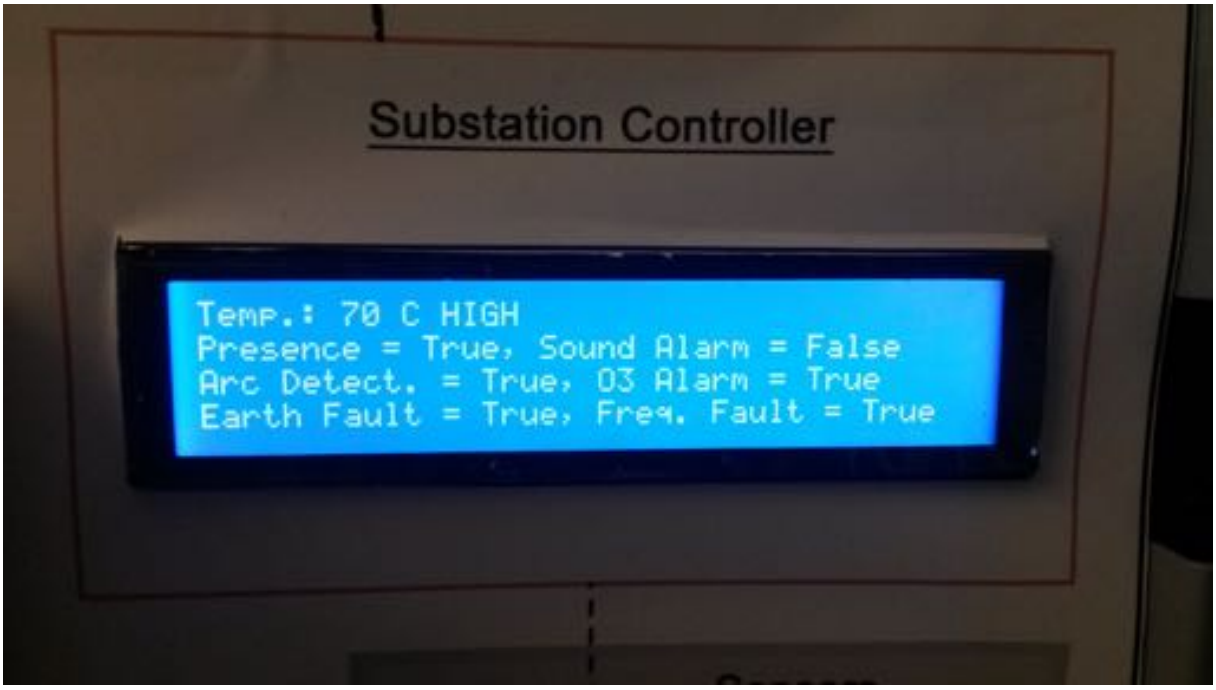

Figure 45, State of substation controller

Transformer surveillance function, in figure 46 and 47 the transformer statuses are shown.

Figure 46, Transformer status, Alarm active and OK temperature

Figure 47, Transformer status, Alarm deactive and HIGH temperature

7. DISCUSSION

7.1 SMART GRID APPLICATIONS

The use cases implemented or prepared in the demonstration platform are hoped to be used for real smart grid applications. In table 4 a matrix with mapping of use cases to smart grid functions are shown. The definition of smart grid defined by the Swedish Energy Market Inspectorate says that smart grid applications should:

"Ease the introduction of renewable electricity production."

By being able to limit the output power of a solar power installation it would be possible to introduce larger solar power installation in the grid. Also by controlling the instantaneous output power with respect to its impact on the grid to could be possible to install more solar power in areas where the grid is weak and lower the costs for the DSO. In areas with a lot of local production the instantaneous output power could be controlled so that the limits of the grid is not exceeded.

"Improve incentives to more efficient energy usage"

Having a connection to the end user facility would make it possible to send hourly electricity prices to the end user and make the end user more aware of the costs of energy and also make it possible for the end user to save money by changing the facility's energy consumption accordingly to the electricity prices. With local intelligence built in to the facility, automatic choices could be made to use energy more efficiently.

"Contribute to power reduction at peak load."

Being able to control production and consumption via demand response the power usage over a time period could be smoothed out to reduce the peak load and to make sure the grid can operate as efficiently as possible. By controlling which phase single-phase production is connected to it is also possible to reduce the peak load.

"Create better conditions for active electricity customers."

Having the end users facility connected with distributed computing power will make exchange of information and both local and remote control simpler. This enables the customer to make choices in their energy usage and also enable them to set pre defined condition to suit their need and some small alterations can be allowed to make it cheaper or more efficient.

The above mentioned functionalities covers the most important aspects of smart grid applications and by finding solutions that can cover as many as possible of them a less complicated and more interoperable future smart grid can be accomplished.

Table 4, Mapping of use cases to smart grid criterias

Functions: / Use Cases	*Ease the introduction of renewable electricity production*	*Improve incentives to more efficient energy usage*	*Contribute to power reduction at peak load*	*Create better conditions for active electricity customers*
Prioritized Automatic Disconnection	X		X	
High resolution logging	X	X	X	X
Substation Controller / Surveillance System	X		X	
Demand Response Controller/Enabler	X	X	X	X
Protocol bridge			X	
Increased size of solar PV installation in strong and weak grid	X	X	X	X
Anti-Islanding protection	X			
Phase-shifter for single-phase production	X	X	X	X
Distributed load analysis	X		X	X

7.2 DEMONSTRATION PLATFORM

The demonstration platform has proven versatility and has been made so that it is possible to extend the functions of a box, and also create new boxes with other functions than the ones implemented in this thesis. The software has also been made versatile by separating the different function in to different threads. So even if, for example, the protocol to read the I/O status changes and this part is rewritten, no changes are needed in the other parts since none of the threads are communicating directly with each other but uses the general objects that represents the facility and I/O configuration.

It is also possible to extend the facility representation whenever this is needed to improve the demonstration environment to include more information, for example adding voltage on each phase.

What is missing software wise on the demonstration platform is a general setup method. It was meant to make a simple Ruby on Rails server application that could be used to set all values in a demonstration box. For example the maximum power output from the production might be different on different facilities. Now this is hardcoded but a common setup tool would make it much simpler to set up a larger demonstration environment.

The server software could also be used as a SCADA system that can receive messages and alarms from the different boxes and it would be possible to add extra information so that some information in boxes gets set up automatically depending on what other functionalities there are in the demonstration environment.

The hardware in the simulation boxes could be made better. Now it has been made as test and pilot equipment, but if there are plans on extending the demonstration environment with more boxes it could be beneficial to make proper PCB design of all self made hardware. This would make it more reliable and give it a smaller footprint.

The interface with peripheral units as the Arduinos handling I/O and LCDs could be made simpler if the bugs in the Intel Edison are fixed and it would be possible to communicate with the Arduinos over I2C bus instead of USB serial.

7.3. MESH RADIO SOLUTION BY CONNODE AB

7.3.1. THE HARDWARE PLATFORM, INTEL EDISON

There have been a lot of problems with Intel Edison as a testing platform for the Connode mesh radio. The problems with the hardware have been caused by the fact that the Intel Edison is not a finished product from Intel. It still has bugs and there is no clarity, for the moment, in how Intel works to resolve these bugs and when a stable solution could be available. As of now (2015) it seems as a product for the “hacker” and “tinker” community to create solutions that previously used another embedded Linux compatible hardware like the Raspberry Pi. Another issue has been that the Connode Agent on the Intel Edison has required an older firmware that contains even more bugs. Connode has been working to correct the bugs on the newer firmware and claims now to have patched the problems, though this newer version was never tested in the scope of the thesis.

7.3.2. CONNODE AGENT

The Connode Agent for Intel Edison is basically the same program running on their microprocessor that is used in Connodes hardware to connect meters via 6LoWPAN mesh. It as been modified to fit the Edison and is running in userspace.

One large problem the Connode Agent had was that it was impossible to use the internal I/O-library, MRAA, in conjunction with the Connode Agent. This due to that the initialization of MRAA resets the SPI (Serial Peripheral Interface) and then the Connode Agent stopped working. This resulted in reducing the I/O functionality of the Intel Edison to read and write logical ones and zeros to input and output pins. This makes the Intel Edison possible functions in smart grid applications very limited. Another down side with the Connode Agent or rather the Connode mesh stack is that is doesn’t support sleeping end devices making it hard to connect to battery powered devices that only needs to be sending data sporadically or devices that might not always be on.

When analysing the existing solution from Connode with connected terminals on electricity meters some down sides where found when considering use cases for smart grid with distributed intelligence. The Connode agent installed in the electricity meters is not, as of now, directly accessible on the Internet. It is directly tied to the Connode server so the use cases where it was thought that values from the grid could be directly accessed in the meter via radio was changed. To be able to get values from electricity meter one would have to request the values from the Connode Server and not the meter directly. The Connode Server then requestes the meter over their closed and secure DTLS-channel and when the server gets the response it is returned in the original request.

7.3.3. CONNECTION TO INTERNET OVER CONNODE 6LOWPAN MESH

Since the Connode Agent on the Intel Edison is basically the same as the program running on Connodes microcontrollers the Connode Agent receives an IP address from the Connode Server and the Connode Server and Agent can communicate via a secure DTLS-channel. On the Intel Edison the Connode Agent then gives the Intel Edison a global IP address. The Intel Edison does not know of the Connode agent’s IP-address and the Connode Agent and Server does not have any knowledge of the Intel Edison IP address. This means that the Intel Edison can send information via a simple UDP-socket but to receive information the external sender needs to know the Intel Edison's IP address. Since this is not available from Connode software or services there is need to setup a server service to receive messages form the Intel Edison so that their IP address can be registered and stored. Most importantly since the Intel Edison itself has a different IP address than the Connode Agent all communications with the Intel Edison are open unless extra security is added. It is not possible to use the secure DTLS connections that the Connode Agent has with the Connode Server. Having to implement extra security creates a problem for rapid development of applications for smart grid since it will add workload and complex development. It also requires extra applications just to keep track of all devices current IP addresses.

7.3.4. REVIEW OF RADIO PERFORMANCE

No deep study has been made on the packet throughput of the Connode radio when running on Intel Edison. It has been seen that there, from time to time, can be significant packet losses in the communications, but the exact reason is unknown. The IP packets that are sent are UDP-packets and hence they have no handshake that the packet has been delivered. This problem is also present in the communication between the Connode Agent and the Connode Server. To handle the problem Connode use CoAP to send the messages. CoAP supports confirmable messages so if a message is not confirmed with an acknowledgment within a certain time the message is sent again. But having messages to be resent if no acknowledge response is sent is no guarantee for the messages actually arriving. If the radio environment is poor there might be cases where a message is not received for a long time. This makes the technology somewhat unreliable for security solutions, as breakers and protection, where there is need to have an action issued within a certain time.

But for non time-critical solutions as sending values and information, like setpoints or electricity price, to systems that are operating mostly locally using Connode mesh radio could be a valid solution. Connode has also implemented a HTTP-COAP proxy that has not been investigated in this thesis but it might prove to be a solution that can simplify the making of systems that use Connode mesh radio. The proxy takes the information that is sent via HTTP and translate it into CoAP so that is can be sent efficiently over mesh radio. This might make it possible to access meter values in other systems easier but in the case of using the Intel Edison there is still no CoAP implementation running on the Edison to interpret the messages.

When the Intel Edison's with Connode mesh radio hardware where mounted in the demonstration boxes the problems with packet loss and slow transfer speed where reduced significantly. Now it takes a few seconds for a message to travel from one box to the other via the relay server.

7.3.5. POSSIBLE IMPROVEMENTS

Since the I/O accessibility has been heavily reduced when using the Intel Edison together with the Connode Agent the functions that are possible to get out from it are very simple. Running a full embedded Linux environment to do these tasks is a bit excessive. It could be preferable to see that Connode goes back to using microcontrollers for their mesh radio and implements an API so that external hardware can communicate with their hardware and then the Connode hardware sends the message over 6LoWPAN mesh. The Connode hardware would then function as a modem and it wouldn't really matter what application or hardware you use it with as long as it has, for example, serial output. It could be a microcontroller that performs a simple task or an embedded Linux computer or a PC that performs advanced tasks. If a customer is using a very simple task to read some information it would also be possible to put that program in the same microcontroller as the Connode Agent and reduce hardware need even more. The Connode hardware could also be made so that it acts as an Ethernet interface so that it would be possible to use operating systems that are developed for running on constrained devices and be used for Internet-of-Things like TinyOS (TinyOS, 2015) and Contiki (Contiki, 2015). They support a range of communications protocol and would make it easier to develop applications for smart grids.

Connode would be able to offer its services to a much larger range of customers and industries. It would also be of interest if in the API it would be possible to choose if the communications should go via normal UDP-socket or if it should be sent to the Connode Server using Connodes secure DTLS channel and when the messages are received by the Connode Server they would be transported via TCP to other services. That would simplify applications development for customers and probably lower cost of hardware since the customer wouldn't be bound to the Intel Edison platform but can choose the proper hardware for its need. Also the use of HTTP-CoAP proxy would be an effective way of handling communication via API or direct CoAP implementation.

This would also mean that a device would only have one IP that the Connode Server knows about and this would be accessible to external applications via web services. Also if the Connode "modem" is made versatile with some extra memory it could be used to push new program updates and reprogram the microprocessors that are connected to it via the Connode Server. Having this possibility would mean that a customer could easily expand its functionally without having to invest in new hardware.

7.4 SMART GRID INTEGRATED IN SMART METERING

One thing that came up during the thesis was the hardware placement and utilization. The arrangement that was defined in the thesis was that an electricity meter is connected at each facility and then small embedded computers are distributed within the facility and the grid. In the smart meters were placed some form of communication capabilities to get the meter values to the central system and to the distributed systems for smart grid applications.

But what if instead of using extra embedded devices that also needs communication capabilities only upgrading the computing capabilities of the meters hardware to be a full embedded Linux environment that could be fitted the appropriate communication hardware. Reading a meter can be done very simply by using IEC 62056-21 and setting up the communication path to the central billing system as a small service in the embedded solution. Then the functionality of the smart meter is satisfied and on top of that it is possible to extend the embedded solution with different external interfaces to make use of, in smart grid solutions. In the end of this thesis one such meter was discovered to be on the market.

This could be a cheaper solution than setting up other systems that also requires communication hardware. It would reduce the need for more hardware and would reduce the investment and operational cost of a smart grid solution. If only the communication hardware that is extended with higher functionality it would still be possible to use the metering hardware and just upgrade old meters to be able to do new things by switching the hardware that interfaces to the meter.

If more functionality and different communication is supposed to be implemented in the meter it might be hard to satisfy the need of bandwidth with radio communication and other communication methods might need to be investigated, like LTE.

8. FUTURE WORK

8.1 CONNODE SOLUTION

One of the main issues of using UDP-based messaging was the conformability of the delivery of messages and the latency in the communication. A larger study in the time aspects and reliability of the solutions should be performed to be able to properly investigate how well Connode's solution works in stressed radio environments and if it is suitable for security and protection applications in smart grid applications. Also in the current implementation there is no application level security of the communication and it should be investigated how easily this could be applied to the solution. Either it could be possible to implement a separate DTLS security mechanism or it could be investigated if it is possible to use the same DTLS channel that the Connode Agent uses in connection to the Connode Server.

To address the confirmability of messages and to make sure messages are delivered a CoAP stack should be implemented and tried out for smart grid applications. By using CoAP it would be possible to use asynchronous networking capabilities and have messages that are not confirmed to have arrived at its destination to be resent. Having CoAP capabilities in conjunction with an HTTP-CoAP proxy could also make it easier to integrate TCP-based web services to the smart grid applications.

If these functions are supposed to be delivered by Connode or if Connode is only to be seen as a provider of IP connectivity and there is need to implement all above mentioned technologies and functions is today not known. Implementing own solutions would make it possible to be hardware and solution independent so that in a wide spread smart grid application the connectivity could be made with different technologies. It would also be possible to use other standards for smart grid control and translate them into CoAP. OpenADR, as an example, is a framework on how to communicate with certified equipment for demand response actions (OpenADR, 2015). But this framework is XML-based and would create large overhead in constrained networks. But having it translated into CoAP might be a good solution for being able to implement OpenADR as a standard protocol when dealing with demand side response. If the equipment is connected to a network with good bandwidth the normal XML representation could be used and if equipment is connected via constrained networks it could be sent via CoAP using a HTTP-CoAP proxy.

Connode has also stated that it is possible to send TCP over their radio, but it is nothing they officially support. But in respect of the handshake and data transmissions reliability it would be interesting in how using TCP over radio for application where UDP is considered an uncertain solution. It would be interesting to investigate what using TCP and larger message headers would do to the radio environment and if the delivery of messages is better then that of UDP and CoAP.

8.2 DEMONSTRATION PLATFORM

In the current setup there is only one facility box and one substation box. To be a proper an versatile simulation environment it would be better to have more facility boxes under the substation. It could also be interesting to have more than one set of substation boxes and multiple facilities under each one.

The software running on the Intel Edison now could be extended to handle many more scenarios and to take into account more data in the simulations. It would be possible to implement voltage variations and by using the network impedance at the facility have the production and consumption affect the voltage. To also be able to affect the voltage reactive power could be added to the simulations. Then it would be possible to have reactive loads in the facility but also control the reactive power that is drawn or output from production inverters or energy storage power electronics. Also the energy storage section in the facility box is not yet implemented since a more advanced model of operation was needed to make it useable in smart grid applications.

One important issue in the facility box is to receive electricity price and then perform an economical optimisation of the facility's energy use. The end user could also input a preference on how the energy would be used, and the system handles it accordingly. For example if there is a cap in how much energy that is allowed to be fed out during high production hours the system could for example make sure that the excess energy goes to heating water or into battery storage if it could be sold to the grid at a later time from larger profit. For the demand response load it should be possible to choose different modes of operation. If the load is a pump or a water boiler that has a limit on how much energy it can use and how long it takes until the water is at its maximum allowed temperature.

In the substation there is a need to implement an algorithm that can make use of the phase changing equipment for single-phase production in the facility. By analysing each phase it could send messages about which phases should be prioritized. There is a need to investigate the financial side of this since it might not be the best for the end user to switch phase and what rights does the DSO have to optimize the distributed production in the grid. The substation could also sum up all the facility's power consumption and compare to its own consumption to find possible problems or power thefts. Both in the substation and facility simulation fuses could be implemented and if the currents are too large the fuses could disconnect the phases they are connected to and send signals that they are blown. Another interesting function to implement is a background load profile for the substation. This is so the substation could operate like a normal substation when simulating and only the facilities that are implemented in boxes are laid on top of the background load profile.

There is need for a back-end and front-end server application for the simulation environment. The back-end application could handle setting up the internal and static values for each simulation box since all facilities are not the same. It could also handle all the IP addresses to the simulations equipment and even interface against the Connode Server to access meter values in real application to be used in the simulations. The front-end would be a SCADA system for the DSO and a customer interface for the end user. The DSO could get information and alarms from the grid and also define setpoints to automatic demand response actions and other controllers. The end user could interface with its own facility and set options for things like local production handling, usage of energy with respect to price and handling of charging electric vehicles.

To be able to have an effective and smart system that can discover utilities and functions by itself it would be beneficial to have a system that can represent the grid topology and to be able to associate equipment to this topology. When a function then needs a certain value that itself cannot measure or acquire locally it could then query the topology system and depending on function or value wanted the system identifies the correct equipment that the first component need to talk to. Also if there are multiple equipment that can deliver the same value, for example voltage in a multiple household building there will be several meters to get the value from. The topology system could distribute the meters to different functions to reduce the communication load in each meter.

8.3 SMART GRID

All work in this thesis has been on a demonstration environment but below is mentioned some examples of real world implementations that could be implemented in a near future.

By interfacing with a solar inverter via Modbus it is possible to control the maximum output of the solar installation. By using the SunSpecs protocol the equipment could be made to function on many different inverters.

To build a simple server side app to connect substation controllers to. The substation controller could monitor some values like temperature and humidity and interface with capacitive plates for sensing voltage. By placing the voltage sensor appropriately it is possible to monitor if fuses breaks. This could send an alarm to the operation centre so that they know exactly which substation and react to it before the customers have time to call in and report the outage.

Interface against a building automation system or an industrial automation system and send it messages that request it to lower or increase its electrical load. Then the automation system has to handle this the best way it seems fit.

Construct a phase-shifter for single-phase production. By using a microcontroller in conjunction with an electricity meter it would be possible to get information about the load on each phase. Then by using high power TRIAC: it would be possible to make a unit that would connect the single-phase production to the phase with the most consumption on it.

8.4 SMART METERING

It would be of interest to connect an embedded device directly to an electricity meter and power it by the same power the electricity meter uses. Then instead of using a smaller solution to read the meter the embedded device could read the meter and make it accessible on the Internet via, for example LTE modem. Then smart grid function like controlling solar inverters or I/O could be added to the device making it one compact solution.

Smart metering can also extend to other areas with interest in real time measurements and distributed intelligence. Within E.ON the second largest value collection is the collection of heat values from heat meters in the district-heating grid. These meters could be treated the same way as electricity meters and smart grid applications for heat distribution could be developed.

8.5 NEW AREAS OF INTEREST

ABB:s Tropos mesh technology, could be used to provide a city network with high bandwidth that could provide a solid backbone for the data collection in smart grid applications (ABB, 2015). The connection to the facility or house could then be made with non meshed radio to use the penetration that sub-gigahertz radio has compared to 2,4 GHz wifi.

New technologies within LTE are just released (Nokia Networks, 2015). LTE-M and NB-LTE-M are sub protocols to LTE that use narrower bands but in turn still have a fairly high data rate of 1 Mbit/s or 0,2 Mbit/s. The narrower bands make the modems less power consuming and could fit very well to distributed environments.

There are also other mesh radio solutions from different vendors that could be investigated. Some examples are ARM, Zigbee IP and Thread or the hybrid solution of RF and PLC from Itron/Cisco

9. CONCLUSION

In discussion with employees at E.ON, it was found that many could see clear applications for increasing the knowledge about the low voltage grid. By also moving computational power and intelligence out into the grid the solutions could be made more flexible and self-contained. By adding sensors and actuators and extra interfaces to the equipment in the field even more data could be collected and reacted upon. The extra interfaces could make interfacing with these existing systems smoother.

The Connode solution on the Intel Edison seems like a promising platform but has not yet reached a level of maturity to be used in production environments. But as a development tool and usage in proof-of-concept it works fine. The IP addressing of the Intel Edison decouples it from the existing Connode systems. If this is the right choice in the system design varies with the applications and use cases that will be implemented. Having the interface to the mesh radio depend on using an Intel Edison might not be the best choice. It limits the implementation and might also be too much for use cases where the embedded hardware only needs to do very simple tasks. A full Linux environment might be a bit excessive in some cases.

Using IP technology and the Internet-of-Things for smart metering and smart grid applications seems like the proper way to go. It is scalable and easily integrated into systems. Using 6LoWPAN, IP mesh radio technology seems like a good solution for the Internet-of-Things to be able to scale up environments and keep on developing solutions. The use of UDP is a bit of an issue in time critical applications, like relay protection. If a task needs to be performed within a certain time there is no guarantee that the message will reach the recipient in time or at all.

The use cases that were defined were the basis of the demonstration boxes. Hopefully the demonstration boxes can be reused and extended into a more complete simulation and demonstration environment. The demonstration boxes will become a tool for making it possible for other people to grasp what smart grid, smart metering and Internet-of-Things is about.

REFERENCES

ABB, 2015. *Wireless networks*. [Online] Available at: http://new.abb.com/network-management/communication-networks/wireless-networks [Accessed 30 November 2015].

Balijepalli, M. & Pradhan, K., 2011. *Rewiew of Demand Response under Smart Grid Paradigm*. Conference Paper: Innovative Smart Grid Technologies - India (ISGT India), 2011 IEEE PES

CEN-CENELEC, 2012. *Smart Grid Reference Architecture*. Report. Brussels: ETSI Smart Grid Coordination Group.

Contiki, 2015. *Why*. [Online] Available at: http://www.contiki-os.org/index.html#why [Accessed 30 November 2015].

FOI, 2013. *Elnätsföretagens MFK-planering En studie av elnätsföretagens möjligheter att genomföra manuell förbrukningsfrånkoppling baserad på Styrel, FOI-R-3797-SE*. [In Swedish] Report. Kista: FOI Avdelningen för Försvarsanalys.

IETF, 2007. *RFC 6282, 6LoWPAN*. [Online] Available at: https://tools.ietf.org/-html/rfc4944 [Accessed 30 November 2015]

Leisse, I., 2011. *Integration of Wind Power in Medium Voltage Networks - Voltage Control and Losses*. Lic. Thesis. Lunds University.

Nokia Networks, 2015. *LTE-M – Optimizing LTE for the Internet of Things*. White paper. Nokia Finland .

OpenADR, 2015. *Overview*. [Online] Available at: http://www.openadr.org/overview [Accessed 30 November 2015].

SunSpec Alliance, 2015. *SunSpec Specifications*. [Online] Available at: http://sunspec.org/download-sunspec-specifications/ [Accessed 21 July 2015].

Swedish Energy Market Inspectorate, 2007. *Månadsvis avläsning av elmätare*. [In Swedish] Report. Eskilstuna: Statens Energimyndighet EI.

Swedish Energy Market Inspectorate, 2010. *Anpassning av elnäten till ett uthålligt energisystem - EIR 2010:18*. [In Swedish] Report. EI Eskilstuna:.

Swedish Energy Market Inspectorate, 2014. *Uppföljning av timmätningsreformen*. [In Swedish] Report. Eskilstuna: EI R2014:05.

Swedish Energy Market Inspectorate, 2015. *Funktionskrav på framtidens elmätare*. [In Swedish] Report. Eskilstuna: EI R2015:09.

Svensk Energi, 2014. *Anslutning av mikroproduktion till konsumtionsanläggningar – MIKRO*. [In Swedish] Report. Stockholm: Svensk Energi.

Svenska Kraftnät, 2012. *Om utrustning för förbrukningsfrånkoppling, SvKFS 2012:1*. [In Swedish] Constitutiion. Sundbyberg: Svenska Kratfnät.

TinyOS, 2015. *TinyOS*. [Online] Available at: http://www.tinyos.net/ [Accessed 30 November 2015].