Tampere University

Niklas Weckström

INTEGRATION OF A MICROGRID ENERGY MANAGEMENT SYSTEM IN A BUILDING MANAGEMENT SYSTEM

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ABSTRACT

Niklas Weckström: Integration of a Microgrid Energy Management System in a Building Management System
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Maintaining a continuous balance between energy production and consumption is essential for the reliable operation of the electricity system. The importance of managing power balance has been emphasized as the share of weather-dependent renewable energy production has increased and the share of fossil-based control power has decreased.

As local consumer level production increases, so does the need for intelligent energy management. Energy management systems enable the fusion of local renewable energy sources and storages into a small intelligent and independent power grid; a microgrid. Microgrids are able to interact in real time with the operation of the entire energy system, taking into account energy market prices, weather conditions and locally forecasted energy needs and production volumes.

In this thesis microgrids and energy management were studied based on the latest literature to form the starting point for an integration of a microgrid energy management system in a building management system. The thesis literature review comprehensively examined the structure of the Finnish energy system and the management of its balance, both locally and at the system level. In addition, the work focused on the areas that enable energy management in microgrids, such as the determination of the flexibility potential and the modeling and optimization of the energy system.

The integration requirements were evaluated based on the use case examination and the literature reviewed. Implementation approaches were compared based on the reviewed literature. The communication between the two systems was tested with performance tests in a test environment. Communication protocols BACnet IP and Modbus TCP were selected for the performance tests, as they are widely supported in building management systems. The performance of these protocols in a automation server was measured with performance indicators specified from the automation server’s perspective. The suitability of these protocols was evaluated based on the test results. In the use case performance tests, Modbus TCP met the integration requirements with significantly lower automation server resource requirements.

Based on the results, it can be concluded that the communication between these systems is straightforward to implement in a similar use case. The same implementation principles can be applied between different building automation systems as well as energy management systems. In terms of energy management, the most complex area is the energy modeling of the system and the construction of the optimization methods used to fulfill the system goals. A great deal of research has been done in recent history of optimization approaches in different microgrid use cases. Based on the literature reviewed in the work, significant benefits have been achieved with energy management and optimization. These benefits are realized locally and reflect positively to the entire energy system as the overall stability improves.

Keywords: Microgrid, energy management, demand response, building automation, integration

TIIVISTELMÄ

Niklas Weckström: Mikroverkon energianhallintajärjestelmän integraatio kiinteistönhallintajärjestelmään
Diplomityö
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Energian tuotannon ja - kulutuksen jatkuvan tasapainon ylläpito on sähköjärjestelmän häiriöttömän toiminnan kannalta välttämätöntä. Tasapainon hallinnan merkitys on korostunut sääriippuvaisen uusiutuvan energiantuotannon kasvaessa ja fossiilipohjaisen säätövoiman osuuden pienentyessä.

Paikallisen tuotannon lisääntyessä kuluttajatasolle tarve älykkäälle energianhallinnalle kasvaa. Hajautettujen energianlähteiden hallintaan tarkoitetut energianhallintajärjestelmät koostavat paikallisia kuormia, tuotantoresursseja ja energiavarastoja itsenäisiksi kokonaisuuksiksi – mikroverkoiksi. Mikroverkoilla on mahdollisuus vuorovaikuttaa realiaikaisesti koko energiajärjestelmän toimintaan huomioiden energian markkinahinnat, sääolosuhteet sekä paikallisesti ennustetut energiatarpeet ja - tuotantomäärät.

Tässä diplomityössä perehdytään mikroverkkoihin ja energianhallintaan sekä muodostetaan lähtökohtia mikroverkon energiahallintajärjestelmän liitokselle perinteiseen kiinteistönhallintajärjestelmään. Tavoitteiden saavuttamiseksi työn kirjallisuuskatsauksessa tutustuttiin kokonaisvaltaisesti Suomen energiajärjestelmän rakenteeseen ja sen tasapainon hallintaan, niin paikallisesti kuin järjestelmätasolla. Lisäksi työssä perehdyttiin mikroverkkojen energianhallinnan mahdollistaviin osa-alueisiin, kuten joustopotentiaalin määritykseen sekä energiajärjestelmän mallintamiseen ja optimointiin viimeisimmän kirjallisuuden perusteella.

Työn teoriaosuuden ja työssä käsitellyn käyttötapauksen pohjalta arvioitiin vaatimukset käyttötapauksen BMS ja MG EMS järjestelmien integraatiolle. Integraation toteutustapoja vertailtiin kirjallisuuden perusteella ja järjestelmien välistä kommunikaatiota testattiin käytännössä suorituskykytesteillä testiympäristössä. Suorituskykytesteihin valikoituivat BACnet IP ja Modbus TCP, joiden tuki löytyy monista kiinteistöautomaatiossa käytetyistä laitteista ja järjestelmistä. Protokollien kuormittavuutta ja suorituskykyä mitattiin suorituskykytesteissä automaatiopalvelimen näkökulmasta ja niiden sopivuutta järjestelmien väliseen kommunikointiin arvioitiin tulosten perusteella.

Käyttötapauksen suorituskykytesteissä Modbus TCP täytti integraation vaatimukset huomattavasti pienemmillä automaatiopalvelimen resurssivaatimuksilla. Tulosten pohjalta voidaan todeta, että järjestelmien välinen liitos on vastaavassa käyttötapauksessa kevyt toteuttaa. Samoja periaatteita voidaan soveltaa eri kiinteistöautomaatiojärjestelmien sekä energianhallintajärjestelmien välillä. Energianhallinnan osalta monimutkaisin osa-alue on järjestelmän energiamallinnus ja optimointimenetelmien rakentaminen käyttötarkoituksen tavoitteisiin sopivaksi. Tutkimusta optimoinnin lähestymistavoista eri mikroverkkokäyttötapauksissa sekä kiinteistöissä on tehty paljon lähihistoriassa. Työssä läpikäydyn kirjallisuuden perusteella energianhallinnalla ja optimoinnilla on saavutettu merkittäviä hyötyjä paikallisesti, minkä hyödyt jalkautuvat välillisesti myös koko energiajärjestelmän hallinnalle.

Avainsanat: Mikroverkko, energianhallinta, kysyntäjousto, kiinteistöautomaatio, integraatio

PREFACE

First, I would like to thank Schneider Electric Finland and Sampsa Niemelä for the opportunity to work on this interesting topic. This final chapter of my studies was rewarding and gave me new perspectives to look at the bigger picture.

I would like to thank professor L. Martinez Lastra and Luis Gonzalez Moctezuma from Tampere University of Technology for support, examination, and the supervision of this thesis.

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Niklas Weckström

TABLE OF CONTENTS

ABBREVIATIONS

EMS	*Energy Management System*
BMS	*Building Management System*
MG	*Microgrid*
DSM	*Demand Side Management*
FCR	*Frequency Containment Reserve*
TSO	*Transmission System Operator*
DR	*Demand Response*
OTC	*Over the Counter*
AHU	*Air handling unit*
BESS	*Battery Energy Storage System*
EMS	*Energy Management System*
BMS	*Building Management System*
aFFR	*Automatic Frequency Restoration Reserve*
AHU	*Air handling unit*
AS	*Automation Server*
BACS	*Building Automation and Control System*
BESS	*Battery Energy Storage System*
COV	*Change Of Value*
CPU	*Central Processing Unit*
CRC	*Cyclic Redundancy Check*
DC	*Direct Current*
DER	*Distributed Energy Resource*
DR	*Demand Response*
DSM	*Demand Side Management*
EBO	*Ecostruxure Building Operation*
EMS	*Energy Management System*
EWS	*Ecostruxure Web Services*
FCR	*Frequency Containment Reserve*
FFR	*Fast Frequency Reserve*
IP	*Internet Protocol*
LAN	*Local Area Network*
MCC	*Master Central Controller*
mFRR	*Manual Frequency Restoration Reserves*
OT	*Operational Technology*
OTC	*Over the Counter*
PCS	*Power Conversion System*
PDU	*Protocol Data Unit*
PV	*Photovoltaic*
REST	*Representational state transfer, a software architecture for web services*
RTU	*Remote Terminal Unit*
SOAP	*Simple Object Access Protocol, a messaging protocol specification for exchanging structured information with web services*
TCP	*Transmission control protocol*
TLS	*Transport Layer Security Protocol*
TSO	*Transmission System Operator*
UDP	*User Datagram Protocol*

1. INTRODUCTION

The existing energy system is rapidly evolving towards a more sustainable entirety as the share of renewable energy production increases both domestically and globally. Simultaneously the share of fossil fuel based balancing energy production is decreasing. As the weather dependent production increases, so does the need for flexibility in balancing the energy loads and production in real-time. [38]

To support the holistic green transition, subsidies are granted for investments in local renewable energy production and - storage. Additionally, many incentives have been implemented recently to motivate consumers and prosumers adjusting their energy consumption and - production dynamically. [38]

With these incentives the share of local production and energy storage has increased in buildings and the transition towards prosumer microgrids (MG) has started to emerge. Prosumer microgrid consist of distributed energy resources such as adjustable loads and production resources, which are managed by an energy management system (EMS). [57]

Traditionally building management systems (BMS) focus in managing Building Automation System rather than optimizing and managing energy flows between local production and consumption. This need is can be solved with an additional layer of energy management integrated in the existing BMS. As the concrete process control and energy monitoring is executed in the BMS the clustering of these assets into distributed energy resources and adjustable loads enable the utilization of demand side management incentives and smarter energy management. [57]

1.1 Scope and goal of the thesis

The goal of this thesis was to study the different elements that are bound to microgrid energy management and demand side management. These topics form the general scope for evaluating the functional and non-functional requirements of the use case MG EMS – BMS integration. The integration does include the concrete communication between the two systems and the methods how adjustable loads, energy storage and production resources are managed in an existing BMS system.

The research questions of this thesis are defined as follows:

1. Which controlling and monitoring mechanisms are required to manage and forecast power - and energy flows in a MG EMS?
2. What are the communication protocol requirements for a MG EMS – BMS interface?
3. Which communication protocol will meet best the use case requirements?

Answers to question (Q) 1. were searched with a literature review of multiple topics related to demand side management (DMS), energy management, optimization and operation scheduling to get a comprehensive view of how energy management is conducted, which constraints need to be acknowledged and which results have been achieved in the recent literature with DSM.

In answering to the Q2 the findings of Q1 were utilized together with the literature review of the industrial control network (ICS) design principles and use case acknowledgements.

Q3 was answered with an empiric study based on the findings of Q1 and Q2 acknowledging the use case requirements. The communication protocols for comparison were outlined from the integration requirements and use case hardware acknowledgements. The two communication protocols BACnet IP and Modbus TCP were compared by a functional evaluation based on available literature and tested in practice with designated performance tests.

1.2 Structure of the thesis

The literature review begins from chapter 2. It starts with the introduction of the fundamentals of Finnish electricity system composition, demand response (DR) and electricity markets, which are the foundations behind the motivations of demand side management (DSM).

The general architecture of MG's and MG EMS's is then introduced along with demand response functions and most common optimization techniques utilized in MG energy management. The emphasis of these chapter is to outline the necessary system inputs of a building integrated MG EMS.

To support the evaluation of the communication protocol requirements general design perspectives of industrial control networks is introduced. Following a review of the use case BMS and MG architecture to be acknowledged in the assessment.

In chapter 3 the integration design considerations and the proposed system architecture for the integration are described.

In chapter 4 the concrete requirements for the integration are described and the proposed communication protocols for the implementation are introduced.

Chapter 5 includes the general comparison of the functional and non-functional requirements of the proposed communication protocols. Additional to the general comparison this chapter describes the performance tests in detail with the test results.

Chapter 6 concludes the thesis.

2. THEORETICAL BACKGROUND

In this chapter the comprehensive theoretical background of the thesis related topics are reviewed. The topics are divided to six sections as follows. The first topic covers the fundamentals of the Finnish electricity system and demand response, which gives an overview of the different segments incorporated. The fundamentals of the electricity markets illustrate the methods, stakeholders and incentives related to the maintaining of balance in electricity's demand and supply. Microgrids and energy management topic starts from describing MG fundamentals and reviews in detail how energy management and optimization has been conducted in the recent literature. The 4th topic introduces general theory of ICS design perspectives and communication protocols. Lastly the existing use case BMS and MG architecture are generally described.

2.1 Finnish electricity system and demand response

The Finnish electricity system consists of power plants, nation-wide transmission grid, regional networks, distribution networks and electricity consumers. It's connected to an inter-Nordic power system where electricity is transferred between Sweden, Norway and East-Denmark. In addition, this inter-Nordic power system is connected to Russian, Baltic's and Continental Europe's power systems through direct current (DC) transmission links, enabling international electricity trade. The utilization of DC-links is due to differences in the national power system working principles. [22]

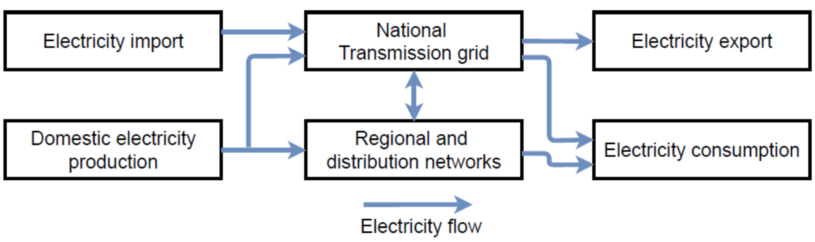


Figure 1. *The operators and the flow of electricity in Finnish power grid. Adapted from [58, p. 4].*

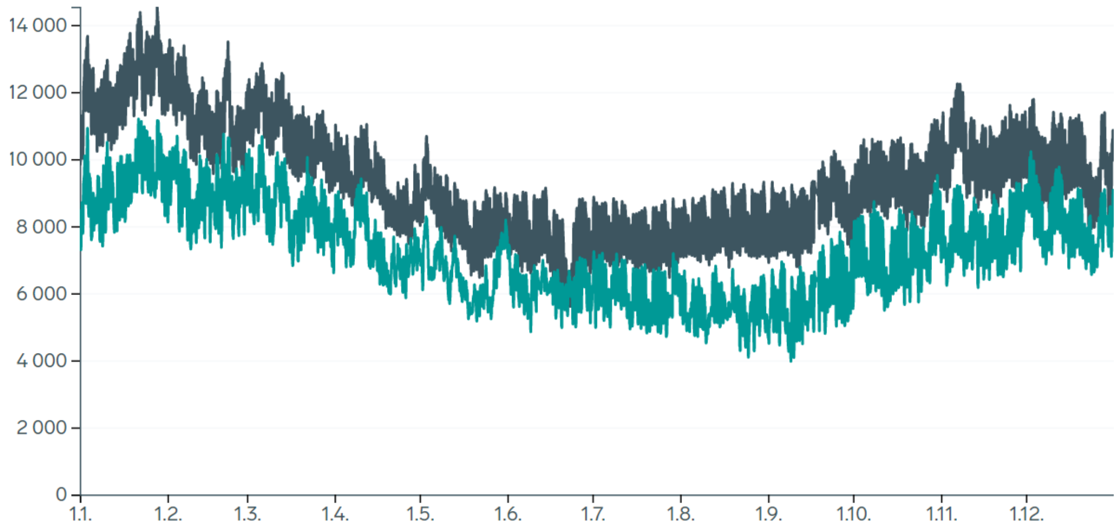
Most of the power consumed in Finland is transferred with the main transmission grid. It's the trunk network which connects the production, industrial plants and regional electricity distribution networks in high-voltage networks. In order to maintain a balanced and reliable production, consumption and distribution of power the Finnish Energy Authority has designated Fingrid Oyj the responsibility of functioning the Finnish electricity transmission grid. The functioning encompasses 116 substations and a significant quantity of transmission lines presented in table 1. [22]

Table 1. *Transmission grid owned and administered by Fingrid Oyj. Adapted from [22].*

Transmission line	Total lenght (km)
400 kV	5100
220 kV	1400
110 kV	7300
400-500 kV HVDC	216
150 kV HVDC	53

The total Finnish electricity consumption is the sum of all loads connected to the grid. That results as a constantly fluctuating power need, which changes by the hour, day and the four seasons. Also, changes in electricity power production occur during short and long terms, which is presented in chart 1. Maintaining a balance between the production and consumption requires precise pre-planning from the market operators. In reality, despite the pre-planning and partly shared responsibility the realized power balance tends to deviate significantly. [21]

The transient balance between the consumption and production is realized as a deviation in the electricity frequency of the grid. The nominal frequency value is 50 Hz and the allowed frequency deviation in a normal state is set domestically to ± 0,1 Hz. The electricity grid frequency increases as the production exceeds the consumption and decreases as the consumption exceeds the production. This deviation needs to be compensated hourly and Fingrid is the party which will initiate the regulating actions. [21]



Trend	Minimum Value	Maximum Value	Average Value
Electricity consumption	5455	14542	9483 MWh/h
Electricity production	3970	11195	7284 MWh/h

Chart 1. *Finnish electricity production and consumption in 2019. Adapted from [30].*

2.1.1 Electricity production and costs

The electricity price for the consumer is composed of costs dealt between electricity acquisition, transmission and taxes. Electricity acquisition covers the production and necessary trading functions, while transmission costs is a sum of total transmission in the nation-wide transmission grid, regional networks and distribution networks. The cost ratio between transmission and acquisition costs vary depending on the consumption volume. For example, a household has a larger share of transmission costs in the total electricity bill than a large industrial consumer. Typically, a normal household will pay approximately 40 % for acquisition, 30 % for transmission and 30 % taxes. [58]

Acquiring electricity claims the largest share of the total costs. Domestic electricity production has developed rapidly towards more renewable energy sources since the beginning of the 2010's. The use of fossil fuels in electricity production has decreased over 50 % during the past 10 years, while the total use of renewable energy sources has increased to 46 % in 2018. [70] Combined power capacity alone has been pulled down in the magnitude of 2,5 GW during years 2015 – 2017. [72] The total distribution of Finnish electricity production is presented in figure 2.

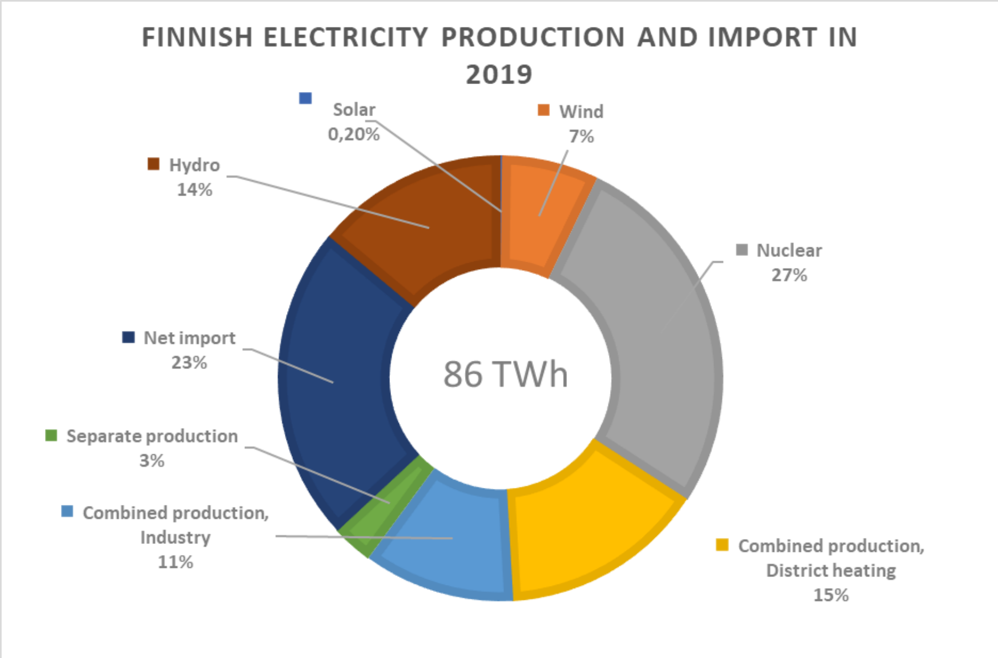


Figure 2. *Finnish electricity production and import in 2019. Adapted from [11].*

The amount of combined production varies significantly, since the electricity produced is a by-product and the primary output is thermal power to the district heating networks. These powerplants are operated by the need for heat, which changes relatively to local outdoor conditions. The weather has naturally an undisputed influence on the present renewable electricity production. The amount of wind, solar radiation and rainwater deposits determine the present production available and hence affects to the demand for conventional electricity producing methods and, also the total supply of electricity. [58, p. 5 – 6]

2.1.2 Demand response

The need for balancing energy, which can react to the fluctuation of the consumption and production is estimated to increase significantly in the North and West Europe. The amount of combined production will continue to decrease and the investments for inflexible wind, solar and nuclear energy production will increase. According to VTT's estimations the need for daily balancing energy will double by 2030. [72, p. 3 – 4]

In order to compensate this balancing energy need, development and implementation of demand response (DR) services has been executed widely during the 2010's [72, p. 3 –

4]. Commonly the balancing activities executed by the demand side is referred to demand side management (DSM), which the Electric Power Research Institute (EPRI) has defined as follows: [59, p. 1]

“DSM is the planning, implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e. time pattern and magnitude of a utility's load. Utility programs falling under the umbrella of DSM include load management, new uses, strategic conservation, electrification, customer generation and adjustments in market share”. [59, p. 1]

Previously DSM has been utilized mainly by industrial consumers i.a. metal -, forest - and chemical industries, where the main objective has been reducing or shifting the consumption to reduce the stress on the power system. Generally, the DSM actions can be summarized in energy efficiency, savings, self-production and load management which are either customer or utility induced. [59, p. 1] The actual demand response programs are included in customer induced DSM as illustrated in a general classification of DMS by Rangu *et al.* in figure 3 [60, p.16].

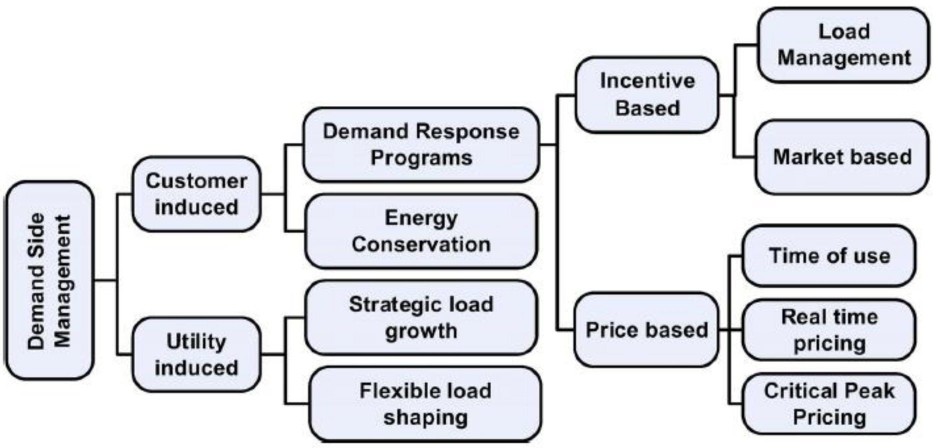


Figure 3. *Demand side management classification [60, p.16].*

The incentive-based load management is in relation with the current description of the demand response (DR) by the U.S. Department of Energy [56]:

“Demand response is an electricity tariff or program established to motivate changes in electric use by end-use customers, designed to induce lower electricity use typically at times of high market prices or when grid reliability is jeopardized.”

Currently the possibilities of participating to demand response have expanded and it can be utilized at the same marketplaces as any production resource. Participants of the electricity demand response in Finland are the customer, distribution network operators, electricity retailer, aggregator and the transmission network operator. The relevance, motivation and earnings of demand response actions between the DR participants is illustrated in figure 4. [38, p. 22]

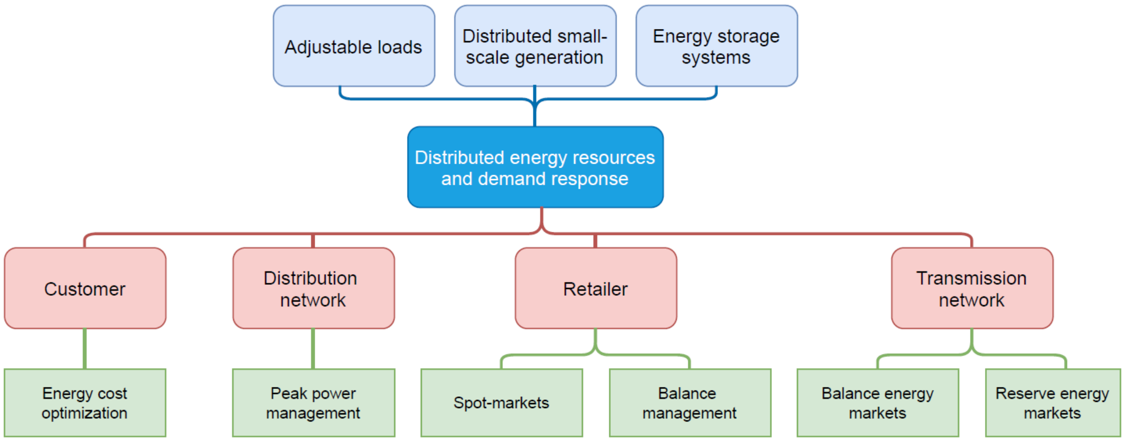


Figure 4. *Demand response stakeholders and relations. Adapted from [38, p. 22].*

Demand response have enabled the transmission system operator new tools for maintaining the grid frequency at a constantly reliable level. The reserve – and balance energy markets are utilized for managing the balance and securing energy assets for exceptional disturbance situations. The retailer can utilize DR in electricity acquisition planning, own electricity balance, balancing energy bids and developing its business activities. Distribution network operators can make good use of DR in long term grid design planning from a rated power point of view and controlling peak loads in real-time. [38, p. 24]

As a customer of the retailer and the distribution network operator, the end-user of electricity can benefit from DR by decreasing consumption during expensive hours and schedule energy consuming activities during cheaper electricity prices. A concept of aggregation has also been recently implemented, which enables i.a. small-scale producers and consumers to participate to DR. The aggregator is a service provider, which operates directly or indirectly in DR by trading individual distributed sets of adjustable loads as one unit to the electricity market. [38, p.23 – 24, 30] The service provider is referred as an independent aggregator which is currently described by the market directive 2019/944 as a market participant which is not bound to the customer's supplier [71].

The description of an independent aggregator has been further specified by the smart grid committee of Ministry of Economic Affairs and Employment of Finland as a participant, which is not the customers electricity retailer or balance manager and doesn't require a separate contract with the electricity retailer or the balance manager while operating in the market. [71] The first aggregation pilots, which were initiated a few years ago by Fingrid, Helen and Voltalis have produced limited knowledge so far. The results still provided insight of the development trends of bidding, trading and operations modelling related to the aggregation concept and the roles of the service provider. [24] The development and fine tuning of the legislation, detailed working principles and practical implementation are currently ongoing [71].

2.2 Electricity markets

According to Fingrid, a functional electricity market is the key in implementing and maintaining a cost-efficient balance of electricity supply and demand. The price formulated in the electricity markets influences efficiently to the production, consumption and long-term investments made by the market operators. The energy transition towards renewable and more sustainable sources has a significant impact on the present marketing model and especially to the electricity trade made close to the physical transmission. [25]

2.2.1 Electricity market price composition

Currently the electricity wholesale bipartite trade between the producers, large clients and electricity retailers is carried out in the electricity market Nord Pool Elspot and Elbas markets and OTC markets. The wholesale price is determined for every moment in time in accordance with the supply and demand. [58, p. 9]

The Elspot electricity price for the day ahead markets is calculated for every hour by the purchase and sales offers placed by the market participants, also acknowledging the available transmission capacity. One aggregated demand curve and one aggregated supply curve is created within a bidding area and all different types of trading offers are anonymized as presented in figure 5. This enables the same standing and price to all producers regardless of the producing method. The calculated whole-sale price corresponds to the variable costs of the most expensive producing method needed to cover the electricity need. [53] These costs will set the present marginal cost for the electricity. When the available production of electricity is sorted from the lowest marginal price to the highest, the production and demand will meet at the lowest price possible at every moment [58, p. 9].

The bidding areas are divided by the relevant transmission system operator (TSO) in order to control congestion in the electricity grid. As an example, Finland is a bidding area at the European markets. While the electricity will flow towards higher demand and price from areas with lower prices the transmission capacity relative to the production and consumption is in a key role in price formulation. If the transmission capacity is adequate between the bidding areas the price will be identical. When the transmission capacity is limited between bidding areas, a congestion will develop, and the area prices will start to differentiate in relation to the amount of congestion.[53]

The Elbas market is an Elspot aftermarket, where the trading is performed close to the physical delivery of the electricity. This trading method enables the possibility to influence to the realized imbalances between the market participants. Participants can offer own unused flexibility in both directions. [10]

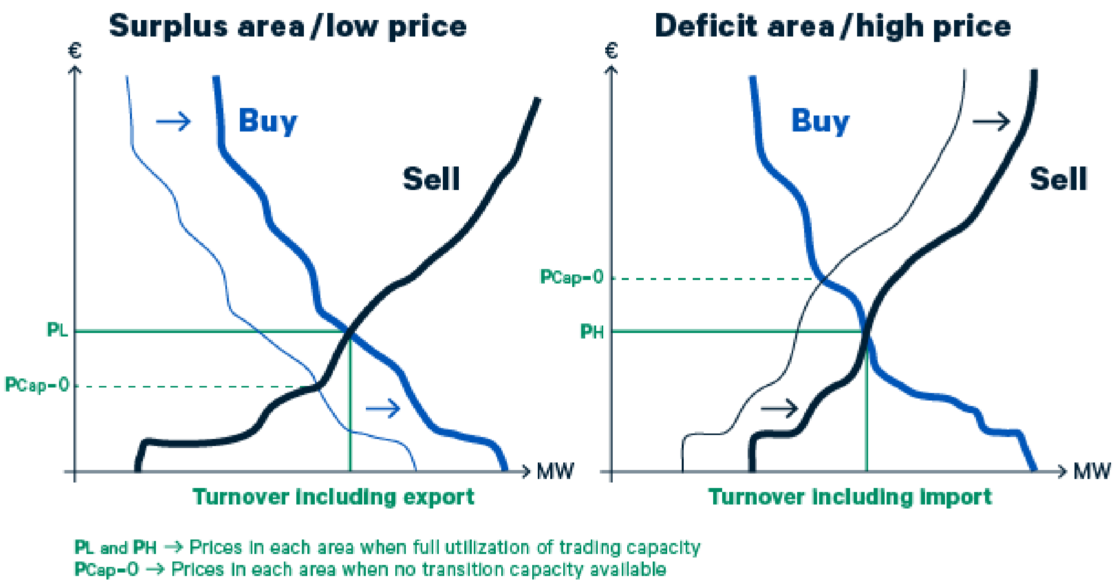


Figure 5. *NordPool price formulation [53].*

2.2.2 Reserve markets

Reserve markets are in a key role in maintaining a constant balance between Inter-Nordic production and consumption regardless of the present operating situation. Fingrid is responsible of functioning the domestic transmission grid and therefore required to upkeep and develop the marketplaces for electricity control, and also obliged to follow the mutual Nordic contract on transfer for use. The concrete reserves utilized are power plants and consumption objects, which participate in regulating the grid frequency by producing or consuming electricity when required. The electricity regulation is currently managed with five different reserve types with different target capacities presented in figure 6. [26]

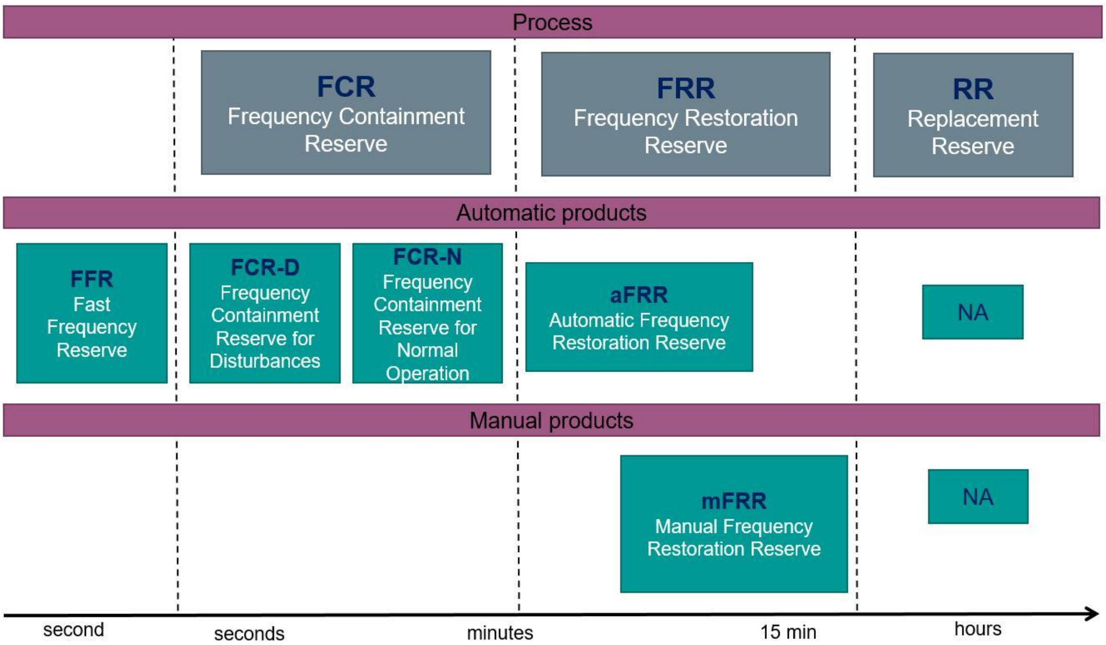


Figure 6. *Fingrid's reserve products [13].*

The Inter-Nordic frequency containment reserve for normal operation (FCR-N) is maintained constantly at 600 MW during normal conditions, where Finland needs to cover a share of 120 MW. The total FCR capacity is evaluated on a weekly basis, where the amount required is matched to cover the largest single production disconnection possible. The FCR capacity required from each Inter-Nordic TSO operator is dealt in relation with the production and consumption of each country. FCR-N reserves are obliged to constantly regulate as a function of frequency, which is practically executed with a maximum delay of two minutes. Every reserve participant is permitted to provide capacity between 0,1 – 5 MW and activates the amount of necessary FCR-N regulation based on a selected electricity grid frequency measurement. The utilized frequency measurement accuracy needs to be at least 10 mHz with a resolution of 1 mHz. The regulation performed needs to be symmetric for both power increase and decrease in order to guarantee a steady activation from every FCR participant. The steady operation of FCR reserves is ensured with a wide set of technical requirements and qualification tests by Fingrid. [13]

A more critical frequency containment reserve is the reserve for disturbances (FCR-D). The FCR-D is a high capacity frequency reserve, which is required to regulate even a disconnection of a large power plant without the frequency decreasing below 49,5 Hz. The activation of FCR reserves as a function of frequency is presented in chart 2. The Inter-Nordic FCR-D capacity need is currently set to 1450 MW, where Finland covers a share of 290 MW. The requirements for an FCR-D event activation is significantly more time critical compared to the constant FCR-N regulation. [18] The FCR-D participant is permitted to provide capacity between 1 – 10 MW and is required to supply 50 % of their reserve power capacity in five seconds after an FCR-D event is triggered and reach to 100% power supply in 30 seconds. [17]

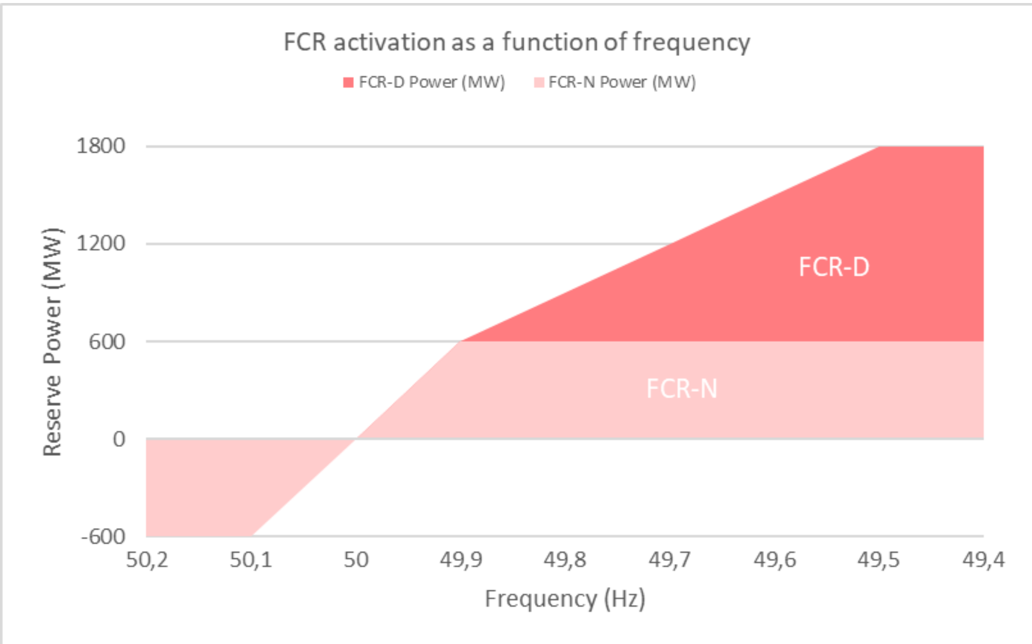


Chart 2. *FCR activation as a function of frequency. Adapted from [15].*

An approved FCR participant can offer their reserve capacity for the yearly and/or hourly markets at Fingrid's Vaksi web. The yearly market competitive bidding is organized only once a year in Autumn. Fingrid determines the reserve capacity price for FCR-N and FCR-D by the most expensive approved bid, which will be the reimbursement for every participant (€/MW) for maintaining the capacity available. Participation to the yearly market requires a submission of a reserve plan to Fingrid, which states the amount of reserve capacity offered for every hour of a CET day. [29] The reserve planning can be completed for 1 - 31 days forward and it needs to be submitted the latest 18:00 o'clock (EET) the day before.[17, p. 7]

Fingrid activates reserve bids from the hourly market if the required reserve capacity is not covered by the yearly market reserve plans and acquisitions from Russia, Estonia and the Inter-Nordic [17, p. 9]. The received bids for the next day are sorted by ascending price for every delivery hour and will be activated if required. The bids can be submitted until 18:30 o'clock (EET) and Fingrid will confirm the possible purchase by 22:00 o'clock (EET). Investing for reserve capacity and participating to FCR markets can be relatively profitable. As an example, the volume-weighted FCR-N average reserve electricity price was 31,4 €/MW,h and for FCR-D 16,1 €/MW,h in 2019. If a 1 MW FCR-N reserve is offered and kept available e.g. for 4000 hours, the reimbursement sums to a total of 125 600 € per year, which doesn't include the reimbursement of the actual activated power.[27]

Fast frequency reserve (FFR) is an automatically operated reserve which is primary used to control small inertia with activation times of 0,7 – 1,3 seconds, where the inertia means the ability of the kinetic energy stored in the rotating masses to resist changes in frequency in the electricity system. The FFR is a relatively new reserve type, which was first commissioned in the Inter-Nordic in May 2020. The proportion of the required capacity is determined by the frequency deviation tolerance of disconnection of an electricity production unit or a HVDC transmission connection. The frequency deviation limit is set to 49,0 Hz, where the amount of FFR regulating capacity is affected by the present amount of inertia and the amount of electricity power loss caused by a disturbance. [18] The total FFR capacity currently operated in the Inter-Nordic is approximately 300 MW, which is obtained daily by demand from national electricity markets based on the inertia forecast [14].

Automatic frequency restoration reserve (aFRR) is a reserve type, which was commissioned in Finland in 2013. It's used to restore the grid frequency to the nominal value of 50 Hz. The Inter-Nordic TSOs have agreed that the regulation present power needed is calculated and forwarded from Statnet supervision system to each main grid operator. [15]

The reserve activation is based on a frequency deviation on a synchronous range and it's triggered by a power change signal sent by the grid operator to the participants. The minimum power requirement for reserve participation is 5 MW. A participant can offer Fingrid only regulation in one direction at once, which needs to be fully activated in 5 minutes after a power change signal is received. The participant receives a reimbursement by the regulated power according to the pricing of the regulating electricity market, which is typically in the magnitude of dozens of euros per MW/h. Currently the reserves are only utilized domestically, but an Inter-Nordic expansion is planned. [15]

2.2.3 Balancing energy - and balancing capacity markets

The Finnish balancing energy market is administered by Fingrid and it's divided by the 64th parallel to the North and South regulation districts. The market is a part of Inter-Nordic balancing energy market, where manual frequency restoration reserves (mFRR) are acquired by activating submitted balancing capacity bids. The bids are submitted to Fingrid's electronic reserve trading system (Vaksi web) by the approved balancing service providers pursuant to the Balancing Capacity Market or the Balancing Capacity Agreement. [20]

Balance bids can be submitted from 31 days to 45 minutes prior the time of the physical energy activation and needs to include information of the regulation power (MW), price (€/MWh), reserve object name and reserve information. The minimum bid regulation capacity is set to 10 MW except for 5 MW bids which can be activated electronically. [20, p. 7] Once activated the regulated capacity is required to reach full power in 15 minutes, and also be available for minimum of three hours in order to meet the participation criteria. The received bids are sorted by the activation hour, regulation direction, capacity and price. For balance management and frequency maintenance the up-regulating bids are used in an ascending price order and down-regulating in a descending order. [20, p.5-6]

The realized financial potential in the balancing energy market is significant. During 2019 the up-regulation price exceeded 100 €/MWh 263 times, which covers 3 % of the yearly hours. As an example, a constant 10 MW bid priced 100 €/MWh would have resulted an average price of 182 €/MWh, since the reimbursement is determined by the most expensive bid accepted during the specific hour. This bid would have yielded during 2019 approximately 478 296 euros as illustrated in the equation below. [27]

10 MW × 182 €/MWh × 8760 h × 0,03 = 478 296 € / year [27]

The balancing capacity market was commissioned during spring 2016 to ensure sufficient reserve capacity to balance disconnections of Fingrid’s own electricity production. A weekly (CET week) competitive bidding is utilized for acquiring the required balance capacity. The capacity bid size is limited between 5 and 50 MW and are also submitted to Fingrids Vaksi web, with the required bid information: regulation direction, capacity offered (MW/week), capacity price (€/MW/h) and regulation district. If a bid is approved, the balance capacity provider is committed to supply the agreed amount of balancing capacity during the procurement period. Fingrid favors bids with low capacity costs but acknowledges the overall bid prices and the amount of available alternative frequency restoration reserves in the bid acquisition process.[28]

2.3 Microgrids and energy management

The utilization of a constantly increasing amount of distributed energy generation requires developments on the modern power system. One step of the evolution towards a future smart grid is to combine the local renewable energy sources and storages into a small intelligent power grid; a microgrid. [57] The microgrid description covers many different use cases varying in size and properties. In this chapter the focus is in microgrids that are integrated in a building, which are commonly referred as prosumer microgrids.

Operating a microgrid requires reliable and effective mechanisms to manage and forecast on-site power and energy flows. Several use case control objectives have been studied with various optimization techniques in the recent literature. Whether the goal is to e.g. minimize operation costs, minimize energy consumption or maximize revenues for sold energy, optimization algorithms are the main tools, which have been proven to realize the desired outcome.

In this chapter the general architecture, demand response strategies and most common optimization techniques are introduced with the emphasis on the necessary system inputs and outputs in a building integrated microgrid energy management system.

2.3.1 Microgrid Architecture

Microgrid is a is an autonomous system which main function is to enable flexible and efficient management of loads and distributed power generation even in isolated circumstances. The significance of microgrids is highlighted when multiple local renewable sources of energy production are utilized locally and in regional demand response. The further development and implementation of microgrids has an important role in the transition from a traditional grid to the future smart grid.[73]

The advantages of a microgrid compared to a traditional local grid are significant. The level of reliability increases as the intelligence in automated management and utilized equipment's increase. Constantly active remote intelligent monitoring enables self-protection during failure and self-healing of power restoration, while manually operated equipment would have caused direct power interruptions. Advanced monitoring gives access to more detailed information of the consumption patterns and enables an intelligent control system to manage the coexisting centralized and distributed control.[73]

A microgrid architecture can be generally divided to four modules: distributed generation, loads, utility grid and demand side management, which are presented in a structural diagram in figure 7, where the energy – and information flows are represented between modules [73].

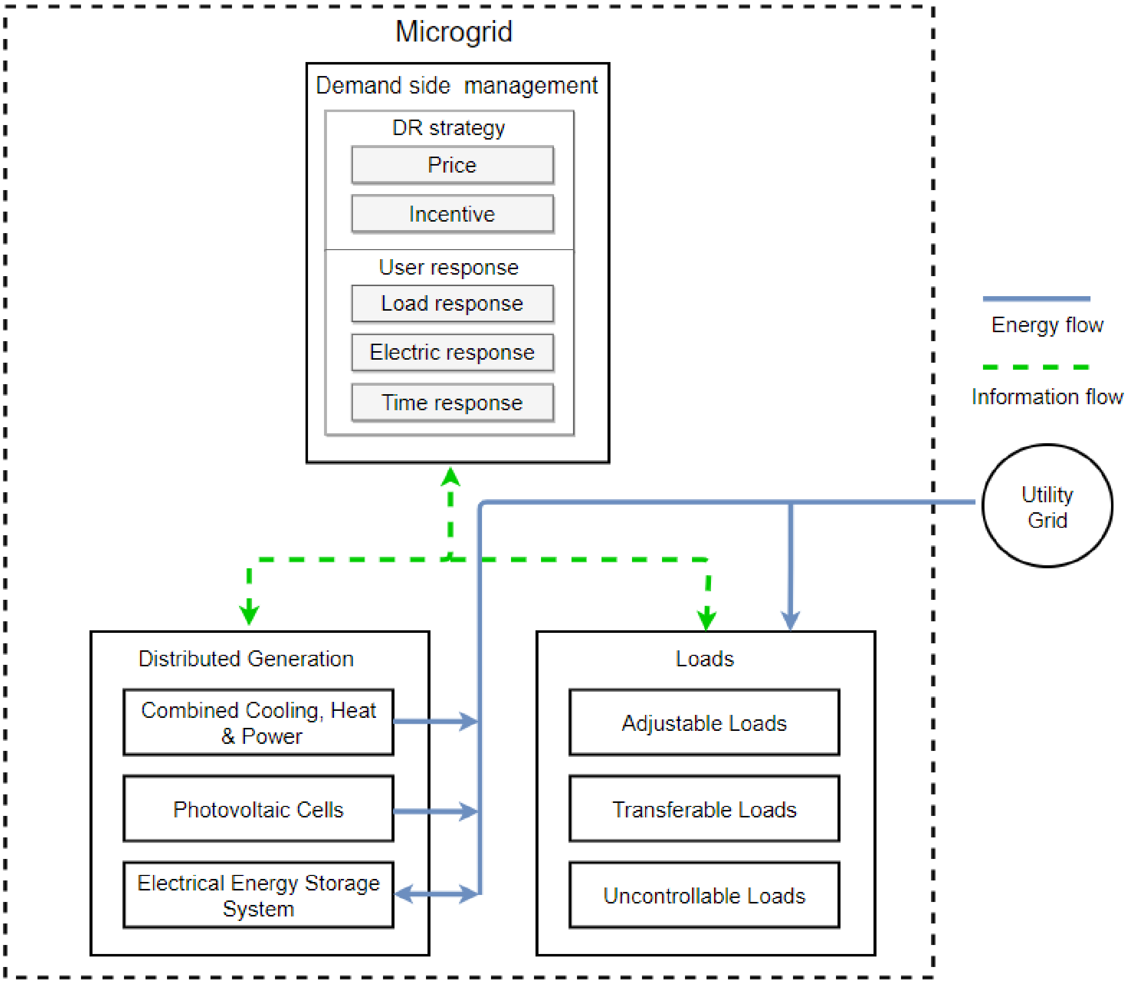


Figure 7. *Energy management of smart microgrid with response loads and distributed generation. Adapted from [73].*

The distributed generation usually include a varied combination of wind power generation, photovoltaic power generation, fuel operated generator (e.g. a diesel generator or a gas turbine) and a distributed energy storage [73]. The loads connected to a microgrid are divided to different categories from the demand response point of view. Adjustable – and transferable loads can be utilized in DR which most commonly are electricity consuming appliances such as heating, ventilation and air conditioning (HVAC). These loads with local power production and storage form the distributed energy resources (DER) of the microgrid architecture. [6]

The uncontrollable loads instead, consist of user operated appliances which are difficult to adjust or re-schedule without disturbing the occupant's comfort, for example an oven or a refrigerator [6]. The demand response module is included in demand side management, which is further divided into demand response strategies and user responses. The demand side management plays a significant role in optimizing the microgrid operation. The demand side management involves the dynamical determining of the systems energy flexibility and managing the entirety. [73]

2.3.2 Demand Response Flexibility

Generally, there are two types of DR schemes as presented in the previous chapter in figure 7. The incentive-based is also described as "direct", "emergency-based" or "system-led", which refers to the monetary incentives received from the DR operator for e.g. shifting or directly controlling loads. The price based can be identified as "market-lead", "economic-based" or "indirect" demand response, where the customers adjust their energy consumption or production by the dynamic price rates of electricity. The system property, which enables these operations is referred to system flexibility. [6] In power systems flexibility is described in [6] as:

"the ability to cost-effectively and continuously balance electricity supply and demand, while simultaneously maintaining acceptable service quality to connected loads."

Load flexibility potential of DR programs with different use cases have been studied significantly during the 2010's. Currently renewable energy, energy storage and HVAC systems play a key role in DR programs, which are progressing more and more towards fully automated DR programs. The energy metering is also in transition to the advanced metering infrastructure (AMI), which enables a reliable two-way connection system between the consumers and power utilities. With the real time data available, smart appliances can utilize the dynamic electricity rates in scheduling and optimizing loads. [6]

Flexibility quantification for both supply and demand side of the system is crucial in determining the flexibility potential. An important requirement for the distributed generation - and load flexibility is the capability to decrease or increase power load over time. This feature along with the ramp magnitude, ramp frequency and response time metrics can be used to characterize and quantify the flexibility. Recent studies present many modelled equations to compute the flexibility for operational systems and their various combinations. [6]

The energy usage of buildings varies over time, so the flexibility potential needs to be quantified with the actual baseline load of the system. The baseline load represents the total power consumed by the system without utilizing any flexibility potential. With the baseline load, the maximum and minimum load curves can be computed. In figure 8, a 24-hour scaled schematic of flexibility principles is presented, where the ideal load curve is defined to be as steady as possible. The time slots presented in the schematic are divided in three sectors by the typical load consumption pattern of a building, where the yellow area denotes load increasing flexibility and grey area load decreasing flexibility. [6]

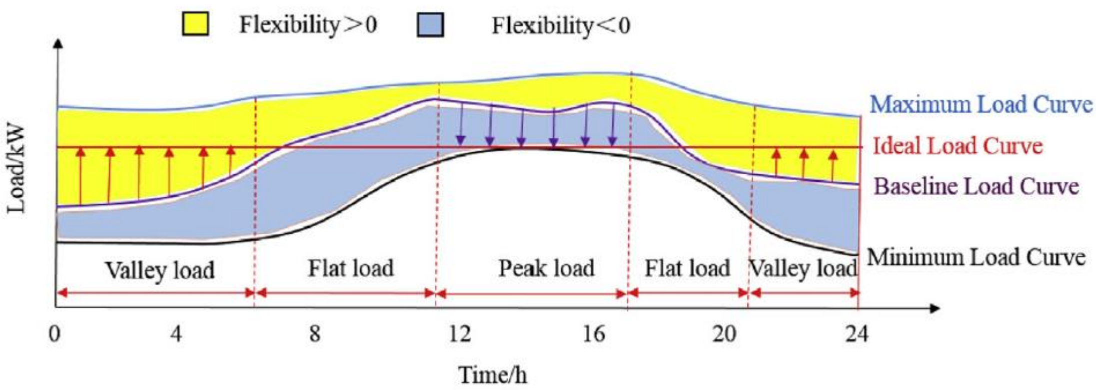


Figure 8. *Schematic of flexibility definition [6].*

Concrete examples of flexibility potentials reviewed by Chen *et al.* from state-of-the-art researches are summarized in table 2. The table contains the results of the maximum shift proportions and peak load reductions among various building energy systems with different DR types implemented. [6]

***Table 2.** Summary of DR potential of load flexibility based on state-of-the-art research. Adapted from [6].*

Building energy systems described	DR Type	Load flexibility results
Thermal energy storage	Price based	Maximum 18.7% total peak load shift to valley time
Space heating with thermal storage	Price based	Reduce the energy payment of the house, and indirectly reduce the market power
Fast demand response strategy using active and passive building cold storage	Incentive based	Up to 34.9% chiller power reduction
Ventilation system in residential building	Price based	A single ventilation system can provide 4.5 kW for power increase and 1.0 kW for power reduction during DR time
Smart building cluster with PV systems	Price based	The proportion of shiftable loads is 25% in the total load profile
Fast demand response of HVAC system	Incentive based	Achieve 39% power reduction
HVAC system and smart appliances	Incentive based	Reduce the daily peak load by 25.5%
Electric vehicles planning in residential, commercial, and industrial areas	Price and incentive based	Achieve 20% peak load reduction and 40% aggregate cost reduction
Home Energy Management System (HEMS) in a residential building	Price based	Autonomously reduce peak load and reduce electricity cost up to 20% a day

These results show a great flexibility potential in renewable energy sources, energy storages and HVAC systems in building energy systems, which enable achieving savings of costs and emissions while also enhancing the balance between the regional power consumption and production.

A noteworthy acknowledgement is the trade-off's that each demand response operation potentially has. Decreasing or increasing loads in a building will usually have an impact on the indoor climate conditions and may generate a symmetric rebound effect in relation with the energy consumption deviated. [61] To minimize unwelcome energy consumption fluctuations triggered by DR, the importance of a holistic approach to forecast the system's operation is emphasized. By acknowledging the internal and external factors affecting the base load can the triggered load deviations be optimized with a steadier shift towards the baseline.

2.3.3 Optimization Techniques

The importance of a microgrid control strategy is vital for the contribution of distributed generation and economic energy utilization. Every system has its goals and constraints, which needs to be taken in consideration while determining the systems operation scheduling. In microgrid energy management, the available distributed energy resources and corresponding transmission capabilities needs to be adapted with the present and forecasted demand and economic incentives in real-time. The optimization of these functions is commonly referred as operation scheduling and the economic load dispatch problem, which can be resolved with techniques that utilizes computational optimization. [32]

Briefly simplified computational optimization is used to find the best solution between a group of different alternatives. It covers a wide set of mathematical techniques and algorithms, which focus on modelling the system and resolving objectives with constraints, while acknowledging a versatile range of objective functions and variable domain types. The optimization problem needs to be thoroughly modelled and constraints recognized in order to have sufficient insight to choose the right computation methods and succeed in the optimization. [32]

There’s a possibility that the optimization problem winds up to be unfeasible or it would require an exponential computation time to find an optimum result. For avoiding these scenarios approximate optimization methods such as heuristic and metaheuristic approaches have been proposed in the recent literature. [32] Heuristic problem solving could be described as finding a good result by “educated guesses” as Mattila describes in [43]. Heuristic approach can provide then faster solutions to Non-deterministic Polynomial-time hard problems with a trade-off for optimality and completeness. The downside of a heuristic approach is the need for a thorough verification of the results without a certain guarantee of success. [35]

The verified heuristic results can be utilized as such or as a good baseline for supplement algorithms as in a metaheuristic approach, in which many heuristic methods can be used consecutively in computing the optimum solution using a higher-level optimization strategy. The metaheuristic algorithms are often classified by two methods: trajectory or population-based, which are generally problem independent, and the solutions are computed from a discrete search-space. [32]

The search process in trajectory methods starts from a single solution, which is dynamically improved each discrete time-step. The generated trajectory will provide useful information about the algorithm behavior and a single optimized solution. Population-based methods start the searching with a set of solutions, a population. The search-space is searched iteratively in a natural and intrinsic way generating sets of solutions by e.g. mutating and recombining the generated populations until a stop condition is fulfilled. [8]

Nature has been a significant inspiration for developing new ways of computing for decades. The same inspiration has enabled the discovery of a large number of optimization algorithms in various categories with the metaheuristic optimization methods. In figure 9 the Euler's diagram of the different classifications of metaheuristics created by Game et al. in [33], gives a comprehensive view of the different optimization algorithms and the methods they may apply.

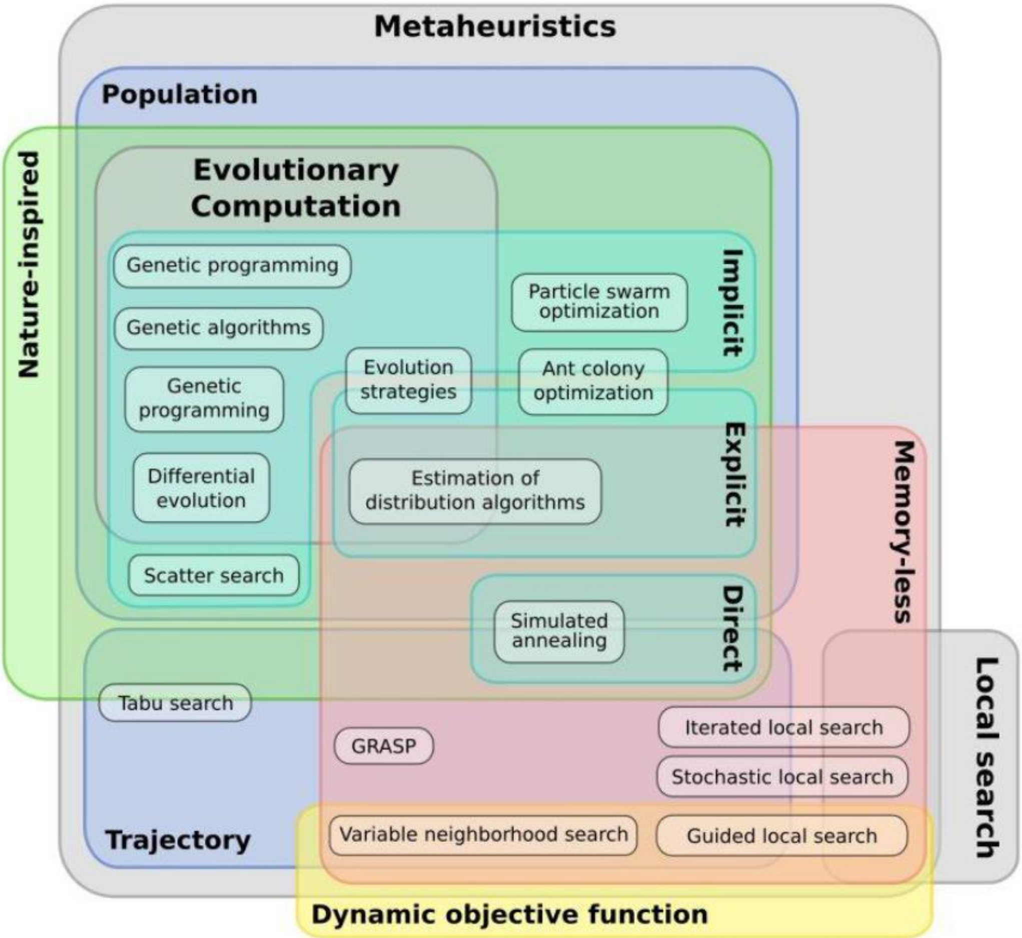


Figure 9. *Euler's diagram of the different classifications of metaheuristics [33].*

A recent review of microgrid energy management optimization made by Rangu *et al.*, illustrates a clear categorization of the different types of optimization problems solved with various approaches in figure 10. [60]

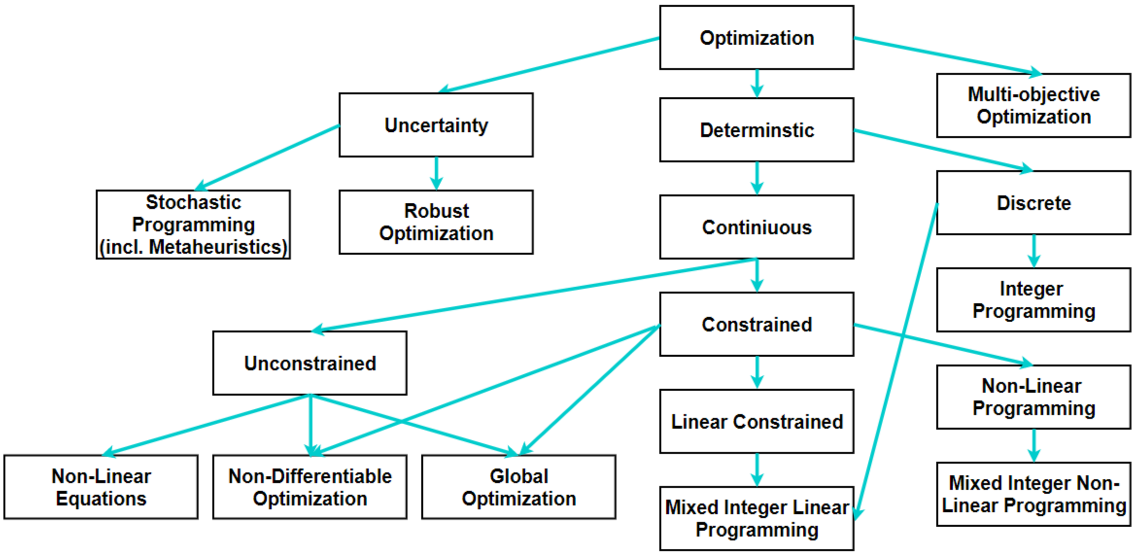


Figure 10. *Optimisation taxonomy. Adapted from [60].*

A common requirement for solving the economic load dispatch problem is forecasting the load demand and generation of installed renewable energy production [32]. The simultaneous optimization of both supply and demand side increases the problem management complexity in mathematical terms [69]. The availability of renewable energy sources is highly weather dependent and thus has a stochastic nature. As it's with everyday weather forecasts the forecast error probability in load dispatch tends to similarly increase as the forecasted timeframe increases [32]. Hence a typical forecast horizon is set only to one day ahead [69].

Generally, many forecast scenarios with different strategies and techniques have been proposed in the recent literature. One technique, which stands out from Gamarra *et al.* review study [32] is the utilization of Artificial Neural Networks (ANN) algorithms in forecasting both production and consumption. The forecasting techniques based on ANN are allocated with specific forecasting objectives such as hourly power outputs. [32] The data produced by the forecasts are utilized by the main optimization algorithms, for example in [5], where ANN produces the power forecasts for an improved Genetic Algorithm, which is in charge of sustaining good operation and making trading decisions.

The amount of optimization use cases with different methods is significant. Table 3 lists various method algorithms used for resolving the economic load dispatch in literature with single- and multi-objective approaches and, also heuristic and metaheuristic approaches. The presented list is sorted from Gamarra *et al.* review study to illustrate a selection of the multiple methods used to optimize load scheduling. [32]

Table 3. *Method-algorithms for operation scheduling optimization. Adapted from [32].*

Approach	Method-algorithm
Single-objective optimization	Sequential Quadratic Programming technique (SQP) Dynamic Programming (DP) Mixed Integer Non-Linear Problem (MINLP) Integer Programming (IP) Linear Programming (LP) Multi-Path Dynamic Programming (MPDP)
Multi-objective optimization	Simulation-accounting (SA) Game Theory (GT)
Heuristic and metaheuristic optimization	Genetic Algorithm (GA) Particles Swarm Optimization (PSO) Vaccine-enhanced Artificial Immune System (VACCINE-AIS) Mesh Adaptive Direct Search (MADS) Modified Gravitational Search Algorithm (MGSA) Adaptive Modified Firefly Algorithm (AMFA) Gravitational Search Algorithm (GSA) Self-adaptive Charged System Search (SCSS) Bacterial Foraging Algorithm (BFA) Competitive Heuristic Algorithm for Scheduling Energy-generation (CHASE)

Nonetheless the different system components and objectives, there's several general DER-specific baseline inputs that are utilized commonly in real-time and forecasted MG EMS operation. The parameters in table 4 illustrates the basic necessary measurements and system constraints reviewed and cross-referenced from studies [67, 49, 55, 4, 50, 54], which are bound to local distributed generation (including energy storage), loads and the utility grid. In addition to these measurements also constraints related to economic performance are acknowledged in the optimizations. These values cover i.a. electricity and heat tariff rates, costs related to operation and maintenance as also emission factors.

Table 4. *MG EMS fundamental inputs. Adapted from [67, 49, 55, 4, 50, 54].*

Parameter	Distributed Generation	Loads	Utility grid
Active power output (kW)	M		M
Active power input (kW)	M	M	M
Available capacity (kWh)	M		
Fuel consumption	M		
Ramp-rate: min, max (kW/min)	C	C	
Power input: min, max (kW)	C	C	C
Power output: min, max (kW)	C		C
Storage capacity: min, max (kWh)	C		

M = Measurement, C = Constraint

2.3.4 Energy Management Systems

A microgrid (MG) incorporates and interacts with an extensive amount of internal sub-systems controlling distributed energy resources (DER), energy storage systems (ESS), loads, regional grid and the energy markets. Sustaining a balanced and optimized MG operation requires a complex and multi-objective control system with the availability of Information and Communication Technology (ICT). The general control structure of a MG is a layered hierarchy, where the EMS operates at the top level: [44]

- Supervisory layer: EMS, functions: e.g. power quality control, ancillary services, energy market participation, operation optimization
- Local control layer: Local controllers, which operate the field level covering basic functions of regulating generation and loads
- Field layer: Integrated physical components, such as DERs, power converters, grid components and loads

A more detailed hierarchical control scheme divided in three levels has been widely approved as a standardized solution for MG management. It’s comprised of a tertiary level, a secondary level and a primary level which are illustrated in figure 11. In this scheme, the control task and objectives of both the tertiary and the secondary levels are integrated in the MG EMS, which comprises all high-level supervision, control and optimization functions. The controllers and power converters at the primary level are responsible for controlling the local voltages and currents with response times in the magnitude of 1 – 10 milliseconds (ms). [44]

The MG EMS receives input from each hierarchical level including the upper level operators and service providers, which provide e.g. weather forecast data and market data utilized in load and generation dispatch forecasting. The gathered measurement data and information is then processed by the optimization algorithms and formulated into decision making executed in discrete time steps varying from seconds to hours. [44]

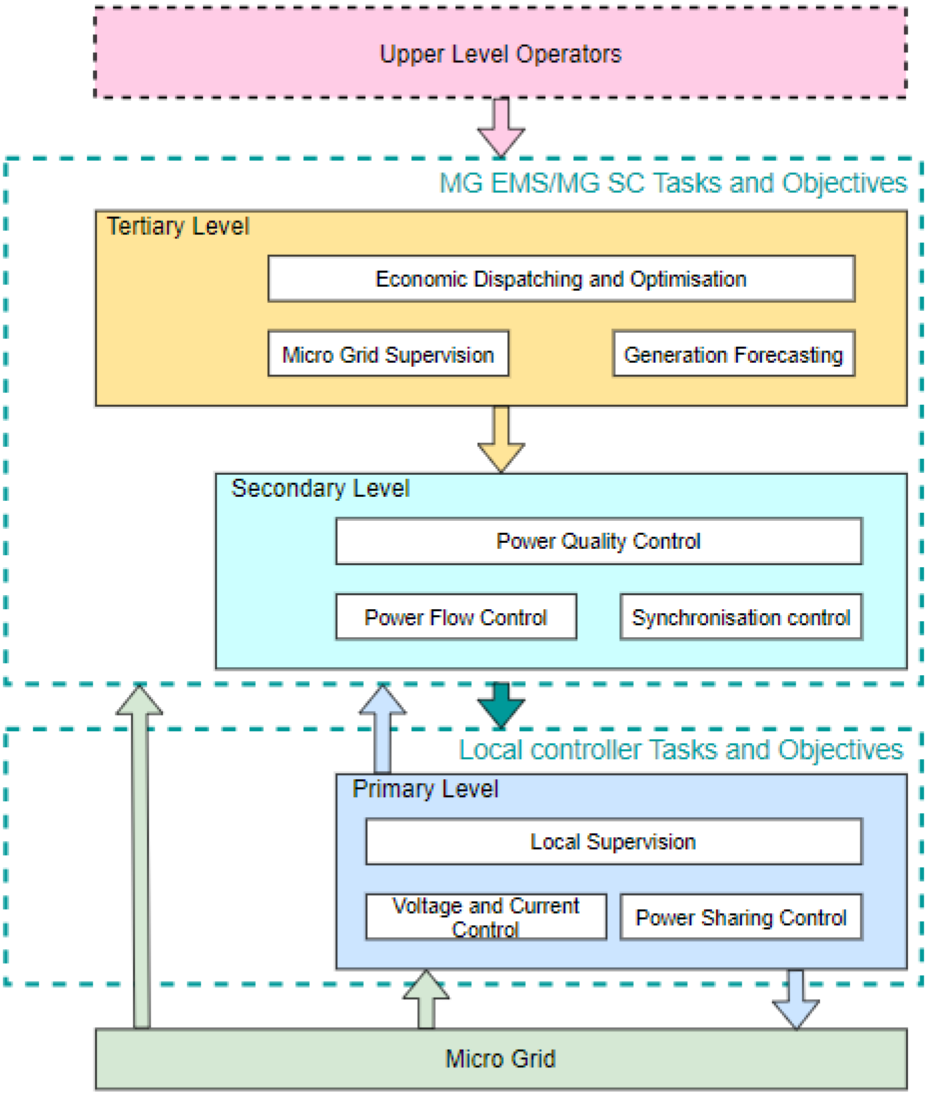


Figure 11. *Microgrid hierarchical control. Adapted from [44].*

With the measurement data inputs and additional control set points the number of data points exchanged between the BMS and MG EMS can be preliminary estimated. Naturally, the number of parameters and variables utilized in optimization models is significantly greater. Despite the relatively obvious set of equipment performance related basic parameters and constraints, it’s not obvious that every piece of hardware has these measurement data’s available by default. For example, in [68] where power metering had to be fully re-instrumented to support demand response operation.

From a FCR point of view, the power realization of every utilized asset needs to carry out Fingrid’s standards for accuracy. The importance of a comprehensive energy metering is hence in a key role in the MG EMS operation, and when the available assets for FCR power regulation are determined.

2.4 Communications Network Design and Architecture

This chapter includes a brief review of the main characteristics of industrial network architecture and communication protocols. The network requirements and design perspectives section review the general design considerations of an ICS system, which are utilized in the assessment of the integration requirements.

2.4.1 Industrial Networks

Despite the industrial networks have progressed towards Ethernet and IP based technology as conventional commercial Ethernet networks, the similarities between their communication requirements are insignificant. Industrial networks are used to inter-connect systems and physical equipment to enable the controlling and monitoring of real-world actions and conditions, which demand higher reliability on fast real-time data transfer and a need for strong determinism. [31]

The general architecture of industrial networks integrated with enterprise systems is conventionally presented with the multi-layered ANSI/ISA-95 architecture model presented in figure 12, where the real-time requirements typically increase level by level as stepped towards the concrete production process [31]. The architecture is divided to high level enterprise management layers (MES, ERP & PLM), a supervisory layer (SCADA/HMI) and the field layer, which comprises a network of all process controllers, such as PLC’s and equipment used in controlling and monitoring the specific subordinate processes [39].

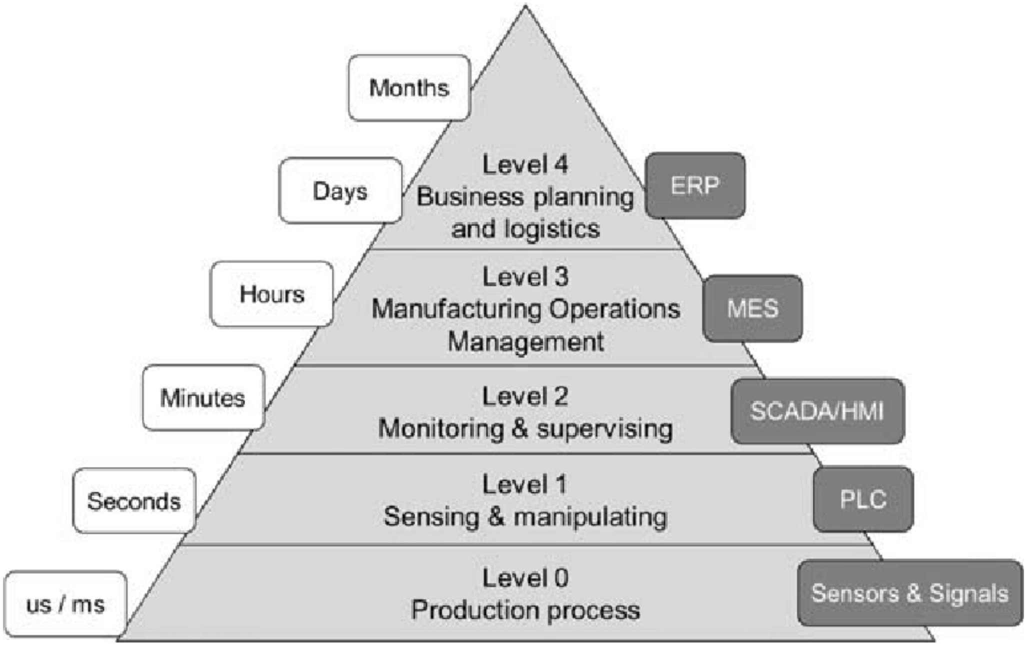


Figure 12. *ISA95 automation pyramid [39].*

2.4.2 Communication protocols

Communication protocols define the rules and procedures between the different network entities. Reference models has been developed to further describe the general communication architecture, it's components, interaction principles and the division of these functions to different layers. [41, p. 70 – 72]. The entities with the same functionalities, such as different services are comprised within a layer and they interact with the adjacent lower layers for exchanging messages [41, p. 41]. The commonly known seven layered Open Systems Interconnection model (OSI) was standardized in the 1980's and yet remains as widely referred reference model in describing the architectural concepts in practice. The seven layers in the OSI model are divided in application-oriented and transport-oriented layers as illustrated in figure 13. [41, p. 70 – 72]

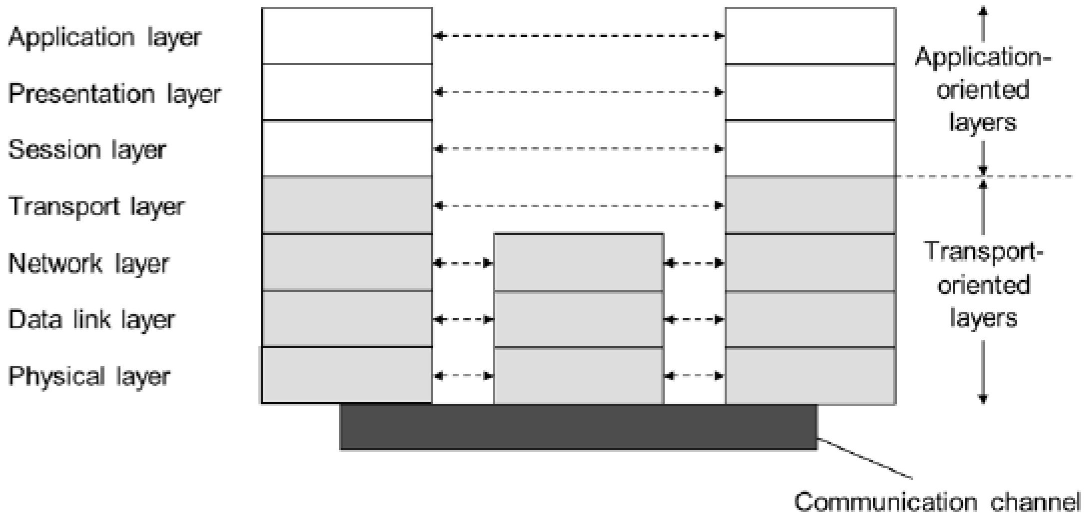


Figure 13. *OSI-model [41].*

The layered protocol architecture has enabled the development of independent, open and/or standardized protocols serving the functions of a particular layer. The existing protocols are often developed for a specific task acknowledging the designated communication and system requirements. [41, p. 70 – 72, 40] Choosing an efficient and standardized protocol stack for interconnecting the systems, interfaces and instruments is then a challenging task, when many possible trade-offs need to be considered while comparing different protocol options.

2.4.3 Network requirements and design principles 100%

Highly specialized protocols have been developed to ensure the reliable and economic operation of various industrial control systems. There's naturally variations between the requirement specifications between each industry, process and network architecture, but generally the requirements can be broadly grouped by the following domains: *discrete manufacturing, process control, building automation, utility distribution, transportation and embedded systems*. [31]

Failure Severity

Controlling industrial processes sets varying boundaries for the tolerance of failure. In industrial processes the chances of economical -, environmental - and even the loss of human life are not acceptable. The operating system is thus required to maintain controlled performance even in exceptional conditions.[31]

Real time requirements

Calling a system real time capable presumes a request response within a predefined time limit [9]. Additional to correct computation, real time operations require precise timing and response times as close to instant as possible. A conventional rule of thumb suggests that *the response time should be less than the sample time of data being gathered*. Each process has its boundaries for response time limits, but generally the magnitude varies from 250 µs to 10 ms at the field network level. [31]

In industrial ethernet systems a real time categorization of three levels is proposed in survey [9]. Depending on how strict the defined response time limits are, the real time type can be categorized as soft, hard or isochronous. Class 1 represents a less stringent soft real time, where the cycle time are scalable and can reach the magnitude of 100 ms, i.e. minor time exceed is tolerable and won't cause any significant consequences. Class 2 is categorized as hard with the cycle time requirements between 1 to 10 ms. Class 3 is referred as an isochronous real time, which includes cycle times between 250 µs to 1 ms with a 1 µs tolerance limit for jitter. [9]

Determinism

Determinism implies to the predictable characteristic of a transmission response time. In addition to the real-time requirements of the lowest industrial network levels, the time difference between a transmitted signal and a response needs to be predicted. In order to create a reliable prediction, the signal latency should have a low variance and be bound to a constant level. A stable response time is a key element in control loops and digital signal processing. The variance of the response time, generally referred to as jitter effects negatively e.g. to the derivative and integral portions of control loops and to signal processing methods, which require fixed sample intervals of data, such as Fast Fourier Transforms.[31]

Data Size

Due to demanding real time and reliability requirements, industrial protocols at the field network level typically trade off additional features to enable higher efficiency. The available bandwidth is typically low and the transmitted message frame is small, containing e.g. a single binary state or one 16 bit value. The message frames usually also excludes any basic security features i.a. authentication or encryption, which would increase the amount of additional overhead and processing times. [40, p. 121 – 122]

Periodic and aperiodic traffic

In industrial networks, traffic can be divided in periodic and aperiodic types. In event driven systems values are monitored at the controller level and sent to higher level supervisory systems if a designated value has e.g. deviated over a predefined alarm threshold or a dead band. There are many implementations how aperiodic traffic can be managed, but a basic requirement is to ensure that a sufficient set of bandwidth is always allocated for it. The relevance is highlighted in process-oriented systems where the periodic controller level data is polled at a fixed interval and open slots in a transmission cycle needs to be organized. The precise orchestration of these transmissions requires implementation of synchronized clocks and bus contention protocols at the field network level.[31]

Temporal Consistency and Event Order

Compared to the “best effort” data transmission requirements of commercial networks, the industrial networks require accurate temporal consistency. Timestamped data and synchronized clocks are utilized to ensure, that the moment of every event and data received can be defined. [31]

Reliability

Ensuring proper operation of a system requires reliability which provides tolerance against device failures and data availability problems. The level of reliability required needs to be evaluated thoroughly in relation with the designated process and applications. Severe system malfunctions could occur if critical information related to decision making is either missing or incorrect. Hence the reliability needs to be acknowledged both on device hardware and software levels by adding resiliency and redundancy when required.[34]

Compatibility, scalability and standardization

MG EMS’s may have many external connections and thus it needs to support a wide range of communication interfaces and protocols. It’s a challenging task for the application and hardware designers to predict the level of future protocol compatibility with the existing alternatives. [31]

Scalability is a common requirement for industrial control systems. Operational microgrids can be expanded with various new or existing sub systems, which need to be integrated seamlessly with the MG EMS.

Favoring open standards simplifies the interoperability of different system supplier applications and equipment's and increases the reliability and stability of a certain protocol. The transparency of open standards also enables the thorough comparison of standardized protocols.[31]

Security

Industrial networks have to confront similar information security threats as commercial networks, even though the attack motivations differ and the consequences of a successful industrial cyber incident can be devastating in many ways [40, p. 41]. Compared to commercial networks, the additional design and performance requirements of industrial networks may increase the difficulty of proper cyber security implementation. As summarized by Gallaway *et al. in* [31] the goal of network security "is to provide confidentiality, integrity of information, availability, authentication, authorization, auditability, non-repudiability and protection from third parties."

Many industrial automation systems were created before the wide spreading of internet connectivity, web-based applications and real-time business systems. These systems incorporated legacy devices and – protocols which have been built primarily for reliability, performance and longevity, and afterwards reworked to operate in routable networks. At that time the "air-gapped" information security was less of a concern compared to physical security e.g., malicious actions of a dissatisfied employee. [40, p. 41 – 45]

As the external connections to industrial networks increased, so did the opportunities for cyber-attacks. The nature of cyber threats has progressed from relatively minor nuisance towards more sophisticated and well-prepared malicious intentions and sabotage. The magnitude of cyber-attacks has been realized on a new level in the 2010's, when e.g., Stuxnet was discovered and the hacking of Ukraine's power grid took place. [40, p. 44 – 55]

Similar threats can be identified with MG EMS's. These systems have many external connections which are implemented over the internet, while simultaneously it's carrying out control level functions. The transferred data availability, integrity and confidentiality needs to be as resilient as possible against potential cyber-attacks.[76]

2.5 Use case BMS

In this chapter the use case BMS and a general description of BMS composition is described. The use case BMS implementation is examined from a MG EMS integration perspective including a brief overview of the device's functionalities and a more detailed examination of the communication protocols natively supported.

2.5.1 Building Management System

Generally, a BMS is a cluster of many different systems in buildings such as Building Automation System (BAS), Energy Management, Fire Safety, Security & Access Control and Workplace Management Systems. The concrete monitoring and control of building processes is incorporated in BAS, which is also described as a "subset of the management and control system and can be part of a larger BMS (or Building Automation and Control Systems (BACS))*"* in [3]. The monitoring and control in this use case BMS is implemented with EcoStruxure Building Operation (EBO).

EBO does enable the centralized control and management of multiple integrated systems from a single platform. The backbone of EBO's edge control is the SmartStruxure server devices, which are responsible for real-time monitoring and control of processes and stand-alone systems. [64] In this case the SmartStruxure devices utilized are AS-P embedded automation servers which handle i.a. traditional I/O, trend logging, alarm supervision and field buses. The AS-P's support a wide range of different open standard protocols commonly used in BACS. The communication protocol variety includes various well-known serial fieldbus protocols such as Modbus RTU, LonWorks TP/FT and BACnet MS/TP, which simplify the access to an extensive range of field devices. In addition, the servers support communication with Modbus TCP, BACnet IP or open standard Web Services on the ethernet wire. [62]

The supported IP-based communication protocols of the AS-P servers are examined more closely in the next sub-chapters.

2.5.2 Modbus TCP

General

Modbus is a communication protocol which doesn't miss introductions and is commonly known as the "de facto" standard. It's has existed since 1979 and is still a widely used in various applications in different industry domains. Its popularity is due to simplicity, light weight structure and open standardization. Modbus is an application layer protocol, which is illustrated in figure 14. Originally Modbus was implemented on serial communication but has been developed to work on routable network as the Ethernet technology became more cost-effective and a common technology to transfer data.[47]

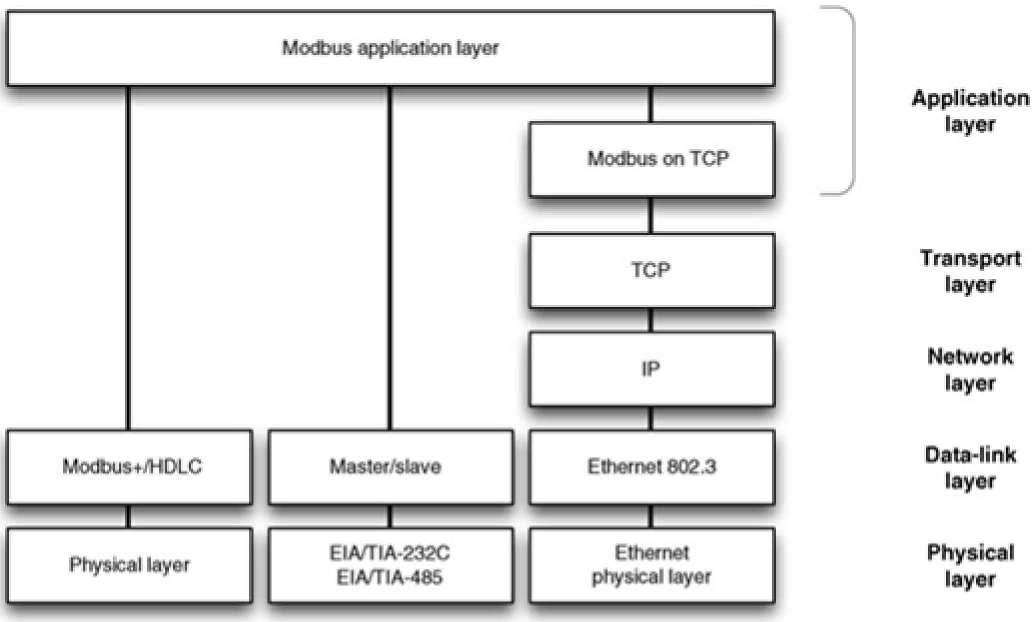


Figure 14. *Modbus OSI model representation [40, p. 124].*

Architecture

Modbus utilizes a simple request / response protocol, which is implemented with three different protocol data units (PDU): a Modbus Request, Modbus Response and Modbus exception response. A transaction between a client and a server begins with data request which is defined by the type of Function code used. The client processes the received message and sends a reply corresponding to the received function code if no errors are detected. If the server is unable to carry out the request or errors are detected the server will reply with an exception code. The sequence chart of the communication architecture is presented in figure 15. [47]

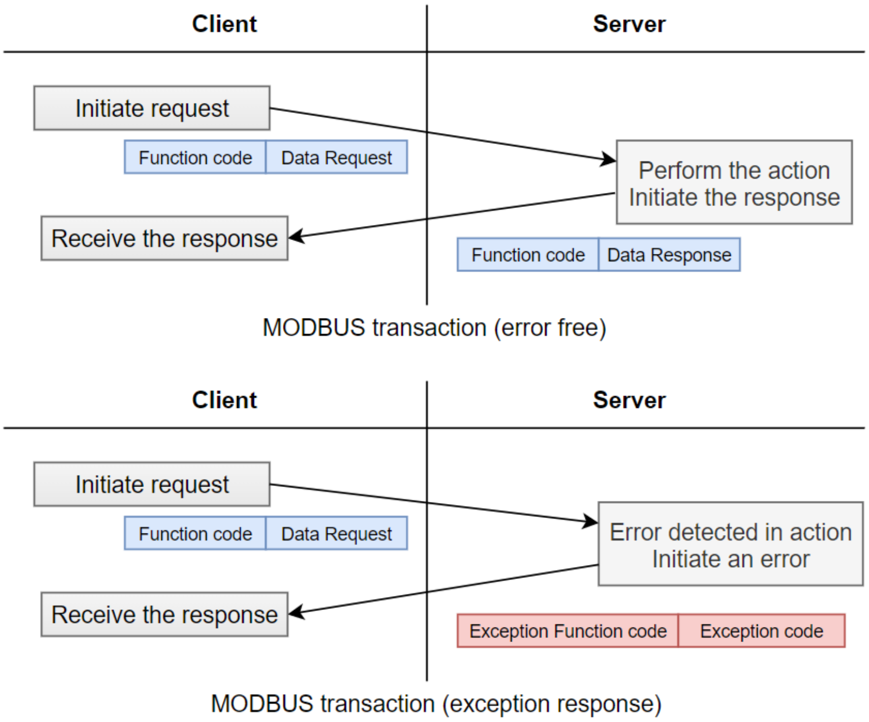


Figure 15. *Modbus request-response communication architecture principle. Adapted from [47].*

Modbus has a variety of different types of data access, which are implemented with different function codes. The function codes are fundamentally divided to three categories: Public function codes, User-defined function codes and Reserved function codes. The most common function codes are illustrated in table 5, which cover a variety of methods to read and write data in different formats. [47]

Table 5. *Common function codes of Modbus [37].*

Data Access	Type	Function Code	Meaning
1 bit	physical discrete input	0x02	read discrete inputs
1 bit	internal bits, physical coils	0x01	read coils
1 bit	internal bits, physical coils	0x05	write single coil
1 bit	internal bits, physical coils	0x0F	write multiple coils
16 bit	physical input registers	0x04	read input registers
16 bit	internal and physical output registers	0x03	read holding registers
16 bit	internal and physical output registers	0x06	write single register
16 bit	internal and physical output registers	0x10	write multiple registers
16 bit	internal and physical output registers	0x17	read/write registers
16 bit	internal and physical output registers	0x16	mask write register
16 bit	internal and physical output registers	0x18	read first in first out (FIFO) queue

Modbus has a byte-encoded frame format data model illustrated in table 6. The data table is divided to four main categories each representing a range of registers and data types.

Table 6. *Modbus data tables [40, p. 125].*

Data Table	Object Type	Access	Data Provided by	Register Range (0–9999)	Register Range (0–65535)
Discrete input	Single bit	Read-only	Physical I/O	00001–09999	000001–065535
Coil	Single bit	Read-write	Application	10001–19999	100001–165535
Input register	16-bit word	Read-only	Physical I/O	30001–39999	300001–365535
Holding register	16-bit word	Read-only	Read–write	40001–49999	400001–465535

Frame structure

In Modbus TCP the Modbus application data unit (ADU) varies slightly from the original serial version. The previous address byte is replaced with a Modbus application protocol header (MBAP) and the protocols cyclic redundancy check (CRC) is removed since the validity of the message content is already verified by the TCP protocol in the transport layer. The Modbus frame adaptation from RTU to TCP is illustrated in Figure 17. [47]

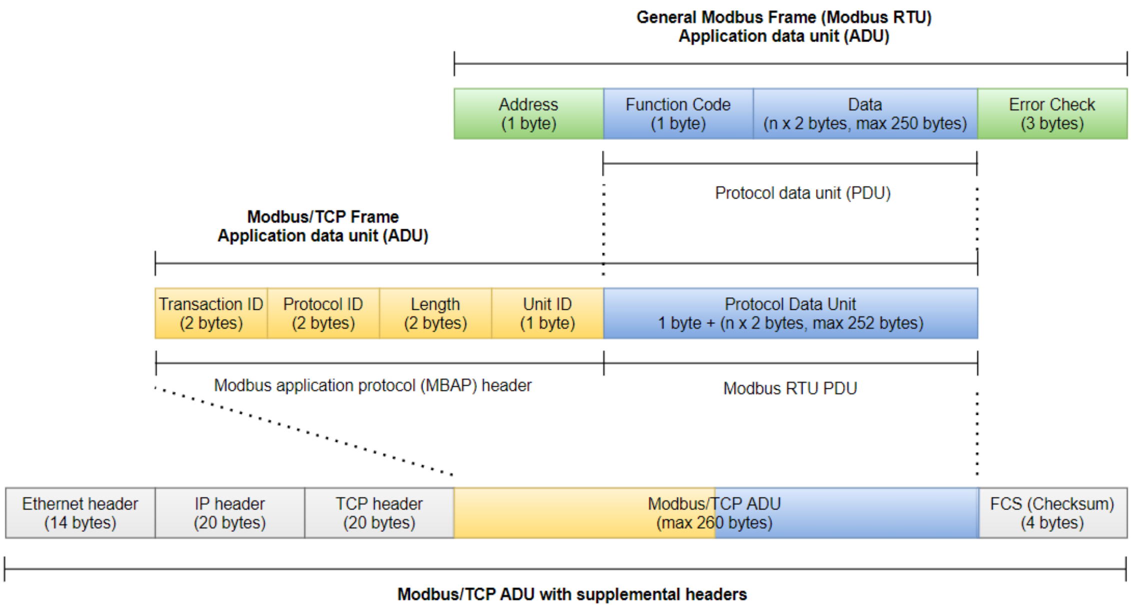


Figure 16. *Modbus message frame structures. Adapted from [40, p. 125].*

The MBAP header utilized in Modbus TCP is divided in the following segments and functionalities:

Transaction Indentifier is used to identify and associate the sent request by the client with the corresponding response from the server [47].

Protocol Indentifier identifies the used protocol which is always 0x0000 when Modbus TCP is used [47].

Lenght identifies the number of the remaining bytes to come, which is the sum of Unit ID and PDU bytes [47].

Unit ID is utilized for identifying a remote Modbus server which is connected on a serial line sub-network or on other buses. The ID corresponds then to the Modbus slave address of the remote device. If the server is directly connected to the TCP/IP network, it's addressed with its IP address and the Unit ID is this case useless. [47]

Function code identifies the function requested from the server [47].

Data compiled in the Modbus data frame is comprised by the nature of the designated register. The total bytes usable in a data frame is 250. Register values are either discrete inputs represented as a single bit or 16-bit words. If there's a need to use 32 - or 64 bit words will they represented by a combination of multiple 16-bit registers, e.g. a large cumulative energy meter reading. Hence the maximum quantity of contiguous discrete inputs is up to 2000 per request or respectively 125 contiguous 16-bit register values. [47]

Efficiency

With Modbus TCP the message overhead is constant while the payload size is proportional to the amount of inquired registers [47]. The lightweight design of the protocol is realized in chart 3, where the relations of the ADU, data frame size and amount of polled registers is illustrated. The proportion of the overhead decreases to a relative low level of ca. 21 % when the full payload capacity is utilized.

The amount of overhead is calculated as follows:

$$Overhead\ (\%) = \frac{Overhead\ (bytes)}{Overhead\ (bytes) + Data\ Frame\ (bytes)} \times 100\ \%$$

Chart 3. *Modbus overhead efficiency.*

The lightweight implementation of Modbus is indicated also from the request processing times of server devices. A typical range of device processing times of a received request is varying from 4 to 20 ms. The device processing time is naturally affected by the device performance and memory resources allocated for Modbus TCP [47].

Reliability and security

The reliability of the message transfer is executed by the TCP protocol, which aims to perform its functions as fast as possible. Practically TCP is a performance-wise a "best effort" protocol, and hence it cannot guarantee a fully deterministic operation. It's commonly recommended that the TCP retransmission algorithms should be carefully evaluated and defined that unnecessary packet retransmissions and resource / bandwidth utilization can be avoided. Keep-alive functions are also recommended between the client and server to maintain an active TCP connection if the value polling interval exceeds the limit for ending the connection. [47]

On serial Modbus the client needs to wait for a response or a response timeout before sending a new request. With Modbus TCP the server can be able to accept several requests if sufficient resources are available. Same principle applies also at the client side if there's a need to initialize several transactions simultaneously. The response timeouts for Modbus requests need to be defined by the characteristics of the ICS network and the messaging performance requirements.[47]

Security can be applied to Modbus by limiting the accessibility of undesirable hosts in the access control module or with Transport Layer Security protocol (TLS) for additional security. The access control module assures that only authorized Client IP addresses can establish a connection, while TLS enables a secure and encrypted communication between the two endpoints. With TLS a handshaking is executed using x.509 certificates before a secure session is established. During the messaging an additional step of authorization is applied where the roles-to-rights algorithms evaluates if the requested PDU can be processed based on the role of the client. [46]

Scalability

Modbus's lightweight structure enables a quick and cost-effective implementation to devices with varying performance. Any modifications or additions to the register data model can be done with relative ease. As the transmitted register information contains only the register number with a corresponding value, the client cannot tell if e.g. the value bound to the server register would have been changed. Hence the documentation of the registers needs to be updated and the register mapping validated in both client and server ends. The lightweight register structure has also the tradeoff for value consistency. The resiliency for data / device unavailability needs to be implemented separately in the server end. The register data model does enable a flexible and diverse implementation of status and alarm values, but it doesn't have any built in by default. [75, p. 384]

2.5.3 BACnet/IP

The standardized data communication protocol BACnet (Building Automation and Control Network) has been serving hundreds of thousands of installations worldwide since 1995. [1] It was developed by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) which later acquired the status of an International Organization for Standardization standard ISO 16484-5 in 2003.[2, p. 194]

BACnet/IP protocol is represented in the OSI model at the network and application levels with two designated layers as illustrated in figure 19. The BACnet Network Layer was developed in order to enable and facilitate BACnet communication between different networks regardless of the data link technologies in use. BACnet/IP utilizes User Datagram Protocol (UDP) on top of Internet Protocol (IP), which is a fast and lightweight way to serve the transporting and broadcasting needs of the BACnet Network Layer. [2, p. 240] The utilization of UDP protocol enables the decrease in message overhead since UDP lacks additional synchronization parameters, prioritization information and sequence numbers. Additionally, UDP doesn't require an acknowledgment of delivery which speeds up the messaging.[41, p.130 – 131]. The BACnet Application Layer integrates the presentation, session, and the transport functions with a collection of BACnet objects and services [2, p. 240].

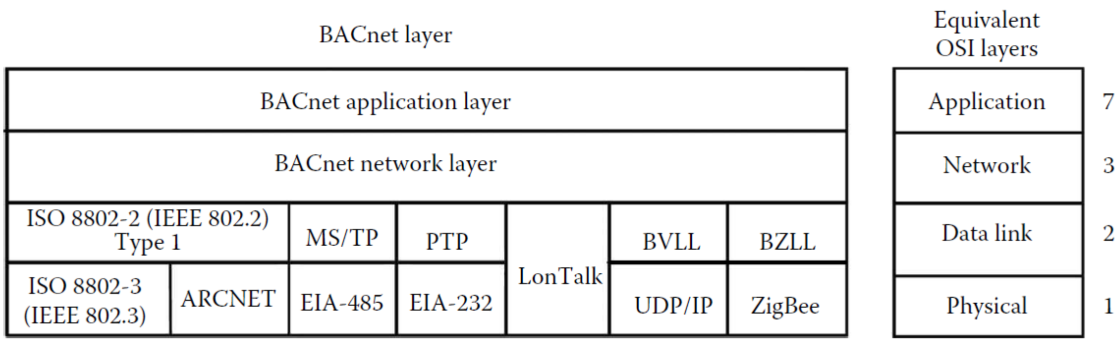


Figure 17. *BACnet protocol architecture [75, p. 1450].*

Architecture

BACnet utilizes a client-server model in its request-response communication architecture between BACnet devices. The BACnet service information is conveyed with four service primitives: request, indication, response and confirm, which are applied with the following BACnet protocol data unit types in table 7: [52, p. 65]

Table 7. *BACnet data unit types [52, p. 65].*

PDU type	Abbreviation	Use
BACnet-Confirmed-Request-PDU	CONF_SERV	Conveys parameters of a confirmed service request.
BACnet-Unconfirmed-Request-PDU	UNCONF_SERV	Conveys parameters of an unconfirmed service request.
BACnet-SimpleACK-PDU	SIMPLE_ACK	Provides acknowledgment that a confirmed service request has been executed without any response data.
BACnet-ComplexACK-PDU	COMPLEX_ACK	Provides acknowledgment that a confirmed service request has been executed and supplies response data.
BACnet-SegmentACK-PDU	SEGMENT_ACK	Provides acknowledgment of a segment of a segmented message.
BACnet-Error-PDU	ERROR	Conveys the reason why a previous confirmed service request failed either in its entirety or only partially. Contains a BACnet-Error with an error-class and error-code.
BACnet-Reject-PDU	REJECT	Rejects a received confirmed request PDU based on syntactical flaws or other protocol errors that prevent the PDU from being interpreted or the requested service from being provided. Contains a BACnetRejectReason.
BACnet-Abort-PDU	ABORT	Used to terminate a transaction between two peers. Contains a BACnetAbortReason.

Below is an illustration of a normal confirmed service transaction. There a BACnet user sends a service request with a confirmed request demand. A remote BACnet user receives the PDU and the indication of the requested service. The acknowledgement is then generated and sent back to the BACnet user. The acknowledgement type depends on the service requested. If the acknowledgement is described as Complex, the response involves a set additional data, such as a value of a property. [52, p. 66]

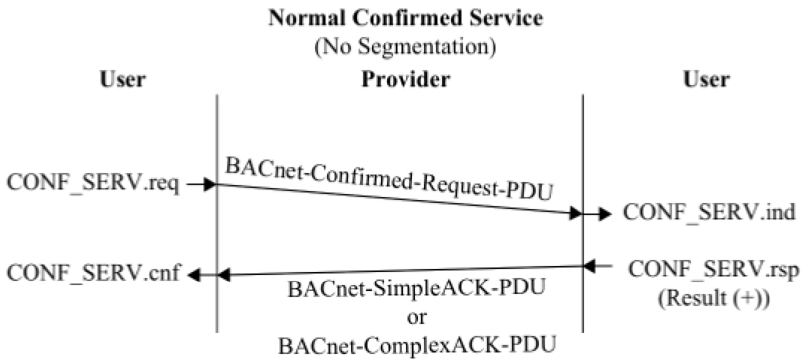


Figure 18. *Confirmed Service Transaction [52, p. 66].*

BACnet services cover a diverse set of ways to execute monitoring and control of BACnet devices. The characteristics of a device are mapped in an object-oriented manner with BACnet objects and their properties. Each physical BACnet device has to have one Device Object and a varying number of BACnet Objects. The Device Object has a large number of properties, which encapsulate the device's operational capabilities and i.a. technical data. [52, p. 66]

BACnet Objects are constructed in a more versatile way. A large number of predefined BACnet Objects with designated properties are specified in the standard to support the various control and monitoring needs of BACS. Each BACnet Object property has an identifier, data type and a conformance code. The identifier is a string of words, which describes the property. The conformance code implies whether the property is a read only - or readable and writable type. The data type supports all commonly used datatypes e.g. boolean, real and string formatted values. [52, p. 242]

For example, a device may have one physical analog input, which is represented by an ANALOG_INPUT object type. That object has a wide set of properties such as a present value, upper/lower limits, average value, status flags, reliability check and so on. BACnet also supports the concept of grouping a selection of objects in a Group Object. The selection can be configured to include one or more of the selected object properties [2, p. 254]. These property values can be read by a request and/or be specified to send a notification if e.g. a temperature limit has been triggered. The standard object types enable an uniform way to map useful and mandatory information available for different applications. The relations of a device, its objects and properties are illustrated in Figure 22. [52, p. 242]

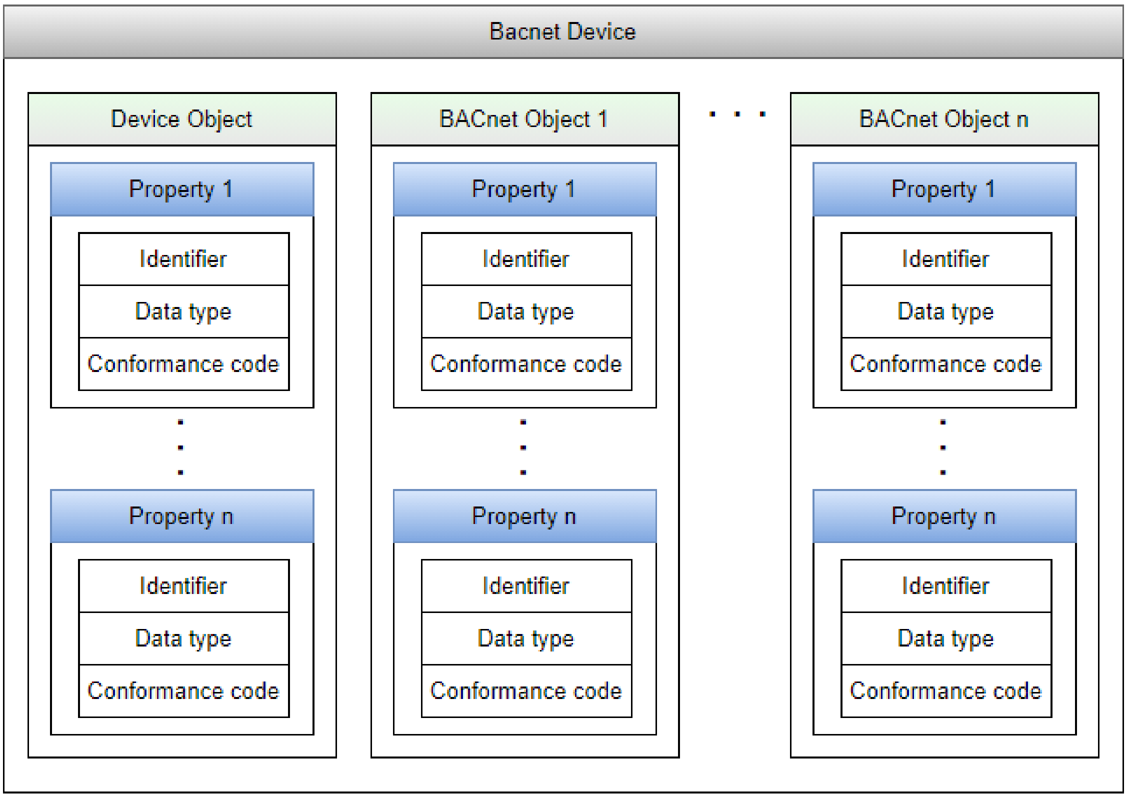


Figure 19. *BACnet Device data model. Adapted from [75, p. 1451].*

BACnet Services and procedures

As mentioned earlier BACnet has a wide selection of predefined services, which have been tailored to especially serve BACS needs. These services are grouped into five different categories. **Alarm and event services** contain typical service functions such as alarm notifications, acknowledgements and subscriptions. **File access services** enable the read and write functions for different files in BACnet devices. **Object access services** has a set of services to read, write, modify, create and delete BACnet object properties. **Remote device management services** comprise a range of miscellaneous management tasks performed in remote devices. **Virtual terminal services** were designed to enable the development of virtual terminal interface to BACnet devices. [52, p. 69 – 71]

BACnet has also implemented a command prioritization for writable object properties. It enables an arbitration between e.g. scheduled, manual and safety-related control. The prioritization schema is divided into 16 levels where 1 is the highest (Manual life safety) and 16 is the lowest. [75, p. 1455]

BACnet telegram encoding

The general BACnet/IP message frame is constructed as follows:

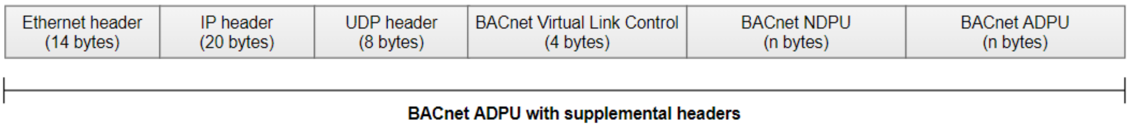


Figure 20. *BACnet message telegram. Adapted from [75, p. 1455]*

The messages are encoded according to the ASN.1 definition specified in the BACnet standard. Each PDU data element is represented with tag octets, length octets and content octets. With the ASN.1 syntax BACnet telegrams containing a sequence of tags and values are relatively lightweight, having a typical length between 64 and 256 octets. [75, p. 1455]

The contents of the NDPU and ADPU depend by the service executed, network and the designated datalink layer. For illustrative purposes the frame structure of a simple BACnet ReadProperty service in a LAN is briefly elaborated. [75, p. 1455]

BACnet Virtual Link Control Describes the protocol type (BACnet/IP), Function (Unicast/Broadcast) and length of the BLVC frame.

BACnet NDPU

The structure of a BACnet NDPU depends on the utilized data link layer protocols and type of the sent message. When a message is transferred between two devices in the same network the NPDU contains protocol version number and a control parameter. The control parameter defines the i.a. Additional messaging priorities and the type of PDU e.g. that a confirmation is requested.

BACnet ADPU

BACnet ADPU contains the following data when a ReadProperty service is requested.

ADPU type: Type of the request e.g. a confirmed request

PDU Flags, Information of the maximum ADPU segments and data size accepted e.g. the data limit of an ISA 8802-3 frame (1476 octets)

Invoke ID is used to identify and associate the designated service choice request with the corresponding response.

Object Identifier identifies the desired object type with 10 bits and an instance number with 22-bits, which enables the distinction between multiple same object types within a device.

Property Identifier describes the requested property (e.g. Present value)

Property Array Index is used to request element(s) from an array property

Property value (Response only) [75, p. 1455]

Efficiency

The monitoring needs of a BACnet client and servers can be implemented by polling or subscribing for events such as COV or alarms. BACnet provides many services for requesting grouped or single BACnet Object properties varying from one to all available property related data. The required monitoring can be orchestrated with a mix of COV subscriptions and fixed polling intervals, depending of the process controlled. This enables flexible ways to implement monitoring by the process needs and to optimize system resource and bandwidth usage.[2, p. 194 – 196]

The BACnet/IP ADPU can encapsulate up to 1476 bytes of payload, which decreases the share of message overhead significantly relative to the 48 bytes of supplemental headers. It's important to acknowledge that the increase in payload size will require more computational resources from the BACnet devices involved. Hence the maximum supported ADPU size needs to be evaluated case by case. [74]

Scalability

BACnet has been designed to be easily scalable. The scalability overarches from the scaling up the device numbers on the network level to scaling up the features of a particular BACnet device. As the BACnet devices can query all Objects and properties in each device, the system commissioning and administration of future improvements are relatively lightweight. [36]

Reliability and security

As mentioned before BACnet utilizes UDP for message transfer, which focuses to transfer the message as efficiently as possible. The reliability functionalities that UDP lacks has been implemented on the BACnet application layer by utilizing a variety of requests that require an acknowledgement from the receiver. The application layer also controls the retransmission of the messages if no responses are not received within a predefined time.[2, p. 236]

BACnet IP doesn’t have any in-built security functionalities such encryption or device authentications. This lack of feature does outsource the security implementation to the upper layers such as segmenting the BACnet IP traffic in a designated VLAN and restricting physical access to the network. [42, p. 726] BACnet does have tackled this hindrance by developing a newer Ethernet based protocol called BACnet/Secure Connect (SC), which does have support for TLS secured data transmission and authentication. [51]

2.6 Case Microgrid Architecture description

In this chapter the use case microgrid architecture and the management of the DER's is described. The presented use case microgrid architecture includes the following distributed energy resources and loads: diesel generators, solar power plant, electricity storage system, thermal storage system, ventilation, heating and cooling.

The structural diagram of the simplified use case energy - and information flows between modules and subsystems is presented in figure 24. The diagram also illustrates the Microgrid Energy Management system (MG EMS) with its general functions and connections. The MG EMS is set to monitor and operate the loads and resources via an already existing Building Management System (BMS).

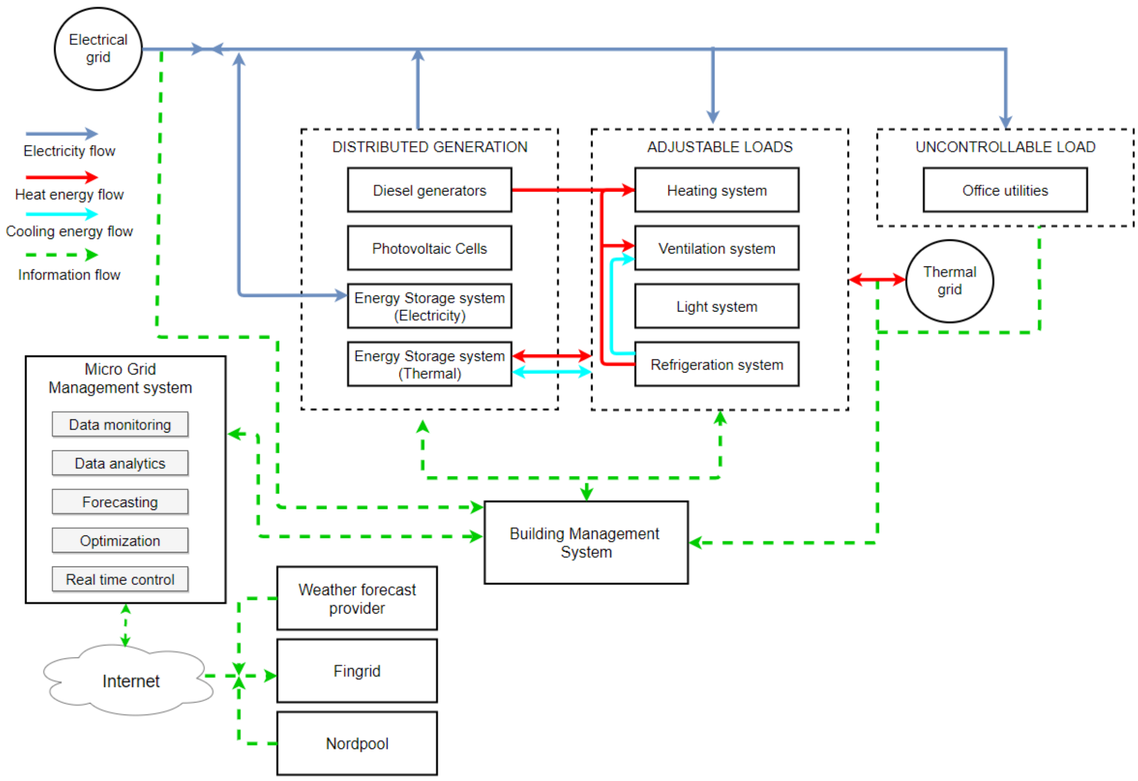


Figure 21. *Structural diagram of use case architecture*

2.6.1 Adjustable and transferable loads

Generally, HVAC systems account for a significant amount of electricity and heat consumption in buildings. The flexibility of a HVAC system can be generally summarized as increasing or decreasing heating and cooling loads, air handling unit fan speeds (fresh air flow control) or the amount of lighting. The flexibility potential for every space and area needs to be estimated case by case in order to maintain tolerable conditions for the users, appliances and the building structures. [61]

Every air handling unit (AHU), heating/cooling system and a part of the lighting are operated by the building management system, which enables a flexibility control implementation. The defined flexibility boundaries correspond to temperature set points and duct pressure set points. These set point limits are scaled in an uniform unit in percentages, which can be deviated ± 100 % by a sub-system specific MG EMS demand. The change in these set points is managed quickly, but the response time of the realized change in power consumption is relative to the controller parameters of the designated heating/cooling valves, pumps and duct fans. Typically, the heating network supply water set points are determined by e.g. the outdoor and indoor climate conditions, which have the characteristics to change with a relatively low rate of time [61].

Every duct fan motor is equipped with a variable frequency drive which enables a smooth and accurate regulation of air flow and power consumption. As the FCR-N activation requirement is 2 minutes can the duct pressure deviations is possible to be implemented in frequency reserves presuming that the minimum capacity of 100 kW is cumulated by the centralized deviation. An accurate realization of the power adjustment requires sufficient distribution of BMS connected energy meters among the site group switchgears.

Large CO2 refrigerator units are responsible for cooling spaces down to subzero temperatures. The refrigerator units consume a large share of the buildings total electricity need and produces simultaneously a considerable amount of heat as a cooling by-product. The excess heat is utilized in the heating needs of the building's heating system, which includes floor heating, ventilation supply air heating and outdoor ground heating. The site has also a two-way connection to local district heating network, which enables the purchase of extra heat or selling of excess heat back to the district heating provider.

2.6.2 Energy Storage Systems

The energy storage systems operate as the backbone of the microgrid and enhances the utilization of renewable energy applications [73]. The energy storage system functions as an energy buffer which is used to shift loads when needed and regulate with the needs of the FCR-markets. There's generally a large number of different energy storage technologies available, for example: thermal water tank, stationary battery, flywheel, air compression and pumped hydro storage [6]. Large proportion of the energy consumed in buildings is related to heating and cooling loads, which is acknowledged in this use case by utilizing a water tank as a thermal storage and a battery energy storage system (BESS).

The use case BESS is integrated with a local master central controller (MCC), power conversion system (PCS), utility connection hardware and Lithium-Ion battery modules. The MCC measures the system voltages and currents and calculates the required PCS current based on measurements, active operation and the battery status [45]. The BESS dimensioning has been implemented in accordance with the site reserve power needs and FCR-N/D capacity requirements.

The thermal energy storage functions as a storage for excess heating and cooling energy. The tank is supplied with heat exchangers, which are connected to the cooling and heating networks. This type of connection enables simultaneous heating and cooling of the tank, which can be utilized in different optimization scenarios.

2.6.3 Generation

The Finnish government subsidies for renewable energy sources generally increases the attraction of an investment to renewable energy production. Despite the unbalance of Finnish peak electricity need and peak photovoltaic (PV) power generation, the investment for a PV power system is profitable with the right amount of production capacity relative to the utility's power consumption. [66]

The site's installed photovoltaic (PV) power generation can always be fully self-consumed since the capacity is less than the minimum base load. The PV system is fully independent and supplies all production to the building's electricity grid, which can then be consumed or stored in the BESS. Locally installed energy meters log the total energy and enables the monitoring of the active power by the BMS. The production data can then be utilized with the weather and irradiation measurements in fine-tuning the future production forecasts.

Another form of generation is diesel engines with rotary generators. Their primary purpose is to function as an emergency power source. These machines have their standalone control systems which automatically start and synchronize the power production with the buildings needs if any disruptions occur with the regional grid. Similar emergency generators have been successfully utilized in different domestic FCR-D pilot projects. The FCR-D activation sets a relatively high ramp up requirement since 50% of the reserve power needs to be activated in 5 seconds and 100% power in 30 seconds if a full stepwise frequency deviation occurs.

3. PROPOSED ARCHITECTURE

In this chapter the control methods and monitoring needs of the MG EMS are summarized based on the use case evaluation and the theoretical background reviewed. Based on these findings and the use case considerations the proposed system architecture is described.

3.1 Monitoring and control

The general monitoring and control performed by MG EMS doesn't differ from a typical relatively loose BACS system control requirements compared to a fully industrial environment. The MG EMS functions at the management level sampling information needed for process modelling, forecasting and decision making. The controlling of DERs and HVAC processes are done with centralized or distributed set points, which will be automatically regulated via existing control-loops at the controller level. While executing these setpoint deviations each subsystem will acknowledge all process-related conditions to ensure a safe and reliable operation, thus restraining or declining the deviation control if needed.

All setpoint deviations related to HVAC processes have long response times. The building's structures and heating networks absorb and release heat energy slowly which smoothens the temperature rate of change. Electrical adjustable loads such as AHU's in this case mostly supply and remove air from spaces with large volumetric capacities in relation with the amount of human occupancy. In these large spaces the indoor air quality is also slowly affected by deviations in volumetric flow controlled by supply and exhaust fans.

An essential part of the HVAC and lighting is the aggregation of distributed measurements and controllable loads in the BMS. The aggregation with a system specific stepwise activation is required when several distributed loads are considered as one DER by the MG EMS. To avoid inconsistency of aggregated data in the BMS, needs the reliability be ensured at the subsystem level of the BMS.

The participation to FCR-N and FCR-D markets sets more accurate requirements to the power control implementation and measurement accuracy compared to MG EMS control of thermal and adjustable loads. Each reserve provider which aims to get an approval to the reserve markets needs to supply detailed system and test descriptions to Fingrid and perform successfully the FCR regulation performance tests. The tests include a linear or stepwise activation of reserve power in relation with the injected test frequency deviation. The tests evaluate the precision, stability and response time of the frequency regulation performed by the reserve unit. [16]

After a reserve provider is approved to the reserve markets, it needs to ensure the availability of history logs measuring the reserve operation with a maximum time interval requirement of one second. The history logs need to include the active power measurement of the reserve unit synchronized with a EET time or with the measured grid frequency. [16]

Currently the regulation of a full stepwise FCR-N activation event needs to be realized in no less than 30 seconds. Still a reserve unit should aim for a as fast regulation as possible. A full stepwise FCR-D activation needs to be realized to 50% power in no less than 5 seconds and further ramped up to 100% in 30 seconds. [16] This sequence is the most time critical operation in this MG EMS scope. The amount of latency tolerance is significantly outlined by the duration of the actual ramp up time regulated by the BESS after receiving an active power set point.

3.2 Proposed System Architecture

The MG EMS integration is performed in an existing BMS system, which is comprised of over twenty distributed automation servers operating DER subsystems in a backbone local area network. A simplified system architecture is illustrated in figure 25, where the MG EMS controller will be installed at the site interfacing the BMS AS's directly in the control layer. The device layer includes all metering, field devices and stand-alone subsystems, which are controlled and monitored by the BMS automation servers distributed around the large building. Additionally, the MG EMS computing considering the optimization algorithms and decision making are outsourced in servers operating in the cloud. The interaction between the MG EMS controller and cloud services will not be included in this thesis.

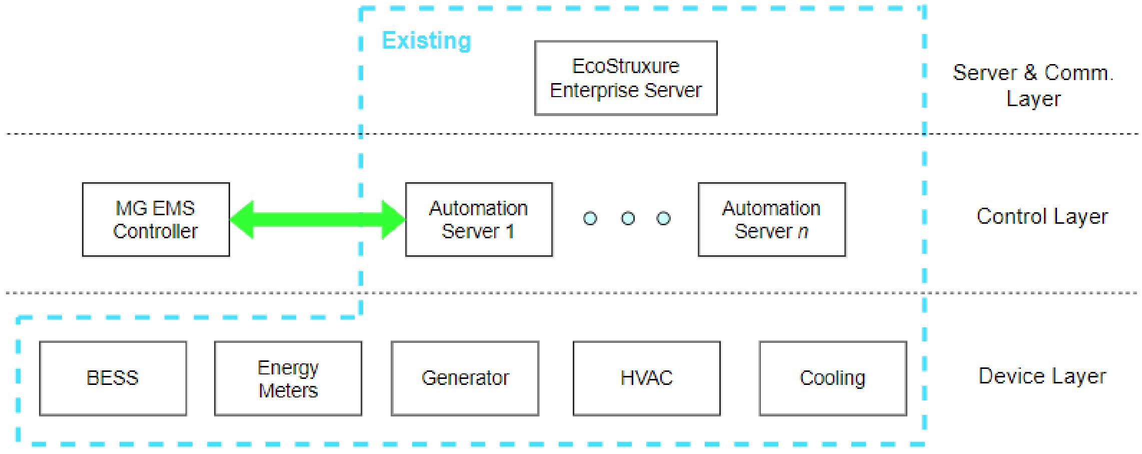


Figure 22. *System architecture.*

The MG EMS is monitoring and controlling the connected resources on a high level, interpreting them as separate entities. Hence the BMS is required to supply the necessary measurement data and forward the centralized control orders to the connected subsystems. To simplify the implementation and reduce the number of separate interfaces between the MG EMS controller and the BMS, all required data is decided to be compiled in one interface located in one of the automation servers.

This approach does make the one non-redundant automation server as a bottleneck for all control and monitoring, which increases the risk for unavailability and loss of real time monitoring data. The tradeoff for implementation simplicity also includes the addition of an extra step of processing and delay between the MG EMS controller and the field level.

These risks are assessed as tolerable since the MG EMS does focus on high level economic dispatch rather than managing the grid power quality with high real time requirements.

4. IMPLEMENTATION

In this chapter the implementation requirements and proposed communication protocols are introduced. First the justification of the requirements specification is discussed, following a requirements summary. Finally, the protocol options are discussed and outlined for the implementation.

4.1 Requirements capture

The requirements of the MG EMS and BMS integration and the communication protocol utilized are determined acknowledging the systems functional goals and communication design aspects described in previous chapters.

The communication related to the integration can be divided to two parts:

- Automation Server (AS) to Automation Server (AS) communications
- MG EMS to AS communication

The recommendations and architectural guidelines are well defined for AS to AS communications. Fundamentally the communication load and intensity should be optimized in order to minimize the negative impact on the device performance and network bandwidth availability. There's limitations and recommendations to the amount of AS to AS connections for sending and receiving data as well with data transfer intervals. The transfer intervals can be managed independently to a fixed timeframe or a change of value (COV) subscription with an adjustable COV threshold. The functionalities can be utilized in fine tuning the operation to the necessary level required.[65]

From an MG EMS perspective the different monitored values have varying time criticality. The only sequences which require relative fast update rates are the controls related to the FCR activity. Setpoint deviations affecting indoor temperatures doesn't necessarily need to be monitored every second, in many BMS applications the sufficient polling rate is in the magnitude between 10 to 60 seconds if COV subscriptions are not utilized [65]. The need for value update rates is hence varying from a second to several seconds depending on usage of the monitored value. It's noteworthy to acknowledge that the actual value update rate is dependent by the transfer rate between the BMS AS's and will be affected by the latency cumulated from data processing and network delays along the way from the field to the MG EMS interface.

The number of data points to be monitored and controlled is directly proportional to the MG architecture and the resources connected to it. The baseline power and energy inputs from utilities and DER’s form the minimum amount of data to be collected from the site. In addition to the consumption and production measurements the feedback from process and indoor condition impacts need to be monitored. Hence the total amount of measurements and control set points may have a large variation. In this case the preliminary amount of total data points is approximately 100. The additional scalability needs to be taken in account hence a reference amount of 250 points is used as the baseline. Also, the required data update rate requirement is set to fulfill the shortest time needed, which equals to a minimum of 1 second interval.

The device performance needs to be acknowledged as well in selecting the appropriate communication protocol. The AS which operates as the interface / cluster does manage simultaneously BMS processes. The implementation of the MG EMS integration should consume device resources as little as possible to maintain safe and reliable operation. The selected communication protocol needs to be an open and standardized protocol, which is commonly used in BACS and natively supported by the BMS AS’s.

The summarized requirements for the communication protocol selection and evaluation are the following:

1. The communication protocol needs to be open standard
2. The BMS AS’s should have native support for the communication protocol
3. The data transfer needs to use bandwidth efficiently
4. The communication protocol needs to ensure a reliable data transfer
5. The communication needs to be two-way
6. Only a low AS’s performance impact is tolerated
7. The modification of the data points should be flexible and scalable with relative ease

4.2 Proposed communication protocols

The AS's utilized in this case support a wide range of different open standard protocols commonly used in BACS. The communication protocol variety includes various well-known serial fieldbus protocols such as Modbus RTU, LonWorks TP/FT and BACnet MS/TP, which simplify the access to an extensive range of field devices. Communication on the ethernet wire can be initiated with Modbus TCP, BACnet IP or open standard Web Services such as SOAP and RESTful Application programming interfaces (API). [62]

The operation of standard Web services in AS's is limited for only consuming data, for example third party weather data. The functionality of serving data has been only implemented to Ecostruxure Web Services (EWS), which is designed to be consumed by other EcoStruxure clients. [65]

This selection of natively supported communication protocols narrows down the available options to Modbus TCP and BACnet IP as illustrated in table 8.

Table 8. *Natively supported AS-P communication protocols suitable for comparison. Adapted from [62].*

Communication Protocol	Communication interface	Suitability for comparison
Modbus RTU	Serial	No
BACnet MS/TP	Serial	No
LonWorks TP/FT	Serial	No
Web Services	Ethernet	No*
Modbus TCP	Ethernet	Yes
BACnet IP	Ethernet	Yes

*Limited for consuming data

Both Modbus and BACnet protocols have existed a long time but are still widely used in i.a. in BACS, where the requirements for real time and reliability are not as critical as with industrial applications. Also, the distributed design of BACS control has favored cost-effective devices which often correlates to cost-optimized performance. Devices with limited performance have the tendency to favor lightweight communication protocols.

In the following sub-chapters, the suitability of the proposed communication protocols will be examined generally highlighting properties and functionalities from the requirements perspective.

5. RESULTS AND DISCUSSIONS

In this chapter the study's empiric results are presented and discussed. In the first section the protocols are functionally compared from the requirements perspective based on the reviewed literature. To find answer to the non-functional requirements separate test implementations were created for both protocols. The measured performance indicators and the conducted performance tests are described in the third section. Lastly the performance test results are presented for both protocols and elaborated in a conclusive comparison.

5.1 Protocol comparison

In this chapter the suitability of the proposed communication protocols is evaluated from the requirements perspective. A general introduction of both protocols was done in the previous chapter 2.5. Both protocols have been commonly utilized in BACS and have overlapping similarities as many fundamental differences as well. To illustrate the main differences a general comparison is presented in table 9.

Table 9. *General comparison of the protocol features.*

Feature	Modbus TCP	BACnet/IP
Infrastructure	Ethernet, Wi-Fi	Ethernet, Wi-Fi, Zigbee
Network layer	IPv4, IPv6	IPv4, IPv6
Transport layer	TCP	UDP
Transport port	502, 802	47808
Model	Synchoronous	Synchoronous, Asyncronous
Pattern	Request-Response	Request-Response
Mechanism	One-to-one	One-to-one, One-to-many
Methodology	Byte oriented	Object oriented
Paradigm	Polling based	Polling based, Event based
Standard	Modbus.org	ISO, ANSI, ASHRAE
Encoding	Binary	ASN.1
Security	TLS	-

For illustrative purposes the results of the protocol comparison are compiled in table 10, where the requirements compliance is presented with three alternative options: Supported; The protocol features support well the requirement, Unsupported; The protocol features don't support the requirement and Supported partially; The protocol features support the requirement partially or reaching a full support would require extra resources or reaching full support does include uncertainty. The justification of these choices is then described for both protocols.

Table 10. *Protocol comparison results.*

Requirements	Modbus TCP	BACnet/IP
1. Open protocol standardization	●	●
2. Native protocol support with case hardware	●	●
3. Efficient bandwidth usage	●	●
4. Protocol support for reliable data transmission	●	●
5. Two-way communication	●	●
6. Low hardware resource usage	◑	◑
7. Simple implementation, configuration, and upscaling	◑	◑

● - Supported, ○ - Unsupported, ◑ - Supported partially or partially with uncertainty and/or demanding extra resources

Modbus TCP

Requirements 1 and 2

Modbus TCP is and has been a communication protocol of open standardization for a long time and is commonly utilized with various BACS devices. Since 2007 Modbus TCP has been defined in standard IEC 61158 and is also referred as CPF 15/1 in standard IEC 61784-2 [48]. As mentioned earlier Modbus TCP is one of the most common native supported protocol in BACS as it's with Schneider Electric's hardware.

Requirements 3 and 5

As Modbus is originally a byte encoded serial bus protocol for monitoring and control, the message frame structure is relative lightweight and has the qualification for efficient bandwidth usage. With Modbus TCP the original PDU has stayed unaltered and can supply 250 bytes of payload with one message. When all available PDU data bytes are utilized the Modbus TCP message overhead decreases to ca. 20 %. A feature that supports the efficiency and lightweight aspect of Modbus is the compressed data content in the payload. With a query of continuous set of registers the response doesn't have to contain any additional information to the actual measurement value, which increases the efficiency of moving measurement data.

The PDU size is relative to the share of overhead as the bytes consumed by the transport layers are constant. Compared to the maximum size of a frame supported by ethernet, Modbus could utilize a better overhead with a larger PDU. Large messages with smaller overhead ratio do involve trade-offs with optimized performance capacity and error probability compared to smaller messages. The data transmission is polling based, which’s interval is proportional to the bandwidth required.

Requirement 4

The reliability of the data transmission is supported by the TCP protocol in the transport layer. TCP does include a variety of in-built algorithms that can be utilized to improve reliability and resiliency for errors in the data transmission. As with the request-response architecture the Modbus TCP application layer is also requiring responses for each request. With the set of TCP and Modbus data transfer parameters an efficient and reliable two-way data transmission can be ensured.

Requirement 6

Fundamentally Modbus has been designed to operate in devices with low performance and memory resources and that applies also to Modbus TCP when controller devices are in question [48]. An exact evaluation of the performance requirements requires testing with the hardware in question. Hence the performance aspect will be investigated with separate performance tests.

From an MG EMS perspective the continuous monitoring need can be clustered to 2 read holding registers - queries, which will sum to a total of 250 16-bit registers. The 16-bit registers are sufficient to represent normal process values such as temperatures, power measurements, setpoints and indications. Cumulative energy values on the other hand need to have a larger value range, hence consuming 32 to 64 bits per value of a single response.

Requirement 7

The possible upscaling needs of the Modbus data model can be done with relative ease. Each register data type has a span of possible register numbers from 0 to 9999, which is highly sufficient for most applications [47]. As the data model does only bind register numbers to values, the register documentation needs to be revised and validated in both client and server ends each time any modifications are made to ensure value consistency. This is a considerable trade-off of efficient messaging.

BACnet IP

Requirements 1 and 2

BACnet is an open standard protocol which has been widely used since it's deployment in the 1990's. With hundreds of thousands of implementations BACnet is a widely supported protocol in BACS controllers. Since 2003 BACnet has been included in the ISO 16484-5 standard. [1]

Requirement 3 and 5

A BACnet message telegram contains 48 bytes of additional overhead generated by the transport-oriented layers. The NDPU and ADPU contents vary depending of the message type, but typically the NDPU is 2 bytes and the ADPU's size varies up from a Simple-ACK of 3 bytes to the maximum of 1476 bytes supported by an ISA 8802-3 frame. The object-oriented data model and large variety of services enables the queries of varying amount of object property related data with event or polling based communication. The BACnet message overhead ratio and bandwidth capacity requirement is hence directly proportional to the type of service initiated and the BACnet objects at stake.

Requirement 4

UDP does transfer the packets connectionless, efficiently, and fast between two endpoints but doesn't provide reliability. Due to this transport service nature of UDP, the verification of reliable data transmission is managed in the BACnet IP network layer. This designated layer handles the flow control, delivery of packets and resequencing. [12]

Requirement 6

Evaluating the hardware resource usage of BACnet IP has many variables that needs to be acknowledged. Currently on the market there's various controller hardware which utilize BACnet IP and generally it's supported by lightweight system resources. The BACnet IP resource usage in this use case is evaluated in more detail with the designated performance tests.

Requirement 7

BACnet's been built to be scalable. It does enable flexible upscaling on a system level as on a controller - and device levels as well. When a BACnet IP interface is concerned the addition and modification of BACnet Objects and properties is relatively lightweight. As the objects can incorporate informative data such as text descriptions the administration of measured values and their sources becomes more consistent. The consistency is also supported by services which enable the query of all BACnet device incorporated objects. These features don’t still exclude the need for a planned and documented revisions of BACnet objects and their usage.

5.2 Integration implementation

In order to evaluate the suitability of these protocols for this system integration, are practical tests required. Hence both alternatives require an actual implementation. As the two compared protocols are natively supported by the AS the integration can be implemented without any additional protocol gateways between the two endpoints.

In this implementation the MG EMS controller was simulated by a Modbus TCP client and a BACnet IP client running on a test PC. The AS-P served as a BACnet IP server (a BACnet device) and a Modbus TCP server in the two scenarios. All data points in both interfaces are bound to generic EBO variables which are further bound to the DER values clustered from other AS’s in the planned system integration. With this approach the data clustering and forwarding is independent from the communication protocol and interface used in the system integration. In figure 26 the system components and relations are illustrated on a high level. A more detailed description of the implementations are described in the following sub-chapters.

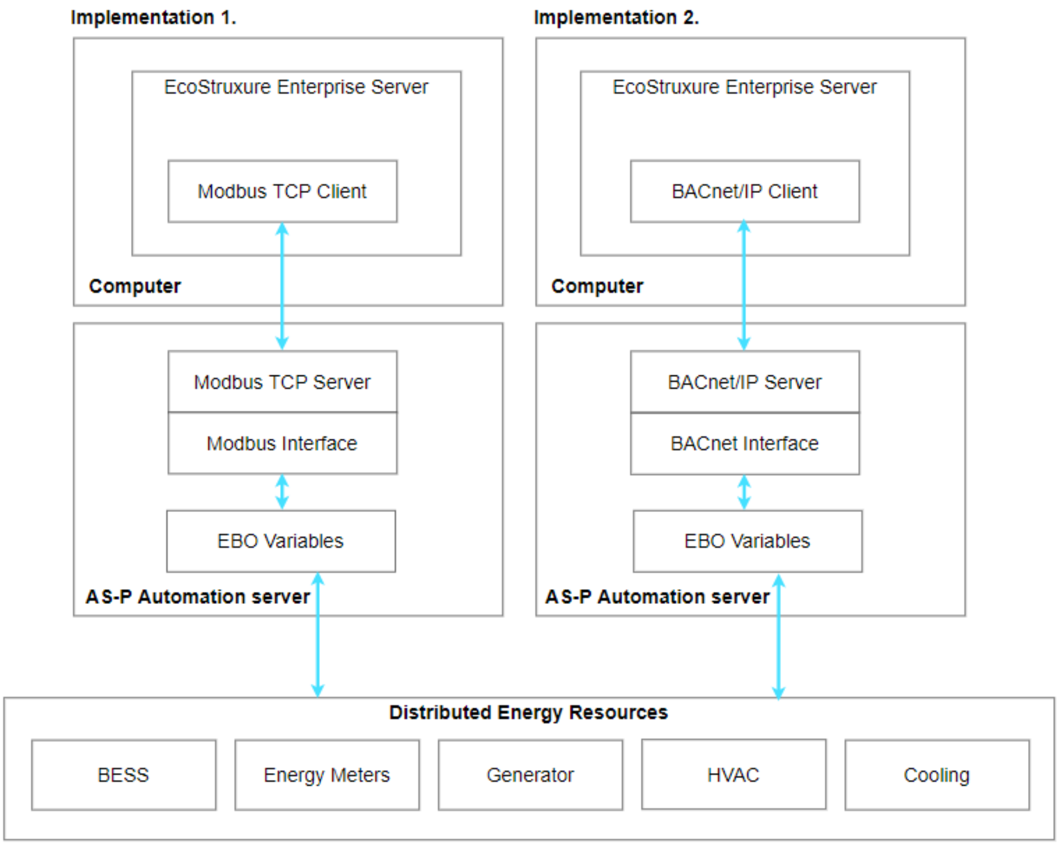


Figure 23. *Integration implementation.*

5.2.1 MG EMS Modbus TCP client and BMS Modbus TCP server

In this approach the test-PC was functioning as a Modbus TCP client, which utilized request – response architecture for querying monitoring data with a fixed interval and writing set points asynchronously to the BMS AS-P Modbus TCP server. The test-PC was running an EBO Enterprise Server in which the Modbus TCP client was created. This approach was chosen for the implementation simplicity's sake as the performance evaluation focuses on the AS-P's performance not the clients. Since the AS-P has a native support for the protocol is also the interface implementation relatively lightweight.

The Modbus TCP server associated to the hosting AS can be created from a predefined template, which then listen to the port 502 allocated for Modbus TCP. While creating the server it's important to outline the client IP-addresses which will be served, and which Modbus functions are accessible by the clients. By default, a Modbus TCP server will execute all read and write requests received, which is far from ideal when security is concerned. Also, the Modbus payload is non-encrypted by default so the need for TLS authentication should be evaluated case by case.

An important consideration in this implementation is the creation of the Modbus registers, communication parameters and relations to EBO variables. Modbus has a limited amount of ways how data can be read and written as described in chapter 2.5.2. Practically Modbus supports the reading and writing of single or multiple registers per query with a predefined time interval. As the interface data points are variables representing values the data is mapped to the Holding register range which are accessed with Read/Write Holding registers functions. The value register mapping is recommended to be set with a continuous numbering since the query for multiple registers is structured as "read x-amount of registers starting from register y". Hence the register numbering should be created and documented with a clear and straightforward manner such as grouping each set of DER register continuous.

5.2.2 MG EMS BACnet/IP client and BMS BACnet/IP server

In this test implementation the BACnet IP client was created in the EBO Enterprise server running on a test-PC. The BMS AS-P served as a BACnet Device which listens to port 47808 and incorporates a set of generic BACnet Analog Objects serving the purpose of MG EMS inputs and outputs. Each BACnet Analog Object has descriptive Object properties and a mandatory unique 22-bit Object Identifier number, which is generated automatically when a new BACnet Analog Object is created in the BACnet IP interface. EBO doesn’t support the BACnet Group Objects which would enable an organized grouping and polling of sets of selected Object properties. This lack of feature narrowed down the value monitoring options to predefined value specific polling or COV subscriptions. In this implementation the set point writing is done asynchronously by the MG EMS control needs with a request response architecture using a BACnet-Confirmed-Request-PDU.

Value specific confirmed-COV subscriptions were chosen as a communication architecture for monitoring since the messaging consumes less bandwidth from the frame size’s perspective and the amount of continuous traffic required. The COV notifications can be set to follow a certain COV threshold and a minimum refresh rate when the value is sent even if the value has stayed between the threshold limits. In EBO the COV subscription is by default active when available BACnet Object values are updated from a BACnet device. After the subscription for COV notifications has been made by the client and accepted by the device the service will be active until a stop condition is met. During an active subscription the COV notification sequence consists of a Confirmed-request notification sent by the server and a Simple-ACK acknowledgement from the client.

5.3 Performance test description

Performance tests are required for a concrete evaluation of the protocol suitability for the implementation. The goal was to test and measure the performance of the AS-P which functions as the BMS integration gateway and cluster. The test focused on measuring the processing times and CPU usage in relation with different amounts of baseline variables moved between the two endpoints. Also, the bandwidth need of each test scenario was measured to evaluate the impacts of network performance. The test PC and AS-P was connected with a 100 Base-T connection using a CAT6 ethernet cable without any external devices connected in the LAN.

The processing times between requests and responses as well as the bandwidth usage was recorded with Wireshark network protocol analyzer version 3.4.2. The captured traffic data was further processed in Microsoft Excel to generate the test results.

In order to get as comparable results as possible, the same test principles were applied with both implementation scenarios. In reality the COV subscriptions will decrease the need of constant flow of messaging especially when variables with large inertia are measured. Simulating the change rate of values accurately is complicated and would be an educated guess at best with the resources available. For this reason, the COV update time was set equal to the poll-interval of the Modbus read requests. This acknowledgement does have a significant impact on the BACnet IP test results as they represent the most performance stressing scenario possible.

The tests for both implementations were executed in four steps. In each step a fixed amount of baseline variables was either polled or COV-notified once a second for 50 cycles. A test step cycle represents the process when the client has received an update of each baseline value. With Modbus TCP the AS-P processing times were computed by the time difference of the logged request and response messages. The AS-P processing times of BACnet IP COV updates was determined by the update rate of single values and, also by calculating the total time spent updating all values per cycle. The variation of processing times per step were calculated in Microsoft Excel and the results are illustrated in minimum, maximum and average processing time values.

The baseline variable amounts were divided to 2, 50, 100 and 250 between the four steps. The one second interval was chosen since it’s the highest data update requirement of the integration. The chosen variable amounts correspond to the estimated maximum variable requirement with the MG EMS DER’s involved. A stepwise increase of variables was chosen in order to correlate the increase of moved data with the corresponding performance utilization. AS-P does have support for monitoring of various performance indicators such as system memory and CPU usage. The performance related value logging is constrained to a 5000 ms update cycle, which does limit the evaluation accuracy of the AS-P system utilization [63]. These performance indicator values were cumulated, and an average value was computed during each test step to represent the reference utilization rate.

Additional to the messaging between the two endpoints a simple program was created to simulate the performance load of value updates from the clustered EBO variables to the endpoint values. This program updates the values of all generic EBO values used in each test step each second. The programs 1 second execution cycle time was defined accordingly with the required update rate of the integration data transfer. The EBO variables are logically bound to the endpoint values, hence the endpoint values are updated after each program cycle. A simple illustration of the sequence steps and relations of each 1 second test cycle is presented in figures 27 and 28. The basic functional principle was similar in both test scenarios. It's noteworthy to acknowledge that these illustrations do exclude sequences that are initiated before a constant messaging is established between the two endpoints, such as establishing a TCP connection with Modbus TCP and the COV subscription process of BACnet Objects with BACnet IP. These distinct sequences were excluded as the performance evaluation was seen more consistent in an already running process.

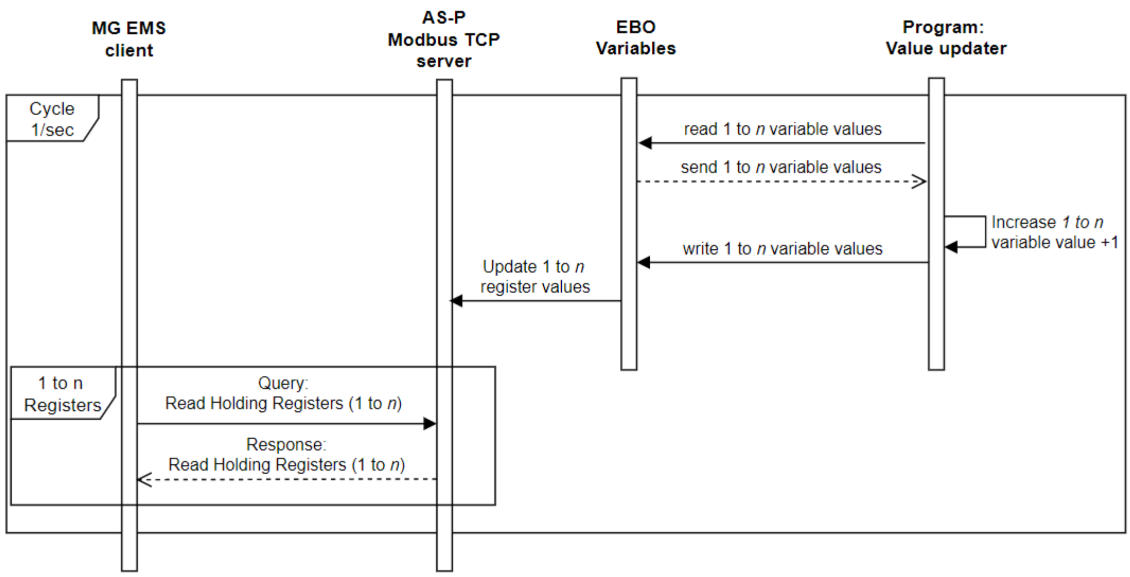


Figure 24. *Modbus TCP test application with main components.*

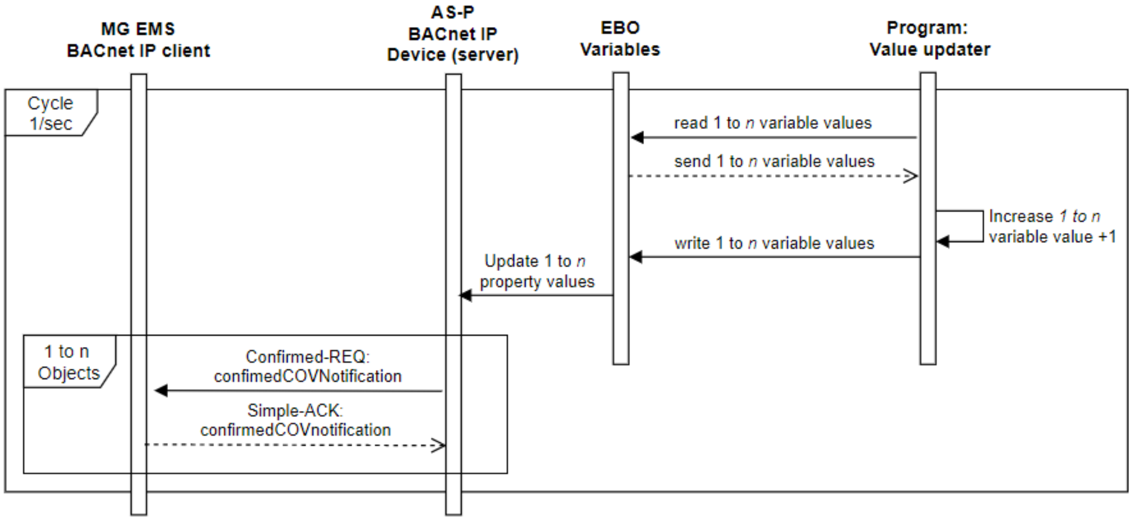


Figure 25. *BACnet IP test application with main components.*

5.4 Performance test results

The performance tests were conducted for both communication protocols in 4 test steps described in the previous chapter. In this chapter the results are illustrated for both protocols individually, following a summarized comparative performance evaluation.

Each set of results are presented in the same order: bandwidth utilization, AS-P processing times and AS-P CPU usage. With these performance indicators the communication protocol and – architecture suitability for the integration implementation was evaluated.

5.4.1 Modbus TCP

Bandwidth utilization

In these four test steps the request message frame length stayed as a constant 66 bytes including all supplemental headers additional to the Modbus TCP ADU. The request response message frame length increased linearly as the number of registers per query increased. The three first test steps with less than 125 values updated per second fit in a single response. The fourth test step with 250 values need to be updated with two request response cycles consisting of full 125 values per response.

The captured data traffic was analyzed, and the bandwidth need for each test step was the following:

Table 11. *Modbus TCP Bandwidth requirement.*

Analog values updated / sec	Request length (Bytes)	Response length (Bytes)	Total Bytes / sec	Bandwidth requirement (bps)
250	2 × 66 = 132	2 × 313 = 626	758	6064
100	66	263	329	5264
50	66	163	229	3664
2	66	67	133	2128

As can be seen from table 11 the bandwidth need for Modbus TCP messaging is low consuming only ca. 6 kbs of bandwidth with 250 analog values updated per second. This share of bandwidth is miniscule compared to the theoretically available maximum of 100 Mbs with 100BASE-T Ethernet. This result doesn't particularly surprise as the protocol is fundamentally designed to be as lightweight as possible for moving value-bound information.

AS-P processing times

During the four test steps the AS-P processing times were measured while it served the requests of the Modbus TCP client. During 50 update cycles per test step the average processing time of a single request varied between 2,1 and 2,9 ms. There was relatively more variation in the maximum processing times as it they increased in relation with the number of updated values. The calculated results are illustrated in chart 4 and a more detailed presentation in table 12.

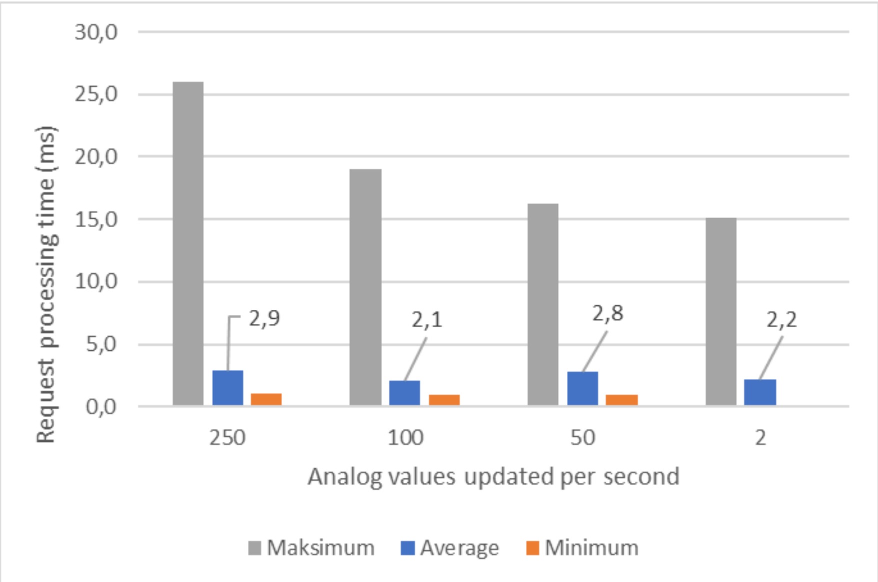


Chart 4. *AS-P request processing time.*

Table 12. AS-P request processing time.

Analog values	Average (ms)	Minimum (ms)	Maximum (ms)
250	2,9	1,1	26,0
100	2,1	1,0	19,1
50	2,8	0,9	16,3
2	2,2	0,1	15,1

Regarding the fourth test step with 250 registers, the full update requires two request response cycles per second. Hence the total duration for a full value update does include the time client spent processing between the first received response and the second sent request. The total update time of all analog values was significantly affected by the client's performance and the execution sequences of its internal processes. For illustrative purposes the duration of an update cycle from the client's perspective was also computed. These results are presented in chart 5, where the average duration of 250 value updates is 17 ms in total. In this test scenario the client did process approximately 14 ms on average after the received response before sending the next request.

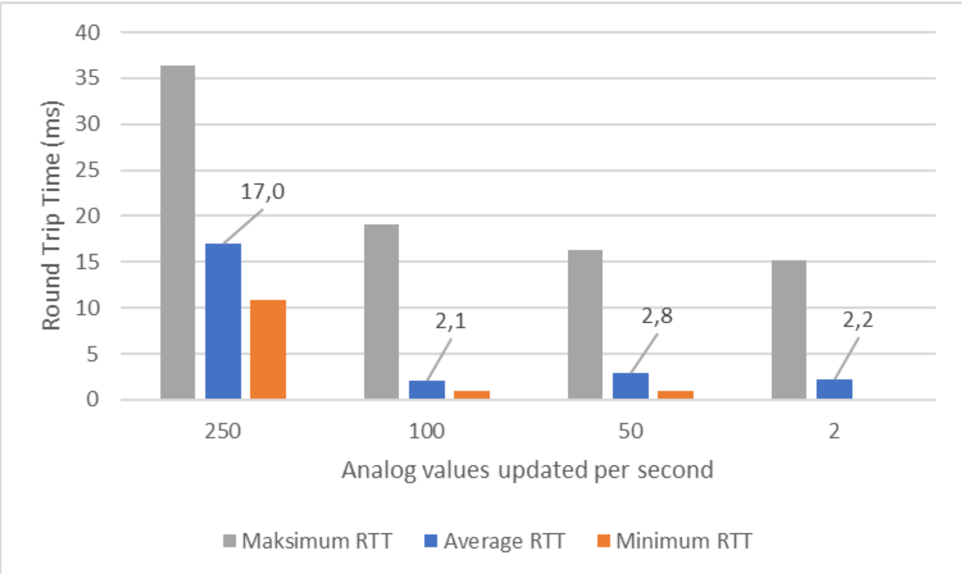


Chart 5. *Round trip time of a full update cycle of analog values.*

System CPU usage

The AS-P did succeed in serving the Modbus TCP requests quickly. In order to evaluate the performance load the CPU usage values were logged during each test step. The CPU base load in a factory setting restored AS-P was fluctuating between 0,4 to 0,7 percent's according to the performance logs. The CPU usage during the test steps is illustrated in chart 6. The log values indicate that the CPU usage was hardly affected of running the test application and serving Modbus TCP requests. The highest CPU average load was measured during the fourth test step. The highest average usage was ca. 1,4 percent, which corresponds to a ca. 0,7 percent increase compared to the highest measured base load value.

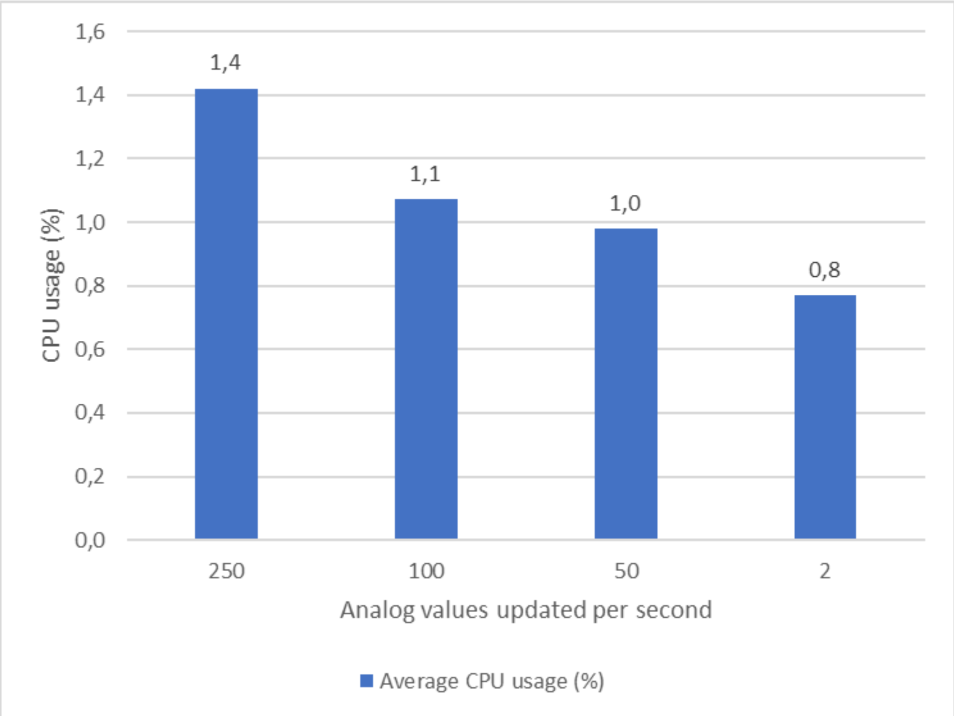


Chart 6. *AS-P CPU usage during test steps.*

5.4.2 BACnet/IP

Bandwidth utilization

With BACnet IP COV subscriptions all single COV-notifications and acknowledgement message frame lengths stays constant. The standard confirmedCOVNotification of a BACnet Analog Object reports two object properties and their values by default after a COV threshold has been exceeded. As the present value is altered by the test application the AS-P BACnet IP Device (= server) sends the updated values of the present-value and status-flags properties in a one 85-byte long message frame. The COV notifications are sent individually by the need for each BACnet Analog Object. The receiving BACnet Device (client) responds to each notification with a 51-byte long Simple-ACK acknowledgement. As the amount of messaging per test step is proportional to the analog values updated per second and the message lengths are constant, the bandwidth need increases linearly with the number of values updated with this test rate.

The captured data traffic was analyzed, and the bandwidth need for each test step was the following:

Table 13. *BACnet IP Bandwidth requirement.*

Analog values updated / sec	COV-notification length (Bytes)	Simple-ACK length (Bytes)	Total Bytes / sec	Bandwidth requirement (bps)
250	250 × 85 = 21250	250 × 51 = 12750	34000	272000
100	100 × 85 = 8500	100 × 51 = 5100	13600	108800
50	50 × 85 = 4250	50 × 51 = 2550	6800	54400
2	2 × 85 = 170	2 × 51 = 102	272	2176

As can be seen from table 13 the bandwidth need for BACnet IP COV messaging is relatively low consuming ca. 272 kbs of bandwidth with 250 analog values updated per second. The share of bandwidth in this optimal test scenario without any retransmissions is ca. 0,27 % of the theoretically available 100 Mbs with 100BASE-T Ethernet.

AS-P processing times

During the four test steps the AS-P processing times were measured while it was supplying COV notifications for the subscriber BACnet IP client. After each test program cycle the BACnet Analog Object present values updates were triggered. The average update rate of a single sent COV notifications varied between ca. 0,3 to 0,8 ms during all test steps. The update rate less than 1 ms of sent COV notifications was considered as fast in this implementation. The measured update cycle average duration values are illustrated in chart 7. The minimum and maximum values are presented in table 14, because of the large magnitude of deviation between the minimum and maximum values.

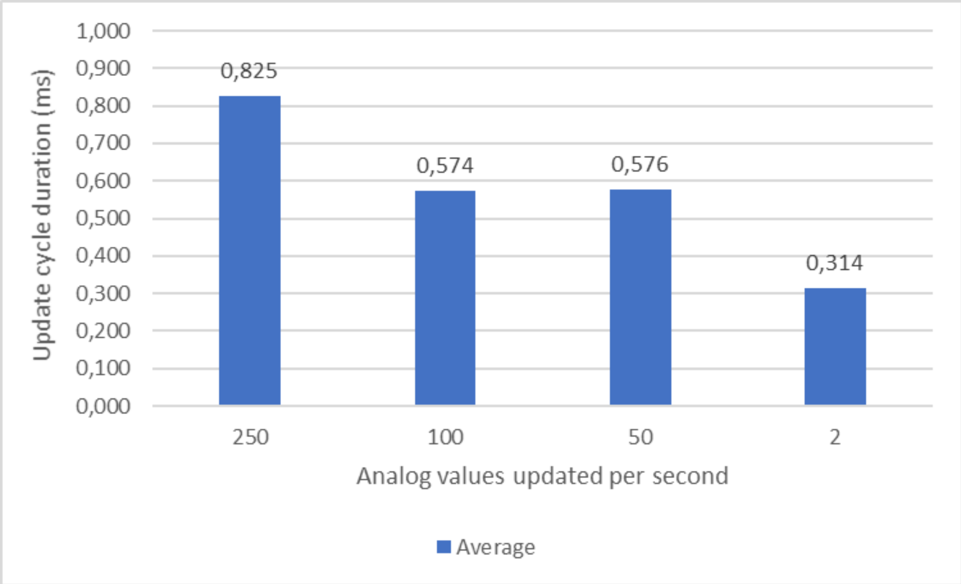


Chart 7. *Average update cycle duration between single COV notifications.*

Table 14. *Update cycle duration between single COV notifications.*

Analog values	Average (ms)	Minimum (ms)	Maximum (ms)
250	0,825	0,001	10,881
100	0,574	0,001	20,524
50	0,576	0,001	16,535
2	0,314	0,001	2,103

Additional to the COV update cycle duration of single values, also the total time spent for updating all values per cycle during each test step was measured. The relatively small variation of single COV update rates extends to the full value cycle examination. The duration of updating each value per test step cycle does have a relatively linear increase in relation with the total amount of analog values. The measurements of full update cycles are presented in chart 8 and table 15.

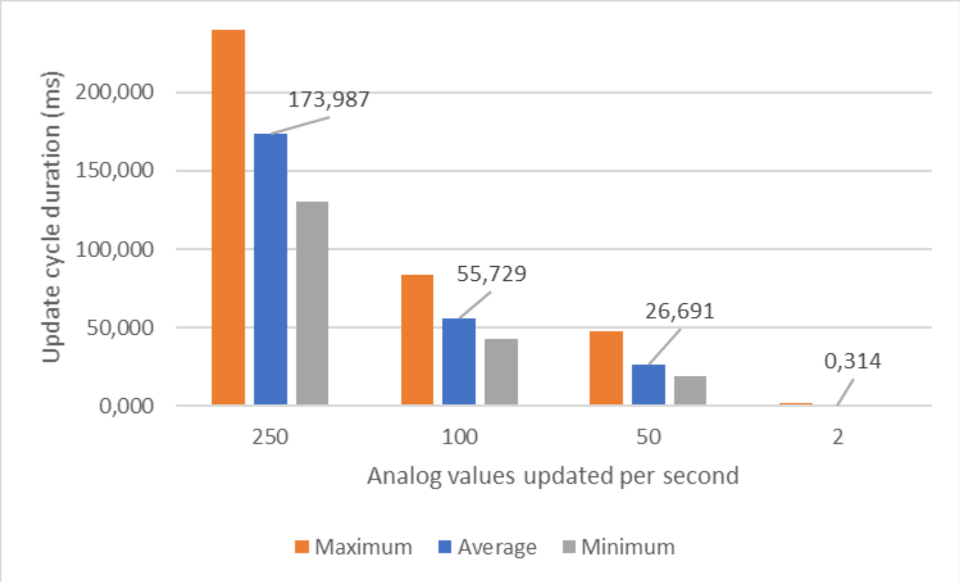


Chart 8. *Update duration of a full test cycle with COV notifications.*

Table 15. *Update duration of a full test cycle with COV notifications.*

Analog values	Average (ms)	Minimum (ms)	Maximum (ms)
250	173,987	130,516	239,919
100	55,729	42,837	83,965
50	26,691	19,230	47,543
2	0,314	0,001	2,103

System CPU usage

The AS-P succeeded in notifying the subscriber with a steady update rate in all test scenarios. The CPU usage logged in each test step did indicate that COV updating of a large number of values with a constant update rate of one second does consume a notable share of CPU resources. The CPU usage during the test steps is illustrated in chart 9. The log values indicate a relative linear increase of CPU usage in relation with the analog value amounts updated per second. The highest average CPU usage was logged in the fourth test step where the usage average peaked at 12,5 percent. This amount can be considered as high since the AS-P is usually handling a large quantity of simultaneous tasks, I/O-modules and field bus devices. The recommended maximum CPU base load for an AS-P is at 60% according to [65], of which the most stressful test step consumes a remarkable proportion.

As these test steps do represent the most stressful scenario with BACnet IP, the results do give an overview of the performance indicator ranges with COV notifications. Practically the bandwidth usage, AS-P processing time and CPU usage will vary between these limits depending of the actual rate of change in process values and the COV threshold.

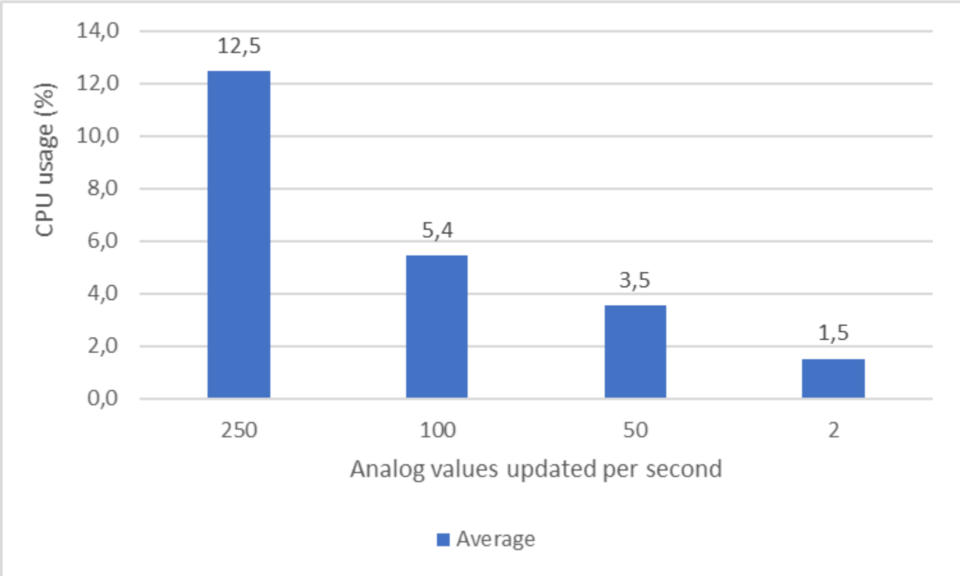


Chart 9. *AS-P CPU usage during test steps.*

5.4.3 Result comparison

Bandwidth usage

The measured bandwidth utilization for both protocols were considered low with modern network capabilities. The bandwidth requirement of BACnet IP with COV subscriptions did exceed the Modbus TCP's when three or more analog values were updated each second. So even if the COV thresholds are optimized with the process inertia there most likely will be more traffic and bandwidth utilization with BACnet IP as illustrated in table 16. Generally, with Modbus TCP the flow of messaging and bandwidth utilization is easier to predict as it's with BACnet IP and COV subscriptions.

Table 16. *Bandwidth usage comparison.*

Analog values	Bandwidth requirement: BACnet IP (bps)	Bandwidth requirement: Modbus TCP (bps)	Bandwidth requirement: difference (bps)
250	272000	6064	265936
100	108800	5264	103536
50	54400	3664	50736
2	2176	2128	48

Additionally, in chart 10 the Modbus TCP's share of BACnet IP's bandwidth requirement is illustrated. As the chart highlights, Modbus TCP did consume a minor share of 2,2 – 6,7 percent of BACnet IP's bandwidth requirement during test steps 2 to 4.

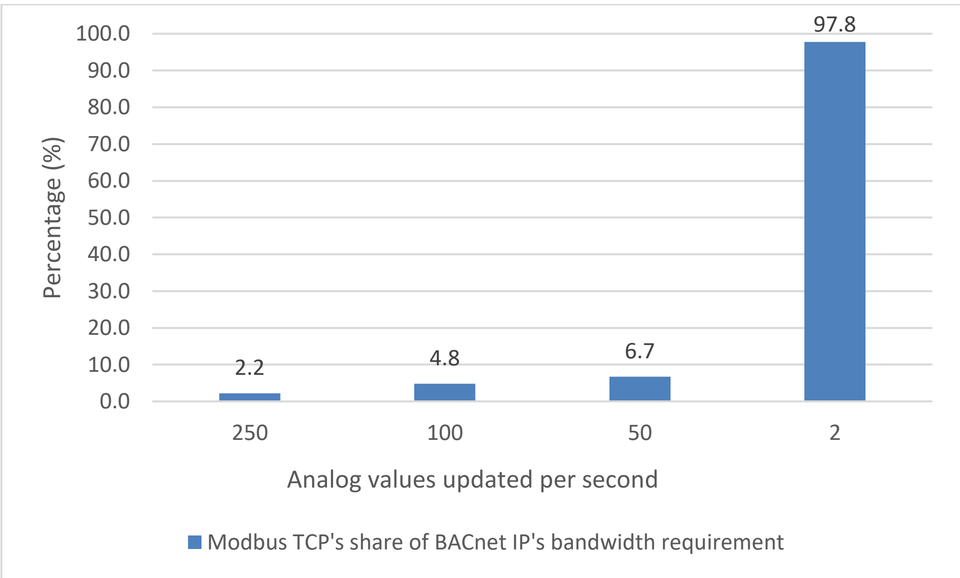


Chart 10. *Modbus TCP's share of BACnet IP's bandwidth requirements*

AS-P processing times

The AS-P did perform efficiently and fast with processing single COV notifications and request responses. The total test update cycle duration did have a large variation between the two protocols and the different communication architectures. From a test cycle point of view Modbus TCP did perform way faster compared to BACnet IP. A huge factor was the difference in the sent message amounts per test cycle, which does reflect to every performance indicator measured in these tests with BACnet IP.

In chart 11 the shares of BACnet IP's and Modbus TCP's CPU usages are illustrated. During test steps 2 to 4 Modbus TCP's share of BACnet IP's AS-P processing was significantly low, which points out the efficiency of Modbus TCP compared to BACnet IP in these tests. A numerical comparison of the AS-P processing times with actual differences are presented in table 17.

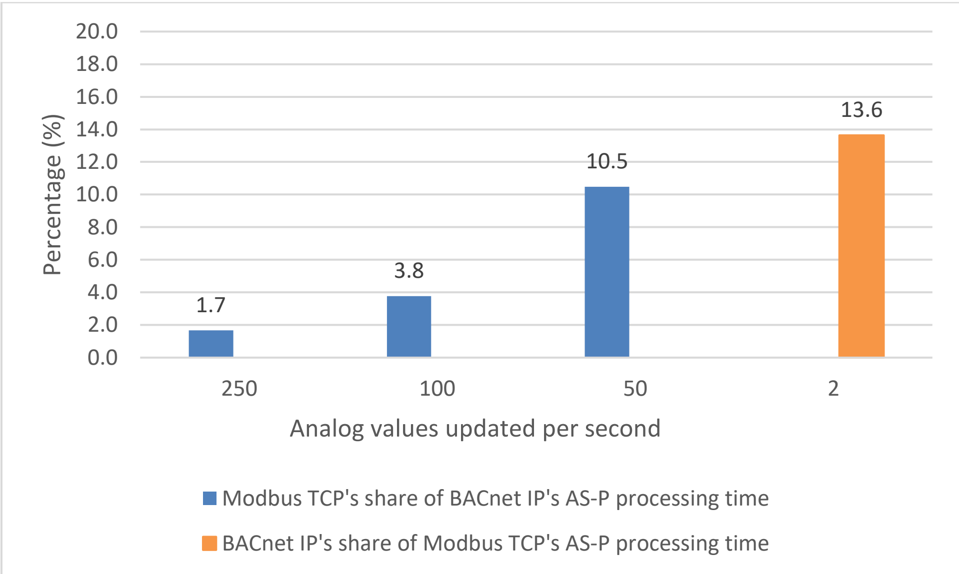


Chart 11. *AS-P processing time comparison by share.*

Table 17. *AS-P processing time comparison.*

Analog values	AS-P processing time per cycle: BACnet IP (ms)	AS-P processing time per cycle: Modbus TCP (ms)	AS-P processing time per cycle: difference (ms)
250	174,0	2,9	171,1
100	55,7	2,1	53,6
50	26,7	2,8	23,8
2	0,3	2,2	-1,9

CPU usage

The CPU usage results varied significantly between the two communication architecture implementations. The simplicity of Modbus TCP was realized as a very low CPU usage in each test step. With these implementation requirements and test scenarios Modbus TCP did consume less CPU resources than BACnet IP regardless of the number of values updated. It's noteworthy to acknowledge that BACnet IP does support a larger variety of services and will provide more flexibility in implementations which have more diverse requirements regarding resource related information, such as operational status information.

In chart 12 the Modbus TCP's share of BACnet IP's CPU usage is illustrated. Modbus TCP did consume a share of 11,2 percent of BACnet IP's CPU usage at the final test step, which is a significant difference. A numerical comparison with actual differences is presented in table 18.

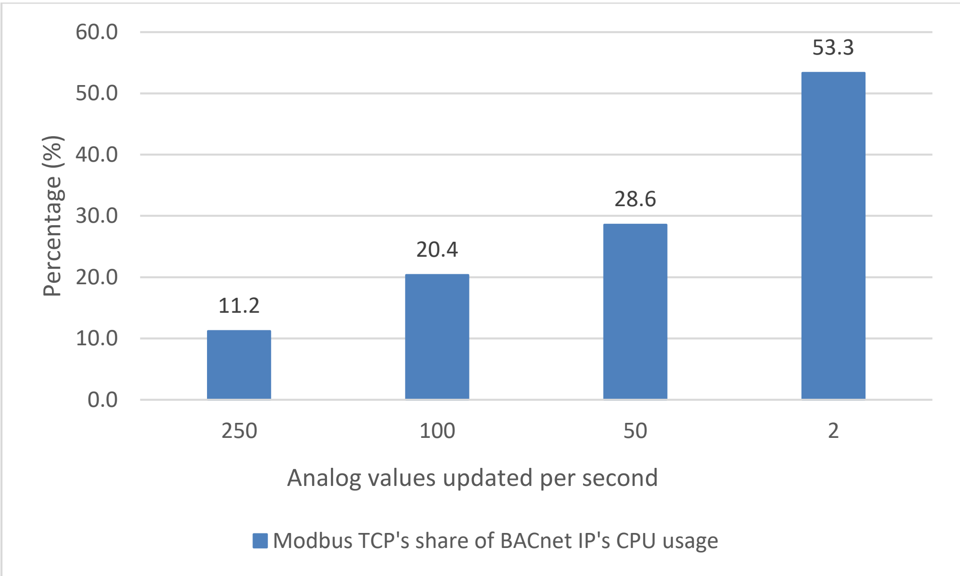


Chart 12. *Modbus TCP's share of BACnet IP's CPU usage.*

Table 18. *CPU usage comparison.*

Analog values	CPU usage: BACnet IP (%)	CPU usage: Modbus TCP (%)	CPU usage difference (%)
250	12,5	1,4	11,1
100	5,4	1,1	4,4
50	3,5	1,0	2,5
2	1,5	0,8	0,7

6. CONCLUSIONS

The energy systems domestically and globally are slightly transitioning towards the future smart grid. An essential motivation of the energy transition is the increased need for demand side management as the magnitude of weather dependent energy sources increase and the relative share of balancing power production decreases. One enabler for improving the dynamic balance between production and loads both locally and domestically are prosumer microgrids with intelligent energy management systems.

In this thesis a literature review was conducted to formulate a view of the elements that are bound to microgrid energy management and optimizing its operation. These findings were utilized in forming a starting point for a MG EMS – BMS integration and to outline the integration requirements in a use case evaluation. The suitability of the proposed integration architecture with the use case hardware was tested in practice with performance tests.

The thesis workflow was bound to the following research questions:

1. *Which controlling and monitoring mechanisms are required to manage and forecast power - and energy flows in a MG EMS?*

The first research question covers a wide range of topics from demand side management and optimization. The methods how a MG EMS manages power and energy flows are highly bound to the goals and priorities defined for the use case system. Generally, the MG EMS functions can be divided to two independent layers, which both can be implemented either separately or combined. The highest tertiary level incorporates the decision making of the scheduling related to energy consumption and production. The lower secondary layer focuses in managing the microgrid’s power quality in millisecond scale real-time decision making and ensures the safe and reliable operation of critical loads both in grid tied or islanded operation modes.

A common objective on the tertiary level is managing the economic load dispatch which was widely studied in different use case scenarios with various method algorithms in the recent literature. It concentrates to optimize the local energy flows from an economic standpoint acknowledging internal and external variables, constraints and forecasts. To operate it requires thorough system energy modelling and accurate DER specific power-and energy measurements in real-time. Also, the weather forecasts play a significant role of a building incorporated microgrid as it correlates to the amount of weather dependent energy production available and to the energy consumption of the building. With successful optimization and reliable forecasts, the MG EMS has succeeded in controlling the local energy loads and local production to fulfill the economic goals in the recent literature.

2. *What are the communication protocol requirements for a MG EMS – BMS interface?*

Generally, there was many different standard industrial communication protocols utilized in the literature use cases. The communication protocol choices between MG controllers and DER's were chosen case by case acknowledging the specific implementation requirements. In conclusion, the communication protocol requirements need to be defined in context with the case related ICS. From the thesis use case point of view the requirements evaluation was outlined between a tertiary level MG EMS and the BMS. The use case MG EMS's primary goal was economic dispatch which isn't as critical real-time and process-wise as power quality management performed by a secondary level MG EMS.

The general needs of communication between these two endpoints can be narrowed down to moving real-time measurement data, status indications and control set points. The number of required values to be controlled and monitored is proportional to the MG architecture and the different DER subsystems it incorporates. In this case the maximum need for data points in the interface was determined to be 250.

The communication protocol requirements of this use case don't practically differ from the standard requirements of a BMS implementation, where data need to be moved efficiently and reliably. The requirements of FCR operation were also acknowledged in determining the required update rate of the monitored values. As a result, the functional requirements of the communication protocol were relatively loose compared to real-time intensive industrial standards. This acknowledgement did increase the importance of non-functional requirements such as light performance requirements of the BMS hardware, OT-network bandwidth usage as well as the general implementation simplicity and scalability.

3. *Which communication protocol will meet best the use case requirements?*

The communication protocol comparison was outlined to BACnet IP and Modbus TCP, which were natively supported by the AS-P and commonly used in BMS systems. These communication protocols were compared functionally from the requirements perspective based on the available literature. Both protocols did fully support the functional requirements. Non-functional requirements regarding implementation simplicity and scalability were evaluated as partly supported since an absolute full support is difficult to validate. From my personal implementation experience during the set-up of the performance tests both protocols would support fully also these requirements. Noteworthy is to acknowledge that EBO did have predefined templates and tools which enabled a quick, simple and lightweight implementation of the communication protocol interfaces.

In order to validate the performance requirements of the integration implementation concrete performance tests were conducted for both communication protocols. The goal of the performance tests was to simulate a constant full update cycle of clustered DER data points to the MG EMS endpoint via the protocol interfaces in the BMS. As the amount of estimated data points exchanged between the two systems may vary, the tests were conducted in four steps. In each test step a different amount of data points was updated once a second in order to get a comprehensive view of the correlation between performance indicators and updated data points. The number of utilized data points per test step was divided to 2, 50, 100 and 250.

The performance indicators chosen for the tests were bandwidth usage, AS-P processing time of a full update cycle and average CPU usage during the test step. Modbus TCP did perform more efficiently regardless of the test step involved measured by all performance indicators. Both protocols did perform well during the three first test steps, but the CPU utilization of BACnet IP in the final test step was relatively high. Below is illustrated a summary of the relative shares between the two protocol's performance indicators in the final test step.

Fourth test step with 250 data points updated per second:

- Modbus TCP utilized a 2,2% (6 kbps) share of BACnet IP's bandwidth requirement (265 kbps)
- AS-P's processing time with Modbus TCP was 1,7% (2,9 ms) of BACnet IP's requirement (174 ms)
- AS-P's CPU usage with Modbus TCP was 11,2% (1,4%) of BACnet IP's CPU usage (12,5%)

In this test implementation Modbus did achieve better results with the selected performance indicators. The simple implementation requirements did favor the lightweight structure of Modbus TCP's register bound information model. It's noteworthy to acknowledge that BACnet IP does have a more versatile data-object model and a wider range of supported services than Modbus TCP. These functional characteristics do increase the favorability of BACnet IP especially if there's a need to move more data-point related information such as descriptions or event information. In conclusion, Modbus TCP is a convenient and lightweight option for the MG EMS and BMS integration in this use case evaluation.

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