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Degree Project

Utilization of Energy Storage to Improve Energy Efficiency and Power Quality

Case Study – Holtab AB Factory

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Summary

Industries worldwide are embracing eco-friendly energy solutions to counter challenges with conventional methods of energy production. However, this shift introduces instability and reduced AC grid quality. To address this, the thesis proposes integrating a battery energy storage system (BESS) with existing sources, aiming to enhance power quality and system efficiency.

The study focuses on distributed energy generation, combining grid power and solar microgeneration. Key power attributes like power factor, peak shaving, and harmonic distortion are analysed for efficiency improvements. Data is collected from ABB Ability and modelled using MATLAB/Simulink for Holtab AB factory in Sweden.

The BESS integration targets improved power factor, reduced harmonic distortion, and excess energy storage. Objectives include data collection, system analysis, modelling, BESS incorporation, and inverter integration. Research questions assess battery utilization for efficiency and power quality enhancement.

The significance lies in industrial application, benefiting utilities, industrial users, and the environment. Outcomes include reduced costs, increased clean energy, better power supply, emissions reduction, and higher PV plant utilization.

In conclusion, integrating Battery Energy Storage enhances efficiency and power quality. BESS positively impacts peak shaving, power factor, and harmonic distortion. Recommendations include ESS installation, capacitor integration, and active harmonics filter use for optimized power quality and efficiency. The study advances sustainable energy practices in industries.

// Sammanfattning

Branscher över hela världen anammar miljövänliga energilösningar för att möta utmaningar med konventionella sätt att producera energi. Men denna förändring introducerar instabilitet och minskad AC-nätkvalitet. För att ta itu med detta föreslår avhandlingen att integrera ett batterienergilagringssystem (BESS) med befintliga källor, i syfte att förbättra strömkvaliteten och systemets effektivitet.

Studien fokuserar på distribuerad energiproduktion, som kombinerar elnät och mikrogenerering av solenergi. Nyckeleffektattribut som effektfaktor, peak shaving och harmonisk distorsion analyseras för effektivitetsförbättringar. Data samlas in från ABB Ability och modelleras med Matlab/Simulink för Holtab ABs fabrik i Sverige.

BESS-integrationen siktar på förbättrad effektfaktor, minskad harmonisk distorsion och överskottsenergilagring. Målen inkluderar datainsamling, systemanalys, modellering, BESS-integration och inverterintegration. Forskningsfrågor behandlar batterianvändning för effektivitet och förbättring av strömkvaliteten.

Betydelsen ligger i industriell tillämpning, till nytta för företag, industriella användare och miljön. Resultaten inkluderar minskade kostnader, ökad ren energi, bättre strömförsörjning, minskade utsläpp och högre utnyttjande av solcellsanläggningar.

Sammanfattningsvis förbättras effektiviteten och strömkvaliteten genom att integrera batterienergilagring. BESS påverkar peak shaving, effektfaktor och harmonisk distorsion positivt. Rekommendationer inkluderar ESS-installation, kondensatorintegration och passiv filteranvändning för optimerad strömkvalitet och effektivitet. Studien främjar hållbara energimetoder i industrier.

Abstract

The world including the industries is going green to avert the challenges posed by the conventional means of energy generation. The increasing penetration of intermittent electrical energy sources means increasing the instability of the AC grid resulting in poor power quality and efficiency. Incorporating a storage system in parallel with the existing system may improve the overall performance and stability of the power system.

The proposed work aims to investigate the use of a battery system to improve the power quality in an industrial facility currently operating with distributed energy generation; a combination of grid power via an 800kVA transformer and solar micro-generation of 209kW. Power factor correction, Peak shaving, and harmonic distortion are the main power system characteristics considered for improved power quality. Mathematical analysis of the data collected from the company cloud solution called ABB ability, and a complementary simulation using a model-based design will be used to generate the results. The findings confirm that battery systems contribute to the active power quality improvement and energy efficiency of the case study factory.

Keywords: *Battery system, Distributed generation, Energy efficiency, Harmonic distortion, Power quality.*

Preface

Within these pages lies the research and dedicated effort presented in the master's thesis titled "Utilization of Energy Storage to Improve Energy Efficiency and Power Quality – A Case Study of Holtab AB." Written by two students, this thesis represents the fulfilment of the academic requirements for the Master's in Renewable Electric Power Systems Programme at Linnaeus University.

Our journey on this academic journey spanned eight transformative months, commencing in January 2023, and concluding in August 2023. This timeframe encompasses not only the intense periods of research and analysis but also the patient anticipation for the commissioning of the company's cloud solution, a crucial element for accessing essential project data.

Although our academic aspirations were aligned, we found ourselves hesitating to venture beyond our respective comfort zones. However, the pursuit of our master's thesis provided us with a unique opportunity to contribute positively to society by addressing a real-world problem faced by his employing company. Undertaking the collection and analysis of vast volumes of data proved to be a formidable challenge, given the magnitude of information involved. Nevertheless, we embraced this challenge wholeheartedly, emerging with enhanced analytical proficiency and a newfound ability to dissect intricate problems adeptly. The journey of crafting this dissertation has left an indelible mark, fostering not only professional growth but also personal development.

Our heartfelt appreciation extends to **David Holmberg**, the catalyst behind this project on behalf of Holtab, who provided us with guidance and direction. We are equally indebted to **Peter Ackebjer**, our supervisor from Holtab, for seamlessly assuming the mantle and offering invaluable insights. Their mentorship extended to forging connections with experts from diverse industries, enriching our learning experience.

We reserve a special place of gratitude for our esteemed University supervisor, **Pieternella Cijvat**, whose unwavering support was pivotal throughout the research and writing process. Her patience and encouragement, even in moments of ambiguity, propelled us forward. Pieternella provided meticulous guidance, fostering our knowledge, and refining our research skills through insightful feedback and thorough corrections. We are also grateful to our examiner, **Sven-Erik Sandström** for his valuable feedback that improved this work.

To our professional networks, whose input significantly influenced our work, particularly in the realm of simulations, we extend our appreciation. Equally deserving of recognition are our friends, families, parents, and peers, whose unwavering emotional support provided the bedrock upon which we built our academic endeavours. Their steadfast presence has been instrumental in propelling us to this juncture.

With these words, we share our gratitude, experiences, and newfound insights, hoping that you, dear reader, will find resonance in our scholarly journey.

Mulham Sabouni/Vitalis Okpalanwaka.
Växjö, August 2023.

List of Abbreviations

AC – Alternating Current

AGM – Absorbed Glass Mat

Ah – Ampere hour

AHF – Active Harmoni Filter

APFs – Active Power Filters

Avg – Average

BES – Battery Energy Storage

BESS – Battery Energy Storage System

BoP – Balance of Plant

CNC – Computer Numerical Control

DC – Direct Current

DER – Distributed Energy Resources

DoD – Depth of Discharge

EMS – Energy Management System

ESS – Energy Storage System

EV – Electric Vehicle

IEA - International energy agency

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

IEP – International Energy Prices

kVA – Kilo Volts Amperes

KVAr – Kilo Volts Ampere Reactive

KW – Kilowatts

kWh – Kilowatts Hour

LED – Light Emission Diode

LFP – Lithium ferro-phosphate

Max – Maximum

Min – Minimum

MOSFET – Metal Oxide Semiconductor Field Effect Transistor

MVA – Megavolt Amperes

MWh – Megawatts Hour

NEC – National Electric Code

O&M – Operation and Maintenance

P – Real Power

PCC – Point of common coupling

PV – Photovoltaic

Q – Reactive Power

RE – Renewable Energy

RES – Renewable Energy Sources

ROI – Return on Investment

S – Apparent Power

SMS - Site Management System

T&D - transmission, and distribution

THD - Total Harmonic Distortion

V – Volts

Wh – Watt hour

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CHAPTER 1

1. Introduction

1.1 Background of the study

Energy can take many different forms, such as electrical, mechanical, radioactive, etc., and it is one of the yardsticks used to assess economic growth. It can be produced and transformed between many forms. Electrical energy is one of the most beneficial and prevalent forms of energy. Regarded as the core of every economy and modern life, it is essential in all sectors of the economy and needed daily. Electrical energy to date is majorly generated by turbines with fossil fuel; these include coal, oil, natural gas etc. [1]. The burning of fossil fuels has been identified to cause substantial damage to our environment which threatens our existence. The endless list of the major consequences of the continuous use of fossil fuels includes global warming emissions, air pollution, water pollution, destruction of wildlife, land etc. Therefore, it is entirely unsustainable to continue electrical energy generation through burning of fossil fuels considering the world population which reached 8 billion in mid-November 2022 and is expected to grow up to 9.7 billion by 2050 and 10.7 billion by the end of the current century [2]. However, development path is the most important factor impacting emissions levels.

As a matter of urgency, the world is ramping up electrical energy generation through more sustainable ways like solar, wind, biomass, etc. to curtail the emissions from fossil fuels. The international energy agency (IEA) reported a global total penetration of renewable sources over the years 2018 and 2019 with wind and solar registering +11% and +22.5% robust growth respectively [3]. Since these forms of renewable energy generation present the advantages that they can be installed on small scale, it became possible for these to be grid connected or off grid. It can be installed by utility companies, governments, agencies, organizations, and individuals. Explicitly, the merits of renewable energy are less emission of greenhouse gases, less dependency on variability in international energy prices (IEP), less installation time, diversification of the electric mix, and ease of expansion [4].

Transformation towards a green energy supply has not been an easy one considering the political, economic, and societal challenges especially in developing countries that do not have adequate and stable electricity supply yet. In Germany, industrial customers with an electrical energy consumption of more than 100 MWh per year are paying up to 0.15 € per kWh. Additionally, major consumers must pay a demand charge for the peak power they use outside the contractual values. Their load profile is highly volatile due to starting of production lines, starting torque of auxiliary drives, machine failure or changing workload during shifts [5]. Consequently, electricity costs for industrial customers cannot only be reduced by saving energy but also by reducing peak power demand, e.g., with intelligent peak load management. To ensure technical feasibility, ecological sustainability and most importantly, economic efficiency, practical design methods for renewable peak-shaving and self-consumption applications need to be developed and evaluated.

Photovoltaic systems for industrial peak-shaving applications and direct self-consumption of solar energy which can reduce power demand to a certain degree in case of matching load and production profiles has been proposed by [6][7]. Grid-connected battery storage systems were presented for peak-shaving. In times of low energy demand, batteries can be charged. During peak load demand, the power supply from the grid can be reduced by discharging the batteries and as a result, the grid can be relieved and demand charges for the industrial customer can be lowered among other functions. The study further reveals that the profitability of photovoltaic systems can be raised with increased self-consumption. For optimization of self-consumption, [6] proposed hybrid photovoltaic-battery storage systems. The integration of one or more power generating systems with energy storage increases reliability and profitability of renewable technologies [8].

PV technology is one of the most suitable renewable energy sources to switch electricity generation from few large, centralized facilities to a wide set of small decentralized and distributed systems reducing the environmental impact and improve system reliability in the remote areas. With the expansion of solar manufacturing facilities and the widening of implementation of PV systems, the prices for the PV components, e.g., module and conversion devices, are rapidly decreasing, making the PV systems competitive compared to other energy sources. The grid parity which happens when the use of alternative energies like PV in this case, costs less than or equal to the price of using power from conventional sources such as coal, oil and natural gas has been reached in several countries, worldwide. Moreover, several studies present energy systems with integrated PV plants, Battery Energy Storage units and other RES or traditional energy sources. A review of PV system optimization techniques has been carried out [9]. The study proposes optimization models for the standalone multi-source energy production systems.

Among the various renewable energy sources, photovoltaic (PV) technology is receiving more attention due to the increase in efficiency and decrease in the cost of PV modules. Moreover, the availability of good solar irradiance levels in many countries and ease of operation and maintenance (O&M) of PV modules are making this technology more favorable [10]. However, the intermittent and random nature of the solar source logically suggests the adoption of an energy storage system to meet the load demand, compensating for the gap between the energy availability and the energy demand. Currently, several energy storage technologies exist, and several studies show applicability and economic feasibility for PV load management. [11] evaluates the integration of battery energy storage (BES) systems to the PV systems, while [6] investigates the effectiveness of BES systems for sustainable energy development. [12] compares the performance and costs of different technologies for batteries, adding that a leading technology is yet to emerge. To cope with the intermittency of the power output, battery storage is considered beneficial to be used with photovoltaic (PV) systems [10].

Consequently, since the output of most of these sustainable energy sources (solar and wind power etc.) are variable, they present some undesirable attributes to the electric power systems in general. With increase in the share of renewables in power systems, the ability of grid operators and end users to balance generation and demand are greatly affected. As a result, the significant increase of renewable energy penetration in the grid can negatively affect the overall power quality, the system stability and reliability [13].

Due to increased penetration of renewable energy sources, the power quality has been greatly affected by increasing voltage fluctuations among other things. That is a situation where some power characteristics spike and dip more than normal [13], [14]. In a quest to manage these problems inherent in increasing penetration of variable and uncertain power generations, storage systems can be employed. Studies have shown that battery systems can be employed to reduce the power fluctuations with additional services like voltage and frequency regulations, increase the system reliability and manage energy in times of some disturbances [14].

1.2 Statement of the Problem

The effects of the increased renewable power penetration are system dependent as every power system has different specifications and involves different types of distributed generation.

The periodic nature of renewable energy sources and the cost of meeting peak load demand from the grid are the main issue hindering their rapid implementation. To improve the system efficiency and power quality of systems incorporating some renewable energy (RE) source, conventional generators are generally used as backup systems and energy storage systems for smaller systems [15]. However, this study investigates the use of energy storage device for achieving same.

The significance of the study is to extend the utilization of BESS not only to regulate the generation aspects, but also to tackle the issues with industrial loads. Inductive loads, non-linear loads, and rotating machines contribute to lower the power quality of the local grid and that effect is also transferred to the main grid. Utilizing the BESS in the correct connection point can help improve the local grid power quality and reduce the losses in the local grid.

1.3 Aim of the Study

This study will be carried out at Holtab AB factory, a sustainability conscious company with headquarter in Tingsryd, Sweden. The existing facility is using an 800kVA transformer to power the main buildings as well as production areas. In their pursuit to start an energy sustainability journey, the company installed 209 kW of solar panels in 2017. The factory has operated on the dual power source (solar and grid) to date and want to improve by adding more renewable energy sources.

The aim of this study is to investigate the effects of installing a battery system with an interfacing inverter to the main power line to improve the overall power quality of the facility including power factor correction and improvement of harmonics. The battery system is expected to also store the excess generated energy from the solar installations during high radiation periods. Using the result from system characteristics analysis, insights will be given on how peak shaving will help achieve the intended efficiency.

1.4 Objective of the Study

The study will simulate operation scenarios. Then we will compare current system flexibility and responsiveness versus the utilization of batteries and inverters. Explicitly, the methodology is to:

i. Gather the necessary data from the company cloud resource.
ii. Analyse the data from (i) to ascertain the current system scenarios.
iii. Model the PV plant of Holtab AB Factory in MATLAB/Simulink software.

iv. Incorporate Lithium-ion battery in the system suitable for power storage and peak-shaving management.
v. Install an ingeniously designed inverter into the network for power factor improvements.
vi. Investigate the improvement that can be achieved for elimination of the total harmonic distortion.

1.5 Scope of the Study

This work is centered on studying the current state of the system and investigating how battery storage system can the used to manage the peak demand in terms of peak shaving and how it can improve the system efficiency. The system efficiency parameters for this study are limited to power factor improvement and total harmonic distortion reduction. It therefore excludes many system efficiency parameters like voltage stabilization, frequency management, etc. This study also excludes the economic and environmental benefits of such optimization due to lack of time, and to be kept for future research.

There were some limitations of this research and some of the constraint's factors includes:

i. Delay in assessing data from Holtab factory.
ii. The data quality from cloud measurements has some faults and, in some cases, strange values appear. We had to filter these outliers to keep the study realistic.
iii. Difficulty is getting a software that can efficiently do all the needed tasks. Some of the simulations will be based on a single value using mathematical formula, we created the complete time graphs.
iv. Patents regarding the circuit diagrams of the energy storage inverters. We will use the conventional circuits of the power factor correction and active harmonic filters for our simulations. The energy storage inverters utilize modern technologies based on DC/AC conversion and rely on time shifting from the grid to achieve the required active or reactive power compensation.
v. Funding since the top software require subscriptions.
vi. Time as the project has a definite time frame.

1.6 Research Questions

How can the utilization of battery storage technologies be optimized to improve energy efficiency and power quality in the Holtab AB factory? As a guide for the research methodology, such as the selection of appropriate data, collection methods, analytical tools, and evaluation criteria, the following sub-questions or hypotheses are formulated.

i. How will implementing peak shaving improve the overall power commercial efficiency as compared to the energy usage profile?
ii. How effective is the battery storage system in improving the power factor?
iii. How effective is the battery storage system in improving total harmonic distortion?

1.7 Significance of the Study

The major significance of this study is the fact that most studies involving the use of energy storage systems have been the on the generation side (power utility side) and some others on the load side, for small energy users. This study will add to the little available research for large energy users on the load side, thus the study is done for an industrial customer. Additionally, this research is very useful to the utility company, industrial energy users and the environment for it offers a lot of benefits such as:

i. It will reduce the amount spent on purchasing energy from the power holding company by implementing peak shaving.
ii. Excess energy generated from the PV plant will be stored for use during peak demand periods.
iii. The power reliability of the Holtab factory will be improved.
iv. Clean energy production rate at the Holtab factory will increase.
v. The environment will be spared of carbon emissions.
vi. Increase in the utilization factor of Holtab PV plant.
vii. Increase in the reliability and efficiency of the power supply at Holtab factory by reducing losses due to harmonics and low power factor.

CHAPTER 2

2. Literature Review

2.1 Extent of Past Works

Several studies have been investigated so far to exploit power factor quality and improvement of power efficiency through battery integration based on renewable energy sources. Though studies are concentrated on the power utility end, different indices have been investigated to evaluate the effect of energy storage installation in conjunction with distributed generation resources. In the operation, various methods are proposed to find the optimal location and size of the energy resources, and different objective functions are provided. Since batteries possesses the ability to supply reactive power, this makes battery to operate both in leading, unity or even lagging power factor, thus implies their ability to support the active power profile at the point of common coupling (PCC). This effort is achieved by managing the reactive power transfer between the system and inverter [16].

When it comes to harmonics, the studied facility has DC chargers, CNC machines, and other non-linear loads which generate harmonics that cause overheating in cables and losses in form of heat, also deteriorating the power quality of the grid. Harmonic isolation is achieved by installing a filter circuit in series with the main inverter circuit. The filter circuit will feed the harmonic current of a particular order generated by the non-linear loads, so that the harmonic current of this order is eliminated from the supply current [17].

Also, in power factor compensation, due to the inductive nature of factory machinery, the facility power factor is relatively low. This means a significant number of losses (typically around 15-20% of the total power is going in losses). The inverter will detect the live readings of the power factor and inject reactive power to the main busbar to compensate for a reduced power factor. This will help improve the efficiency of the facility and reduce losses [18].

In the distributed energy system, which can consist of numerous fluctuating renewable energy sources, the energy storage system (ESS) which can including the battery energy storage system specifically is anticipated to play a crucial role. ESS is one way to move energy out of the electrical power system and into different applications. The ESS is revolutionary with different technologies still under development is anticipated to improve the market and system while stabilising the price of power, relieving renewable energy's volatility, preventing transmission congestion fees, and enabling a market-driven electricity dispatch through consumer engagement in the market [19]. However, a few nations especially the developed nations have established guidelines or standards for how the ESS should operate in the power markets. According to some studies, the ESS might provide electricity generation, transmission, and distribution (T&D) services owing to the recent developments. The ESS's primary application within the power systems include stabilising variable renewable energy generation and boosting the grid's dependability and asset utilisation. Detailed applications and their pertinent operational goals in the system have been evaluated, ranging from large-scale bulk storage to substation storage and a distributed energy storage [20]. These applications' size, duration, cycles, and lifetime are evaluated while taking the needs of the market and industry into account.

While distributed energy resources (DER) are becoming more prevalent in the grid system nowadays, it is necessary to obtain more precise forecasts of intermittent renewable energy sources for energy system planning and operation. To keep the electricity system reliable while operating efficiently, energy planning based on short to long term forecasting is used. Forecasting models can be categorised into the following four categories according to [21]: very short term (1 minute to a few minutes), short term (1 hour to 1 week), mid-term (1 month to 1 year), and finally, long term (1 to 10 years). Forecast horizon refers to the amount of time between the actual time and the effective time of prediction. When connected to the grid, the integrated system of the ESS with renewable energy can play a significant role in reducing the loss of capacity as well as power fluctuations caused by intermittent and uncertain energy sources. Therefore, the integrated system including the ESS can lessen the reliance on the grid system for electricity and move its consumption from the pricey peak period to the non-peak period to reduce the customer's electricity bill. [22] claimed that this might be accomplished by storing excess DER power and using it to provide electricity to customers as needed. For our case study, the benefit of implementing peak shaving is to reduce the contracted peak power demand of the factory. This will be directly converted into cost reduction of the electricity price.

Studies have shown that power quality is a paramount concern in contemporary power systems, exacerbated by factors such as non-linear loads and variations in power system parameters. These conditions result in the generation of harmonics, which deteriorate power quality, leading to challenges such as coil overheating, motor vibrations, and diminished power factor [23-25]. To address these issues, Active Power Filters (APFs) have emerged as vital tools for mitigating harmonics and enhancing power quality [26,27]. These devices, installed in shunt configuration within the network, effectively compensate for load-generated harmonics, contributing to improved system performance [28].

A notable advancement in this domain is the integration of Energy Storage Systems (ESS), particularly Battery Energy Storage Systems (BESS), into power networks. BESS-integrated APFs offer a dual advantage: injecting active power into the system while simultaneously alleviating the burden on the main power source [29]. This integration has facilitated refined power flow management between the Point of Common Coupling (PCC) and APF. The excess main power from the source can be directed to charge the battery, whereas a deficit in power from the main source can be compensated by injecting active power to the PCC [30].

Two prominent studies elucidate the significance of APFs and BESS integration for enhancing power quality and harmonics compensation. [30] conducted a case study on BESS integration with APFs, showcasing substantial reduction in Total Harmonic Distortion (THD) within the power system. The THD values plummeted from 4.10% to 2.33% in simulation studies, underscoring the efficacy of this approach [30]. [30] embarked on an investigation into the potential of Battery Energy Source Integrated APFs for bolstering power factor and mitigating harmonics. Through active power injection, the authors effectively lessened the load on the main source. Their study harnessed Synchronous Reference Frame theory to regulate harmonics, yielding commendable outcomes in harmonic compensation [30].

Collectively, these studies underscore the pivotal role of APFs and BESS integration in fortifying power quality, optimizing power flow, and harmonics management. The integration of cutting-edge technologies holds promising solutions to modern power system challenges, ensuring steadfast and efficient power delivery.

Total harmonic distortion (THD) been a significant concern in power systems, leading to voltage and current waveform distortions, affecting the quality and efficiency of power delivery. With the increasing integration of renewable energy sources and non-linear loads, THD mitigation has become crucial to maintain power quality standards. In this context, the utilization of Battery Energy Storage Systems (BESS) has emerged as a promising solution to mitigate THD and enhance power system performance. [29] introduced the concept of a battery energy integrated active power filter (APF) for harmonic compensation and active power injection. The integration of BESS with APF enables not only harmonic mitigation but also dynamic control of active power flow. Excess power from the main source can be used to charge the battery, while deficit power can be supplemented by injecting active power from the BESS to the point of common coupling (PCC). This dynamic power management capability of BESS contributes to THD reduction by ensuring a balanced and controlled power flow.

The study by [29] demonstrated the efficacy of Battery Energy Storage in reducing THD in the power system. By implementing the proposed battery energy integrated APF, the THD was significantly reduced across various battery charging and discharging conditions. The use of synchronous reference frame theory allowed effective sensing and control of harmonics through the APF, resulting in improved power quality with reduced THD values [29].

Furthermore, [31] highlighted the advantages of integrating BESS with a cascaded multilevel inverter to achieve low THD and enhance power quality. The integration of BESS enables dynamic compensation of load harmonics and reactive power exchange with the grid. The study emphasized that BESS can effectively reduce THD levels in the output voltage and current waveforms, contributing to improved power quality and reduced losses. It is thus clear that the integration of Battery Energy Storage Systems (BESS) with power systems offers a robust approach to mitigate total harmonic distortion (THD) and enhance power quality. The dynamic control of active power flow, harmonic compensation, and voltage regulation provided by BESS contributes to reduced THD levels, thereby ensuring a more stable and efficient power delivery system.

Another important concept to this study for optimal power efficiency is peak shaving, a strategic approach to managing electricity costs and ensuring grid stability, has gained prominence with the increasing integration of renewable energy sources and electric vehicles. Battery Energy Storage Systems (BESS) have emerged as a promising solution for peak shaving, enabling efficient load management and reducing peak demand charges. Further in this literature review delves into the utilization of BESS for peak shaving applications and highlights the associated economic advantages.

A pioneering study by [32] introduces an innovative framework that simultaneously accomplishes peak shaving and frequency regulation using a battery storage system. Their joint optimization approach considers battery degradation, operational constraints, and uncertainties in customer load and regulation signals. Utilizing real data, the study demonstrates potential electricity bill reductions of up to 12% through joint optimization. A remarkable finding is that the combined savings achieved through joint optimization often exceed the sum of optimal savings derived from individual applications. This enhancement is attributed to a real-time algorithm proposed by the authors, which facilitates this super linear gain. This study underscores the substantial economic benefits of batteries offering multiple services in unison.

The work by [32] aligns with prior research focused on co-optimization of energy storage for multiple applications. Earlier investigations [33] explore the economic implications of employing storage devices for energy arbitrage and frequency regulation. These studies emphasize that utilizing storage for multiple purposes can yield higher profitability compared to single applications. Building upon this foundation, a systematic co-optimization framework was developed by Xi et al. [34], enabling the evaluation of various application combinations across different time scales. However, these studies predominantly conducted heuristic analyses without direct application of optimization models and did not comprehensively account for uncertainties in energy markets.

In practice, the integration of Battery Energy Storage Systems for peak shaving has been embraced in diverse settings. Commercial buildings and data centres stand out as prominent consumers adopting BESS for load management and backup services [35, 36]. Additionally, the potential for distributed storage systems owned by individual consumers is recognized [37]. Notably, the studies by [35], [36] illustrate electricity cost-saving strategies achieved through energy storage in data centres and commercial building microgrids which can be systematically applied in industrial facility also.

To sum up, the incorporation of Battery Energy Storage Systems for peak shaving applications offers significant economic advantages. Co-optimization strategies, exemplified by the work of [32], highlight the potential for achieving super linear gains when batteries provide multiple services. As the energy landscape evolves, the adoption of BESS for peak shaving remains a pivotal strategy for optimizing electricity costs, enhancing grid reliability, and bolstering overall energy system efficiency.

2.2 Battery Sizing

Energy storage systems have the capability to fulfil a range of critical roles, encompassing the enhancement of power quality through tasks like frequency and voltage regulation, the mitigation of fluctuations in output from renewable energy sources, and the provisioning of backup power to support the system's reliability. The effective dimensioning of the battery bank assumes a paramount significance to attain scientifically meaningful outcomes. In this context, the utilization of sound technical expertise becomes imperative to accomplish optimal sizing for the studied system, which encompasses both grid power and photovoltaic (PV) solar power components.

In determining the appropriate battery size for our system, a lot of considerations are involved to guarantee that it meets the energy demand for our facility. It is worthy to note there are many battery technologies in the market today with the most common found in ***Figure 1,*** being the lead Acid battery which can be flooded, gel & AGM types, and also the lituim-ion batteries. Studies show that the performance of the lead-acid types are comparable to one another but appreciably different from the lithuim-ion batteries. ***Table 1*** presents some important highlights for the common battery types and as such must be considered before battery sizing and selection.

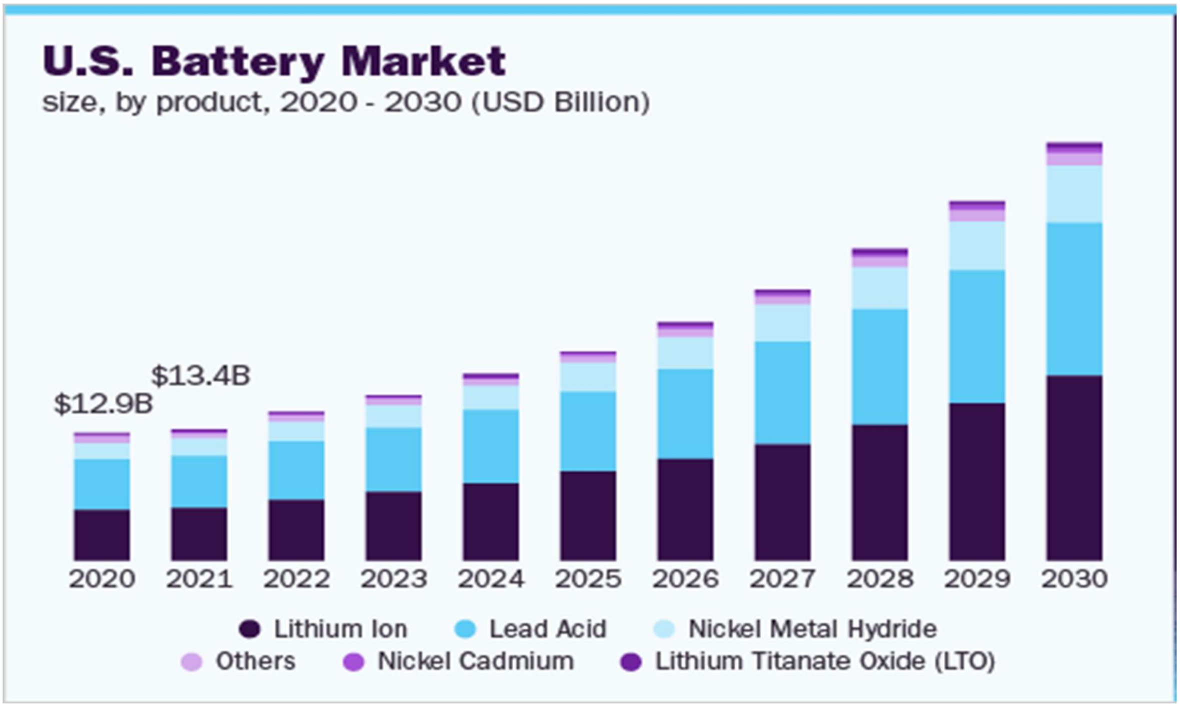


Figure 1: Battery technologies by market size, share and trend, Source: www.grandviewresearch.com.

Additionally, battery performance lifespan also depends on several other factors including temperature, percentage of discharge, frequency of use, availability of charging source, months in storage and several other factors.

Lead-acid type is currently popular where space and maintenance aren't an issue, however, we will consider lithium-ion battery in this sizing considering its numerous advantages and since it is becoming price comparative. It can also store more than four times energy than lead acid batteries. Energy density is around 150-watt hours per kilogram compared to lead-acid batteries with energy density around 40-watt hours per kilogram. Also, the longer lifespan of lithium-ion batteries practically determined by the number of cycles could largely offset the cost difference over time. Other useful information can be found on a battery typical data sheet including the useable energy where we have around 85% for lithium-ion batteries and 50% for lead acid batteries.

Table 1: Comparisons between the most common used batteries [38], [39].

	FLOODED LEAD-ACID	GEL	AGM	LITHIUM-ION
Description optimal use	Wet cell battery filled with electrolyte	Sealed lead-acid using silica gel with suspended electrolyte	Sealed lead-acid electrolyte held in thin glass mats	The most common energy storage technology for all uses overall today
Optimal Use	Medium to high capacity off grid use	Most deep cycle applications	Good choice for off-grid, RV, boat	Li-ion phosphate (LFP) for solar storage
Charging Time	Varies greatly due to many factors. Expect several hours to a day+	Few to several hours depending on a variety of factors	Up to five times faster than flooded battery technology	Varies greatly due to several factors. Expect three hours or longer to full charge
Lifespan	Well-maintained may last up to 15+ years. Expect 4-8 years.	8 years if maintained well with DoD <20%. Expect 3-5 years	10 years if properly maintained & DoD <20%. Expect 6-10 years	High quality battery can last up to 15 years
Cycling	Depend heavily on DoD over life. Expect 300-500 discharge cycles	Varies by capacity withdrawn. 1100 cycles at 50% withdrawn	Varies by capacity withdrawn. 700-1000 cycles with normal use	Varies by several factors including capacity withdrawn. 3000-5000 cycles possible
Maintenance	Requires regular maintenance (add water, clean terminals, and venting)	Maintenance free	Maintenance free	Maintenance free
Temperature sensitivity	High temperature increases capacity, lower temperature reduces capacity	High temperature increases capacity. Tolerates very low temperature	High temperature increases capacity. Tolerates very low temperature	High temperature causes performance degradation
Safety	Toxic/corrosive lead & sulfuric acid. Caution when refilling & recharging. Gaseous hydrogen may explode	Toxic/corrosive lead & sulfuric acid. Caution when recharging. Gaseous hydrogen may explode	Toxic/corrosive lead & sulfuric acid. Caution when recharging. Gaseous hydrogen may explode	Despite reports of fire and explosions in the media, lithium-ion batteries (LiFePO4) are relatively safe when used properly
Cost	Cheapest upfront cost of all types of solar PV applications	More expensive than lead acid, much more than similar AGM capacity	Lower upfront than Li-ion & gel but higher than flooded	Very expensive. High upfront cost offset by long term cost effectiveness
Installation Considerations	Vented to outside/Upright only	Vented area/can mount sideways	Vented area/can mount sideways	No venting needed/can mount sideways
Recyclable?	Yes	Yes	Yes	None currently

CHAPTER 3

3 Project Description

3.1 System Definition

The purpose of the research, entitled "Utilization of Energy Storage to Improve Energy Efficiency and Power Quality", is to study energy storage applications from different qualitative and quantitative perspectives. Sweden today presents a relatively mature environment for the development of energy storage technologies with the country now having one of the biggest battery manufacturers in the world. Not so abreast with regulatory and even non-regulatory gaps or maturity, this report seeks to resolve existing uncertainties about the applicability and effectiveness of integrating renewable energy sources for industrial use. This will assist in the recognition of storage systems in improving the power system qualities whether for grid-connected systems or otherwise.

This project will be executed using the power system characteristics of Holtab AB factory located in the southern part of Sweden, Tingsryd. From this perspective, the project proposes to investigate the improvement options offered by connecting a battery system in parallel to the system. Among the main functions desired for the storage system identified in the project are power factor correction and improving the total harmonic distortion, all contributing to overall system efficiency improvement. These two proposals are tested with a set of Lithium-Ion Phosphate (LFP) batteries, which is a lithium-ion battery technology with a technical-sized capacity incorporated with the company's power system. The choice of this technology was due to the benefits that the LFP battery presents.

The simplified single-line diagram for the system under study is shown in ***Figure 2.*** The installation point of connection for the BESS system is labelled as ***A*** in the ***Figure 2***. The main objectives of using the storage system are to smooth solar production through instantaneous power injection and instantaneous power consumption, counterbalancing its instantaneous output, and, consequently, removing variations introduced by the solar power intermittent power output. Considering other storage system application options, it is expected to use the remaining storage capacity for reactive power compensation, firstly, to improve the power factor and, secondly, to compensate for the harmonics.

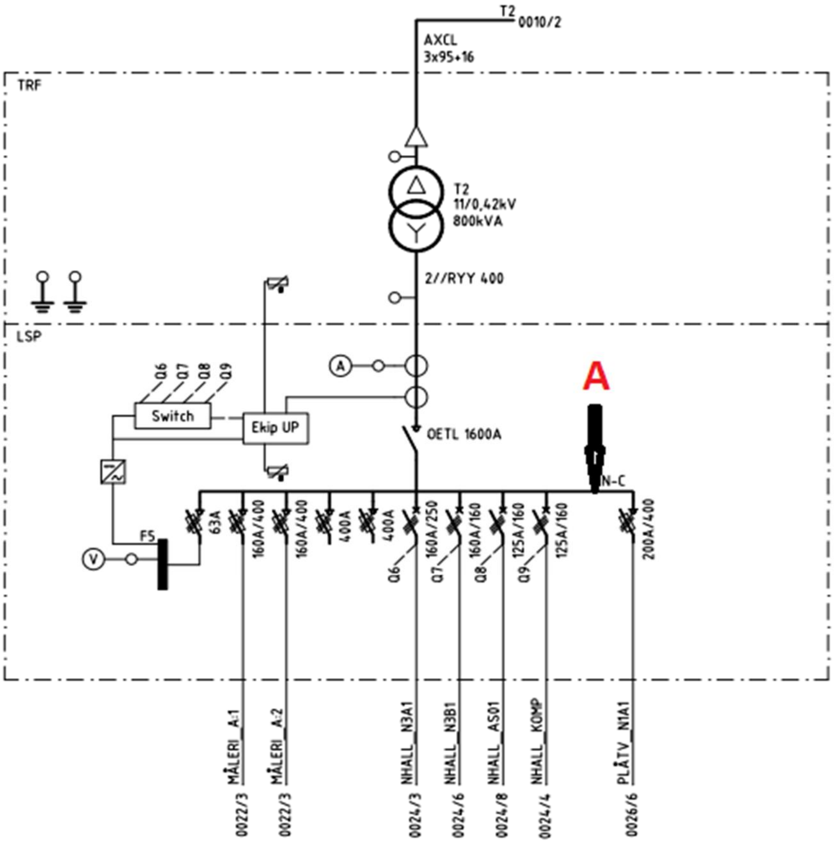


Figure 2: Single-line diagram of the system under study, Source: Holtab AB depository.

3.1.1 Battery System General Overview

A battery energy storage system (BESS) is a vital subset within the broader category of energy storage systems (ESS). While ESS encompasses various technologies capable of storing and returning energy, BESS specifically relies on chemical technology to fulfill its energy storage function. At the core of BESS lies the individual cell, housing the chemical compounds responsible for storing electrical energy. This section provides an overview of BESS, delving into its components, functionalities, and broader implications.

Cellular Foundation and Scale: At the heart of a battery energy storage system are its cells. These cells serve as the fundamental building blocks, each equipped with the necessary chemistry to efficiently store and release electrical energy. In the context of the present work, which contemplates the utilization of a substantial BESS, the system is composed of hundreds of interconnected cells. This interconnected network of cells collectively forms the bedrock upon which the entire BESS operates.

Key Components

Power Control System: The power control system assumes a critical role in the operation of BESS. This system includes a bi-directional inverter responsible for converting alternating current (AC) to direct current (DC), a necessary step for facilitating energy storage within the battery. Depending on the complexity of the BESS, this system may incorporate additional components such as transformers, switches, and other essential equipment. These elements collectively enable seamless integration of the BESS with the existing electric grid infrastructure.

Software Components: Battery systems heavily rely on sophisticated software components to manage their operation effectively. The Energy Management System (EMS) plays a pivotal role by overseeing and optimizing the performance of the battery cells to ensure they operate within prescribed specifications. Concurrently, the Site Management System (SMS) serves as the vital communication link between the battery system and the electric grid. These software components collectively enable the BESS to function seamlessly within the broader energy ecosystem.

Infrastructure and Beyond: Balance of Plant (BoP): Beyond the core components, a battery energy storage system encompasses a suite of infrastructure elements collectively referred to as the Balance of Plant. This term encapsulates a variety of auxiliary systems and structures that contribute to the overall functionality and safety of the BESS. These components may encompass a dedicated building to house the battery system, specialized heating and cooling systems to regulate operating temperatures, and robust fire protection systems to safeguard against potential hazards.

Consequently, a battery energy storage system represents a specialized and pivotal subset within the realm of energy storage technologies. Rooted in chemical principles, the BESS leverages interconnected cells, intricate power control systems, and sophisticated software components to facilitate efficient energy storage and release. Additionally, the supporting infrastructure, encapsulated within the Balance of Plant, ensures the safe and effective operation of the BESS within the broader energy landscape. Understanding the nuanced interplay of these elements is essential for comprehending the role and potential of battery energy storage systems in modern energy systems.

3.2 Battery Sizing

From the cloud resource, we deduced the annual energy demand = 310,114 h

Energy use = h h $= 184.59$ h

3.2.1 Estimation of System Losses

- Round trip efficiency, this is a result that no battery is 100% efficient, thus these measures the energy retention of the battery i.e., loss of power because of charging and discharging which is based on the chemistry of each battery technology. This value is commonly around 85% for lead acid batteries and 95% for lithium-ion batteries.
- Wiring losses: This account for losses that may occur as electricity flow through the battery bank, conversion equipment and the loads and largely depends on the length of the wire.

  This is given by; $(\%) = \frac{* \quad *}{}$

We want less than 2–3% voltage drop according to the NEC Recommendations Sections 210.19(A)(1) FPN 4 and 215.2(A) FPN 2 which recommends that the voltage drop of the feeder and branch circuit should not exceed 5% of the voltage source. Thus, we assume a wire efficiency of 97%.

- Conversion efficiency: This account for the losses encountered in raising the battery bank to the standard AC voltage of 120V or 240V depending on the application. Studies show that battery inverters are typically less efficient than solar inverters with an efficiency range of 92% to 94% depending on the load level [40]. In this study, we assume that the battery inverter in our AC coupled system has an efficiency of 92%.

$$= 0.95 * 0.97 * 0.92 = 0.85$$

3.2.2 Calculation of Battery Size

- System voltage: These often comes in 12V, 24V and 48V. while 12V are employed for small load systems, the two latter provide us with the widest options. Since this system is for an industrial application with somewhat high energy demand, thus we choose a 48V system. Some other considerations may be examined depending on the application.

- Days of autonomy: This simply makes sure we have enough power to run our loads in time of low power from solar or grid. However, the BESS application in this study is not designed for backup (where 3-5 days is recommended) but primarily for peak shaving, power factor correction and THD. Thus, a day autonomy can suffice. Increasing this significantly increases the cost of the BESS system.
- Thermal losses: Most batteries are typically rated at 77°F or 25°C and the capacity will typically drop at lower temperatures. We can account for this using a battery compensation factor. This is found in the manufacturer specification or other resources including the IEEE standards 485-2020. We now consider storing our lithium-ion battery at a winter temperature of 40°F or 4.4°C which corresponds to temperature correction factor of 1.30.
- Depth of discharge: This describes how far the batteries can be discharged as batteries are not designed to be discharged completely. This can be found in the manufacturer's data sheet. Generally, lead-acid batteries have a maximum DoD of 50% against 85% for lithium-ion batteries of their rated capacity without significantly affecting the lifespan.

$$(\qquad) = \frac{* \quad * \;.}{* \;. \quad * \;.} = 6{,}919 \quad h$$

this produces electrical energy of about $6{,}919 \quad h * 48 \quad = 332{,}112 \quad /h$

$$\approx 332{,}112 \quad /h * 8 = 2{,}657 \quad /$$

3.3 System Data Analysis

Understanding the current health and characteristics of the system under test is a pre-requite to the research. We, therefore, start by gathering and analyzing data acquired from the site. The system under study has a cloud resource that stores data measured from the metering devices. The cloud resource is called ABB-ability which is a special system that helps the user to see and keep record of the system data. This data is obtained from the measuring instrument installed at the essential points in the power system and can continuously measure the data in short time intervals. Many system parameters can be measured and stored including voltage, current, power, power factor, frequency, total harmonic distortion, etc. This cloud resource contains millions of data dated as far as the installation year for some parameters.

For each measuring point the system will automatically store the maximum, minimum, and average values and a graph can be drawn with these values as will be shown later in this paper.

Consequently, from the history readings of power quality, we can observe the following key points related to the study:

1. The total demand power of the system does not reach the critical loading point of the transformer, which in return translates into lower hazards of tripping due to load fluctuations and overheating of the transformer windings. ***Figure 3*** shows the active power on the transformer main breaker during the year (from 27 May 2022 to 01 April 2023). The total active power at peak demand reaches around 264kW at max loading and minimum solar generation. The minimum power demand is -186 kW at peak solar generation, and this minimum loading is negative due to PV generation and occurs during summer shutdown.

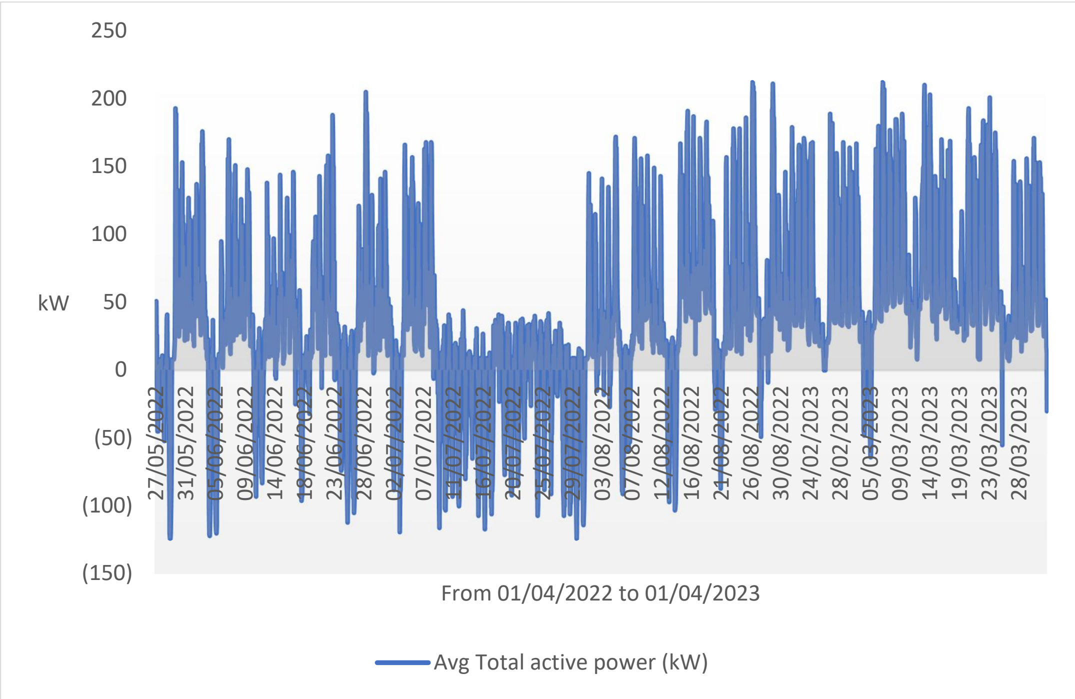


*Figure 3**:** Total active power on station metering at the main breaker, Source: ABB ability connected gateway.*

For deeper understanding, we also analyse the power demand during one of the peak demand days with no solar generation. ***Figure 4*** shows the total power consumption during a cloudy day.

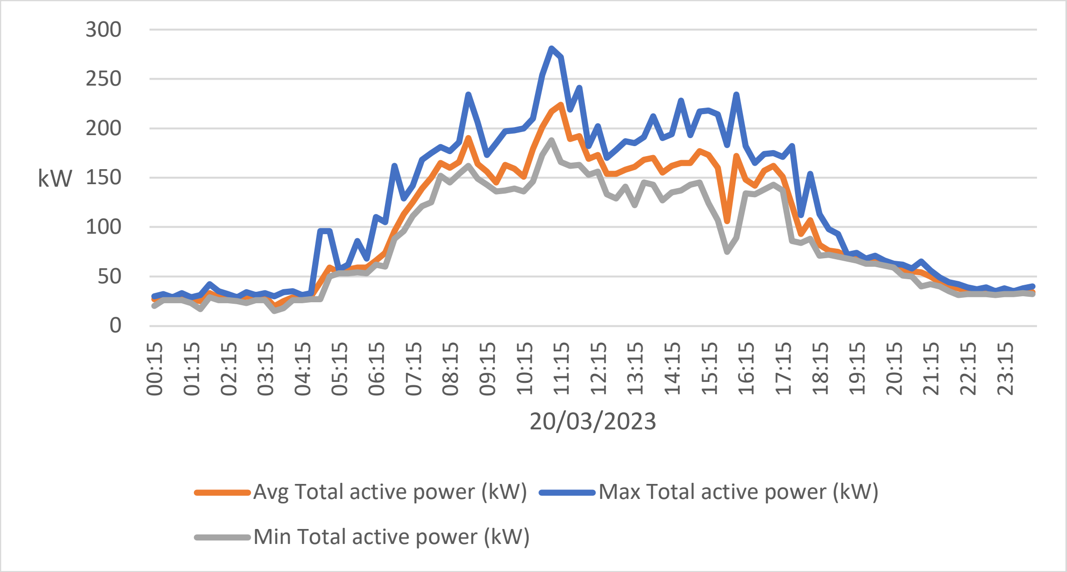


Figure 4: Total active power on station metering at the main breaker, for a cloudy day. Source: ABB ability connected gateway.

The graph shows that the power demand peaks over 150KW during the working hours due to the operations at the factory, presence of employees and EV chargers being active during the day.

Furthermore, we also measured the active power during a sunny day with maximum solar generation. The active power demand in the facility is almost the same, however, we can observe the impact of solar generation reducing the active power demand during the radiation hours. For both cases, the focus is on the average total active power as the systems registers three points for every time slot (Max, Avg, and Min). See ***Figure 5***.

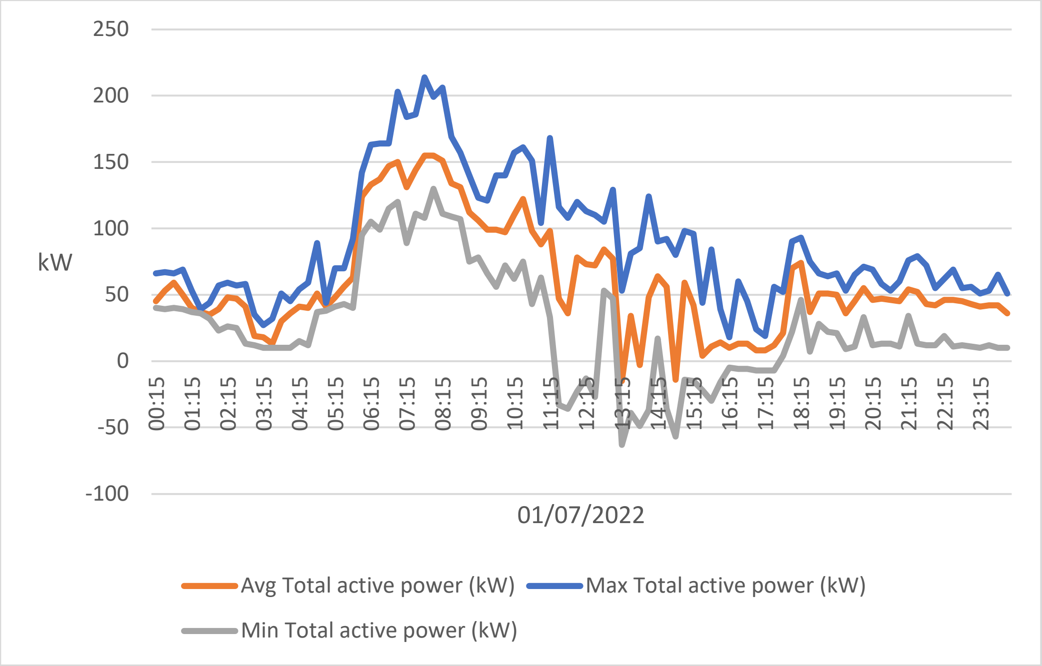


Figure 5: Total active power on station metering at the main breaker, during a sunny day. Source: ABB ability connected gateway.

The total demand is increasing during the early hours of the day before solar radiation is at its peak. During mid-day, the solar panels help reduce the overall demand for power and it is reduced to nearly 50kW after working hours. This is a clear demonstration of the need for peak shaving for the load during peak hours and low PV generation.

2. The utilization of CNC machines, laptops, LED lighting, EV chargers, and other non-linear loads produces high harmonics in the local grid. The following charts illustrate high voltage and current THD in the grid. This may cause overheating in the cables and damage to sensitive equipment connected to the local grid (there have been reports of screen failures, lighting failures, and other low current system damages due to harmonics). ***Figures 6*** and ***Figure 7*** present the THDs for the current (THDi) and voltage (THDv) respectively. They elucidate the readings of current and voltage THDs and clarify the state of the system THDs. The THDi are relatively high and reach almost 80% of the total load current. We can see on the graph that the energization of CNC machines, laptops, and some EV chargers at the beginning of the day causes an increase in THDi, that is also to be added to the solar inverters impact which will cause THDi to above 50% (the focus again on the average values). And because the factory is using EV lifting machines, forklifts, and local transport vehicles, charging them at the end of working hours will be added to the company fleet that charges over night and cause another peak of THDi after 16:00pm. A similar cycle is repeated the next day with seemingly lower solar inverters contribution. The presence of high harmonics within the local grid, cause high losses, damage to cables, and damage to connected sensitive loads. From the graph, we can also observe the impact of non-linear loads during work hours and the solar inverter's contribution as well.

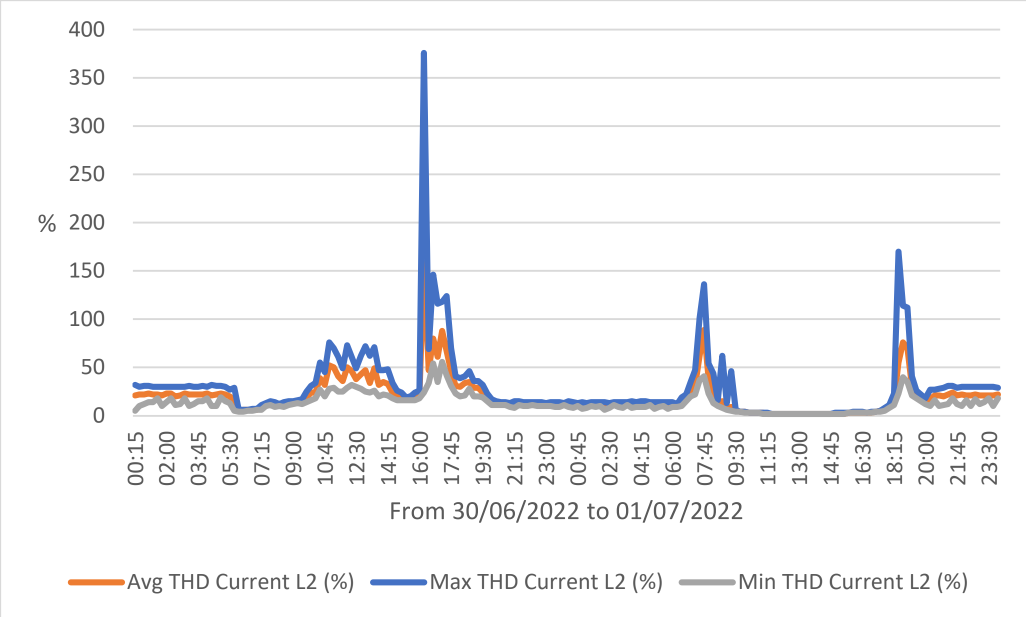


Figure 6: Total harmonics distortion for the current, Source: ABB ability connected gateway.

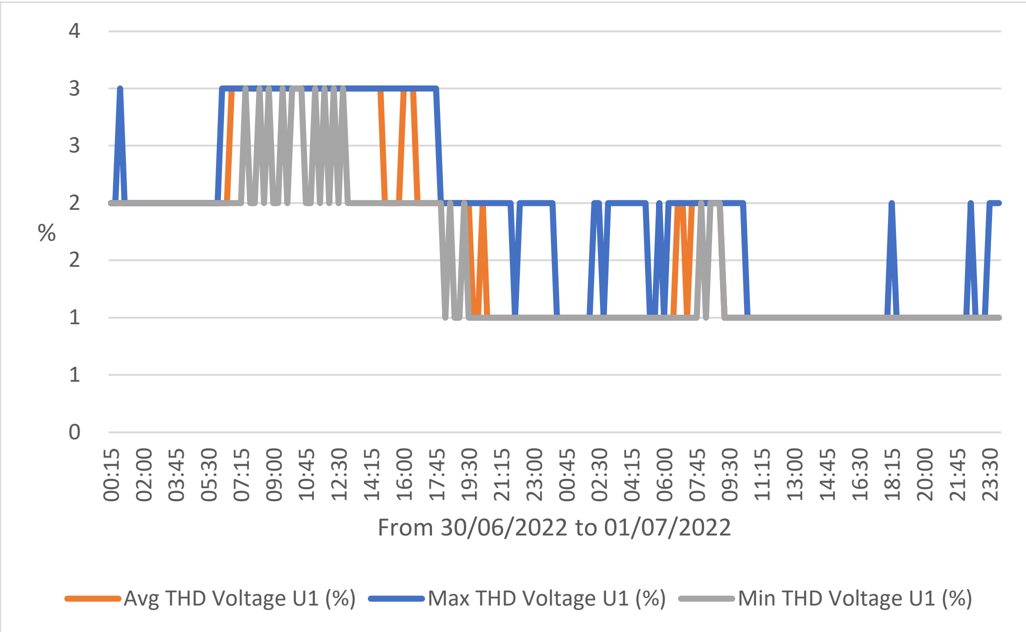


Figure 7: Total harmonics distortion for the Voltage. Source: ABB ability connected gateway.

Deductively, the voltage total harmonics distortion in ***Figure 7*** is at the edge of accepted values as per IEC 61000-2-4 standard.

3. There are some connected inductive loads that draw a lagging current and result in a low power factor. Those loads cause losses due to reactive power in the form of heat in the cables and transformer windings. The next graph shows the low power factor for some of the loads which are affecting the overall system power factor to drop below 0,6 at some points. ***Figure 8*** presents the trend of power factor over a period of 1 month. While the average of the power factor is above 0,9, there is still room for improvement. A goal of 0,95 or above all the time would be suitable.

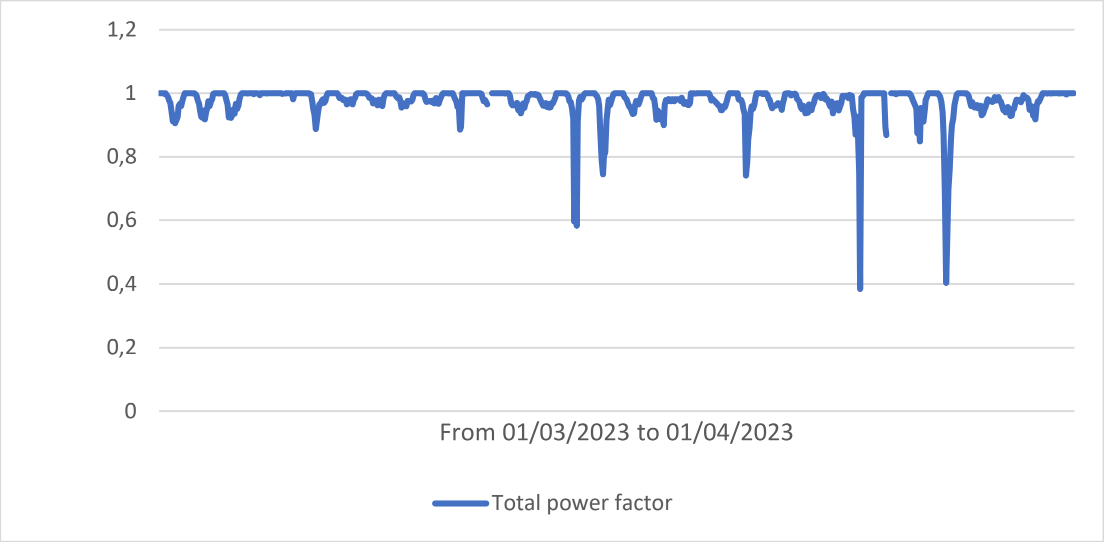


Figure 8: Total power factor for the station, Source: ABB ability connected gateway.

4. From the observed data, the frequency and voltage level fluctuations are in the accepted range as per local and international standards. According to *EN 50160* the frequency fluctuation limit for systems with synchronous connection to an interconnected system is as follows.

50 Hz ± 1 % (i.e., 49,5 ... 50,5 Hz) during 99,5 % of a year,

50 Hz + 4 %/- 6 % (i.e., 47 ... 52 Hz) during 100 % of the time

Also, for voltage fluctuations and under normal operating conditions a rapid voltage change generally does not exceed 5 % Un but a change of up to 10 % Un with a short duration might occur sometimes per day in some circumstances.

For our case study, the maximum voltage and frequency fluctuations are not exceeding these values so they will not be further investigated.

5. Additionally, the total generated energy from the solar panels is suitable to charge the batteries during a long period of the year. The stored energy can be used as a source of power for the BESS. During low solar radiation days, the BESS will function as a peak shaving only which will help reduce the contracted power level of the facility. This will significantly reduce the energy demand of the factory and translates to savings.

3.4 Mitigation Methods

3.4.1 Power Factor Correction

The conventional mitigation of the presented problems can be partially achieved by installing capacitor banks to improve the power factor and ensure a high-power factor of the facility. The required capacitor banks can be calculated by the following formula and ***Figure 9***.

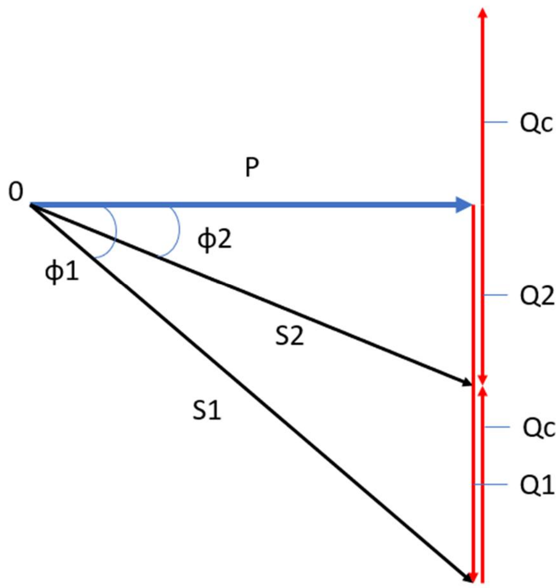


Figure 9: Power factor angle.

$$= \frac{(\ )}{(\ )} = \quad \emptyset \quad \in (0,1)$$

Without power factor correction; $= \quad \emptyset$

After connecting power factor correction; $= \quad \emptyset$

The required reactive power of capacitor to improve the system = Qc

$$= \quad - \quad = \quad \emptyset \ - \quad \emptyset \ = \ (\quad \emptyset \ - \quad \emptyset \ )$$

where P is active power, S1 and S2 are apparent power before and after compensation, Qc is capacitor reactive power, Q1 is reactive power without the capacitor, and Q2 is reactive power with the capacitor.

For our case study, the required capacitor banks sizing will be as follows since we have an electrical system delivering an average of 250MVA apparent power to the loads with an average power factor of 0.85, with a KVAr capacitor bank required to improve the power factor to around 0.95.

$$= 250\,(\quad 36.6 - \quad 11.47) \cong 135$$

The capacitor bank is installed in parallel with the total load and power factor correction is done by a special type of power factor controller. ***Figure10*** shows the connection point of the capacitor bank, to the right in parallel with the total load.

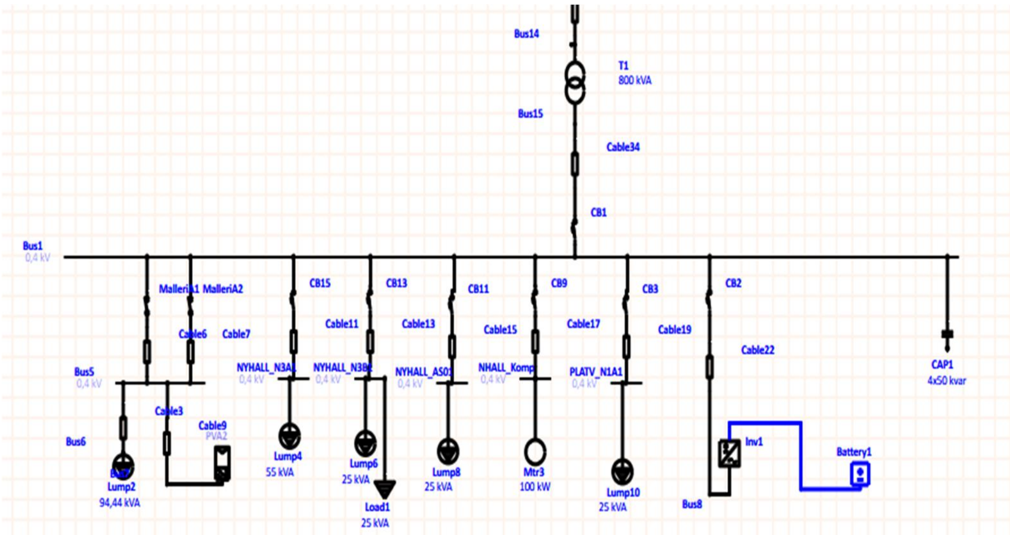


Figure 10: Connection of the capacitor banks to the existing station main busbar.

The capacitor bank controller monitors the voltage and current and compares it with a reference pre-set. Then it commands the capacitors to be connected to the load based on the number of capacitor blocks in the panel. ***Figure 11*** illustrates the logical diagram of the system.

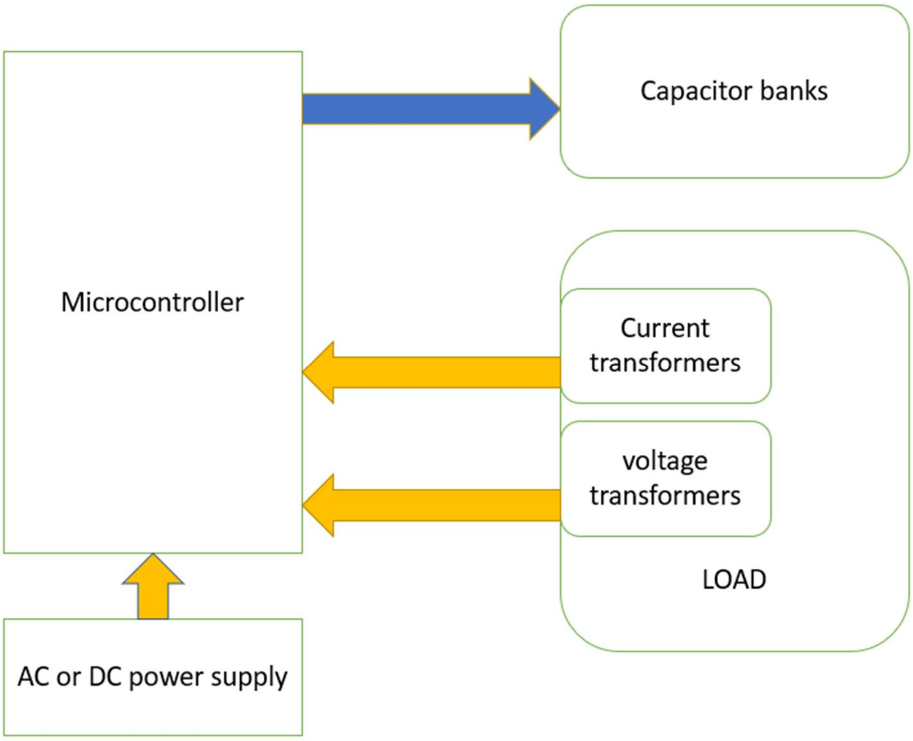


Figure 11: The capacitor banks logical diagram. Source [26].

3.4.2 Harmonics Filtration

Mitigation for harmonics can be achieved by installing an active harmonic filter. The required AHF for our case must be rated at the worst-case scenario which is 55 % THD. From the calculations, we see that a 60A AHF is suitable for THD mitigation of the project.

Normally, the harmonics filter is connected in parallel with the total load at the secondary side of the transformer. ***Figure 12*** shows the single line diagram with the AHF connected.

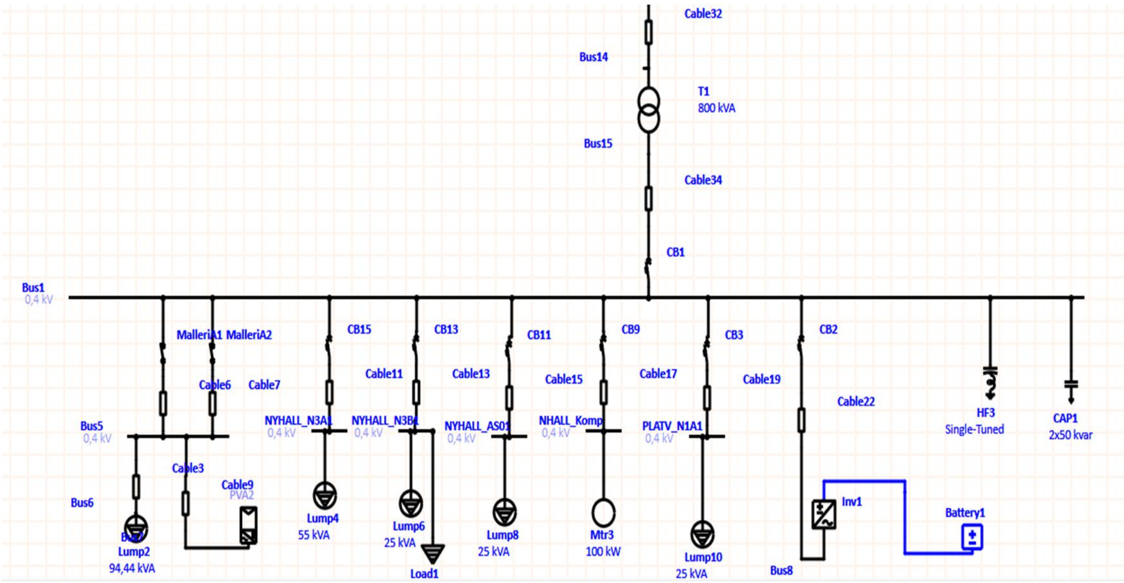


*Figure 12**:** The station single line diagram with AHF connected.*

The block diagram of the AHF logic is shown in ***Figure 13***.

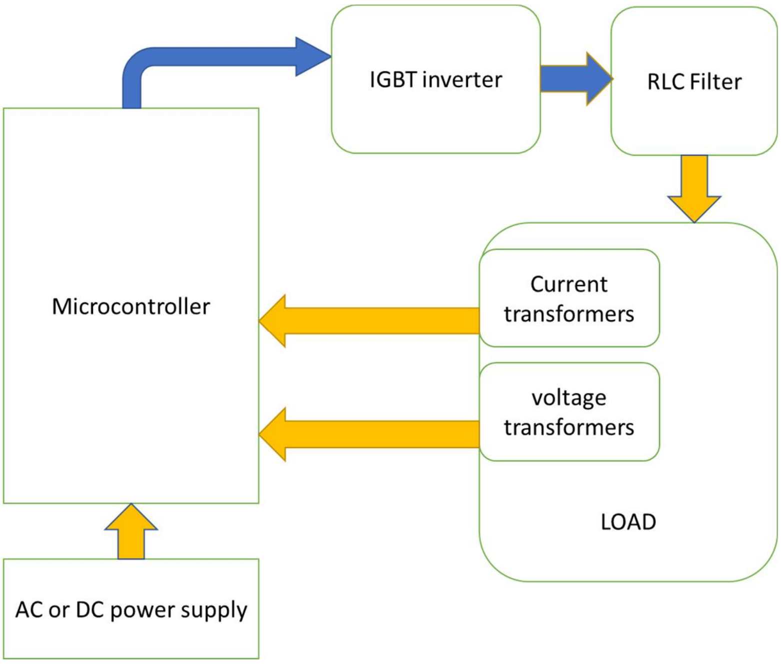


*Figure 13**:** Active Harmonic Filter operation logic.*

The previously mentioned mitigation methods can compensate for the power factor and harmonics distortion but cannot be used for peak shaving functions.

For our study, we are aiming to achieve the required power quality including power factor improvement, harmonics filtration, and peak shaving. Those aspects of the facility's power quality can improve the factory's energy efficiency and significantly reduce power consumption.

In addition, the BESS can be used to improve the grid voltage fluctuations, and frequency fluctuations, and provide energy flexibility to buy less power at grid peak prices. This can be useful when a local smart grid is connected to a nearby grid and this function is compensated according to Swedish local grid regulations. The same function can be used for local facility smart grid stabilization if the frequency and voltage fluctuations exceed the standard accepted levels. However, for our case we found that these values are in the accepted range according to the standard (will be highlighted in the data analysis chapter). Therefore, we will limit our study to the first three aspects since they will have the most significant impact on our case.

CHAPTER 4

4 Results and Discussion

4.1 Modelled Network of Holtab AB Factory in MATLAB (Existing Case)

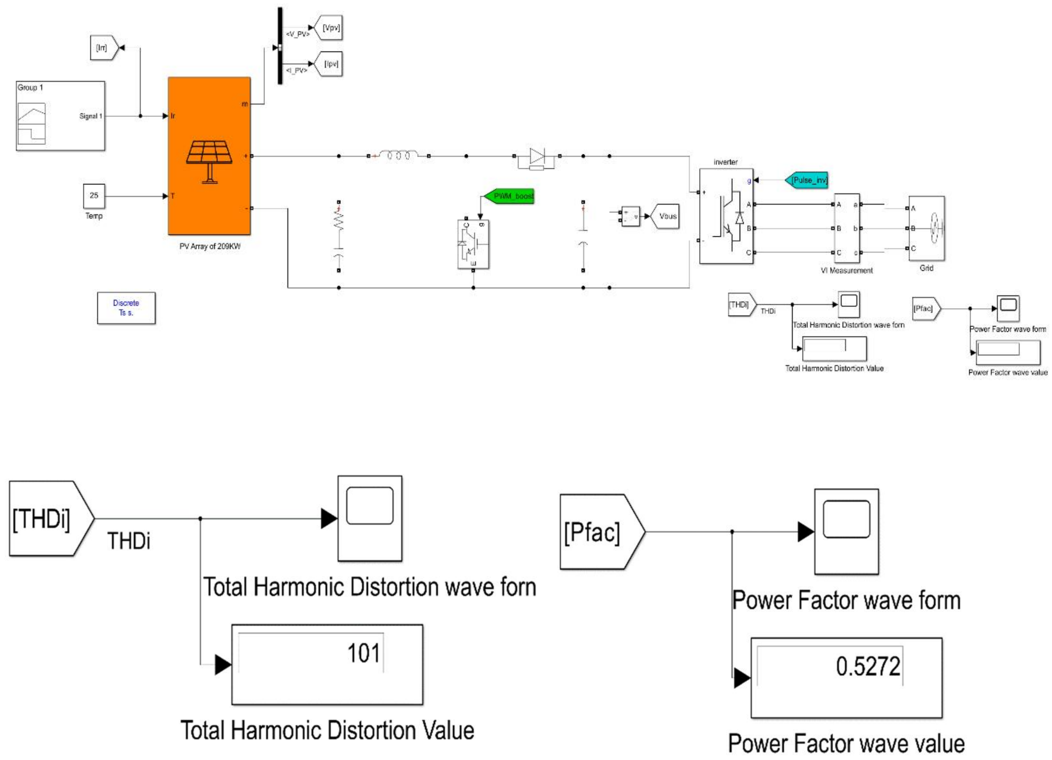


Figure 14: Modelled Network of Holtab AB Factory.

For modelling the system, we considered a passive filter. Although it does not provide the same efficiency and response time of the active harmonic filter, but it is still useful to provide an insight of the system effectiveness for mitigation.

Figure 14 shows the modelled network of Holtab AB Factory when the energy storage system, capacitor bank, and passive filter are not installed in the system. The system is then simulated to study its behaviour with respect to power factor and harmonic distortion as shown in ***Figure 15*** and ***16***.

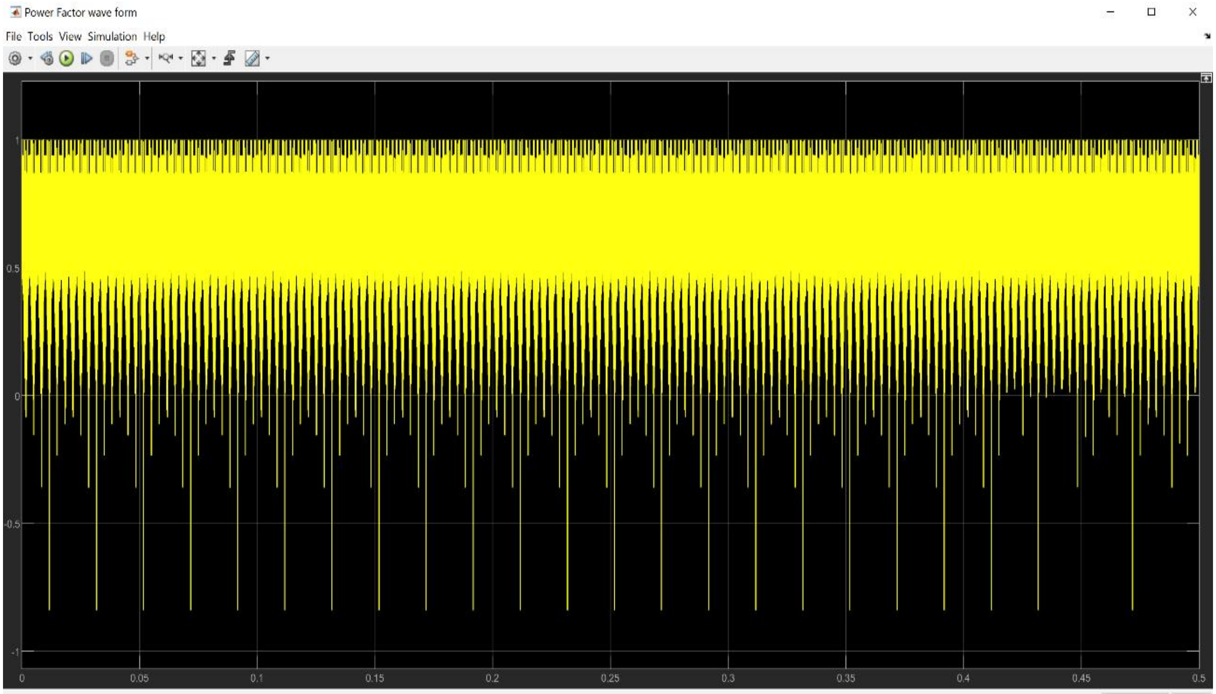


*Figure 15**:** Power factor waveform of the system.*

The graph in ***Figure 15*** shows the result of the power factor of Holtab AB Factory when an energy storage system (ESS), capacitor bank and passive filter are not incorporated. It shows a power factor of about 0.5272 which is low. This low power factor will result to a large voltage drop on the line as a result of much current drawn especially by industrial machines and this is not healthy for the company.

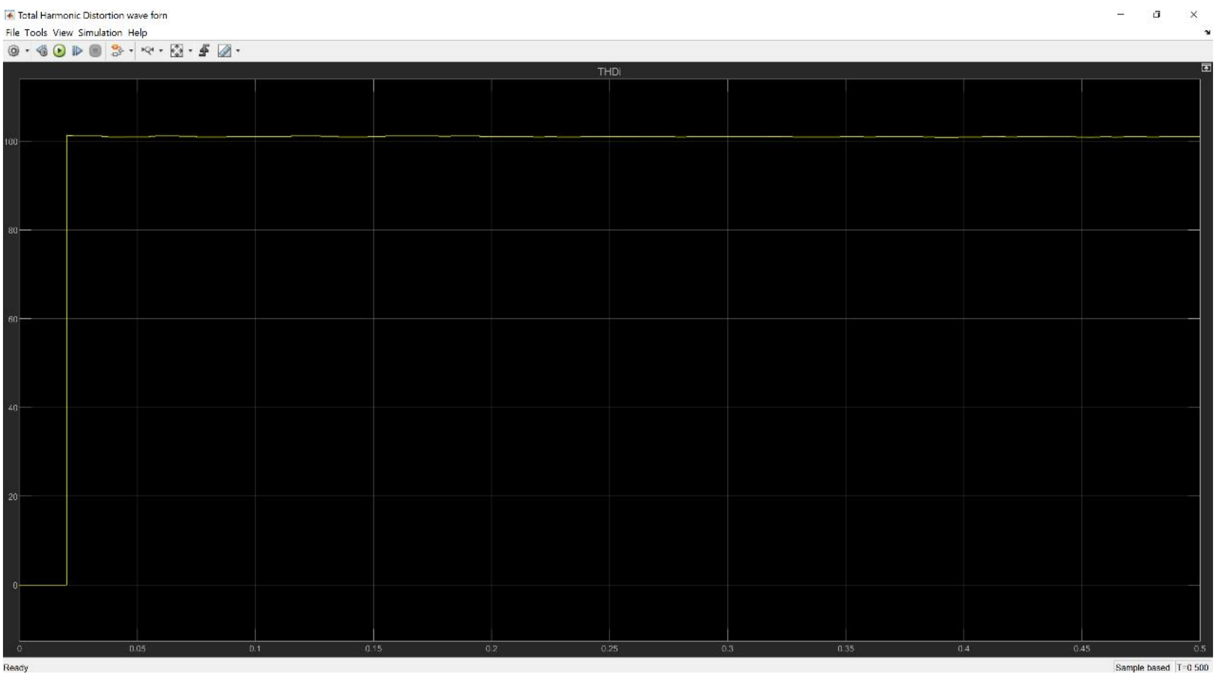


*Figure 16**:** Harmonic distortion waveform of the system.*

Figure 16 is a waveform of harmonic distortion arising from the network when there is no passive filter installed. The distortion takes the form of a square wave with a very high value of 101 which is detrimental to the system and resulting to a low power output.

4.2 Modelled Network of Holtab AB Factory in MATLAB (Improved Case)

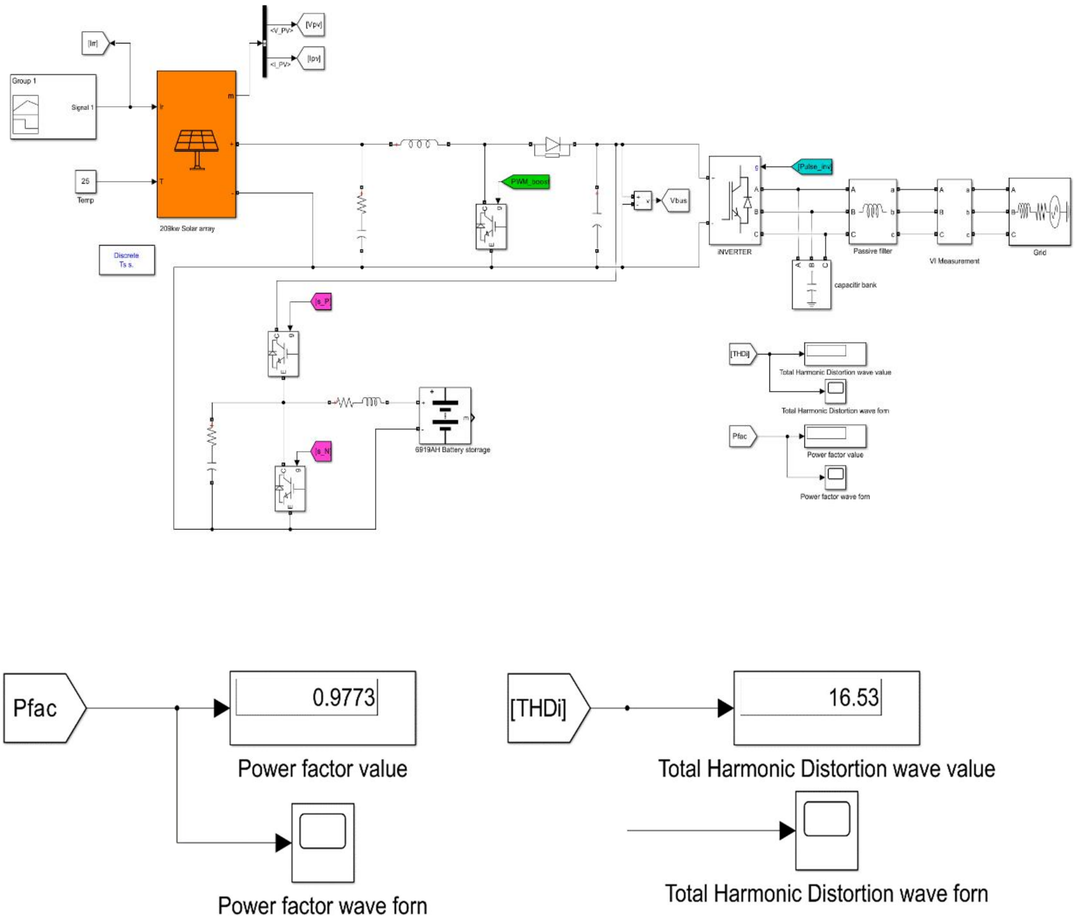


Figure 17: Modelled Network of Holtab AB Factory (Improved Case).

Figure 17 above shows the improved network of Holtab. The installation of an Energy Storage System (ESS) of 6919Ah, Capacitor bank, and a passive filter has brought about reduction in the peak energy usage from the grid, improved power factor of 0.9773 and a significant reduction in harmonics distortion as shown in figure 19, 20 and 21 below.

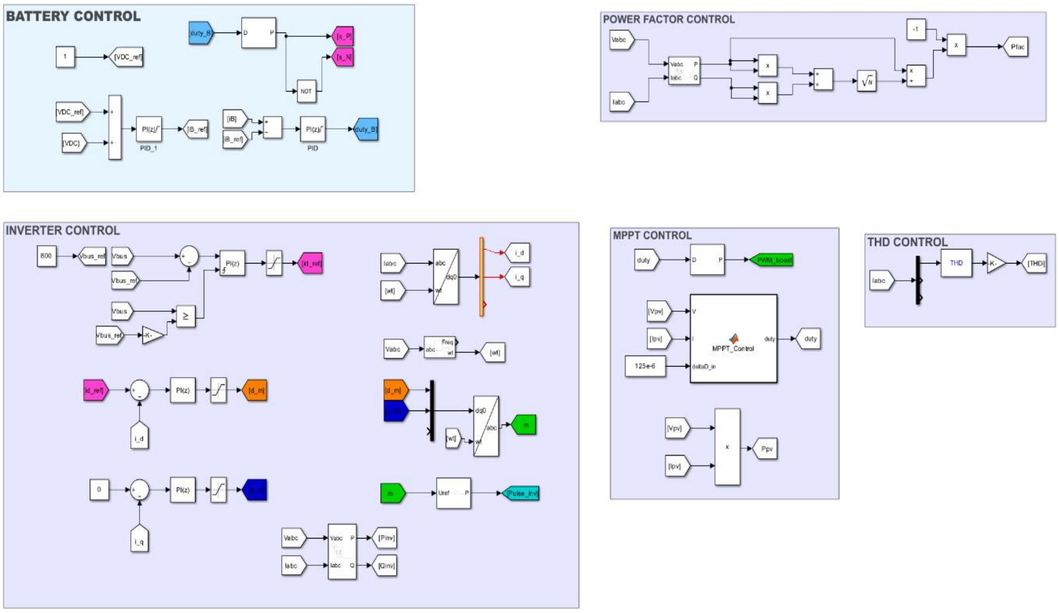


Figure 18: Control Circuit of the Network (Improved Case).

4.2.1 Peak Shaving

Peak shaving is the main functionality of the Energy Storage System (ESS). It is basically achieved by using the stored energy in the battery system which is charged by the solar panels (during high radiation days), or low-cost grid power during low radiation days. The battery system for this study is designed to yield a maximum of 2,657 kW/day. In our case, the required power for a day can reach up to 224kW as shown in the “Avg total power” curve in ***Figure 15***. Considering the data obtained from the digital monitoring system, we can apply peak shaving to reach a maximum of 150kW throughout the working day and the discharge of the batteries will be 93,75kWh. Thus, a fully charged system can achieve peak shaving for almost 20 days based on the curve shown in ***Figure 19***. However, other factors will affect this duration like the energy consumed for power factor correction, the normal discharge of batteries, temperature effects, and a minor contribution of the harmonics filtration function. ***Figure 19*** illustrates the peak shaving of the facility.

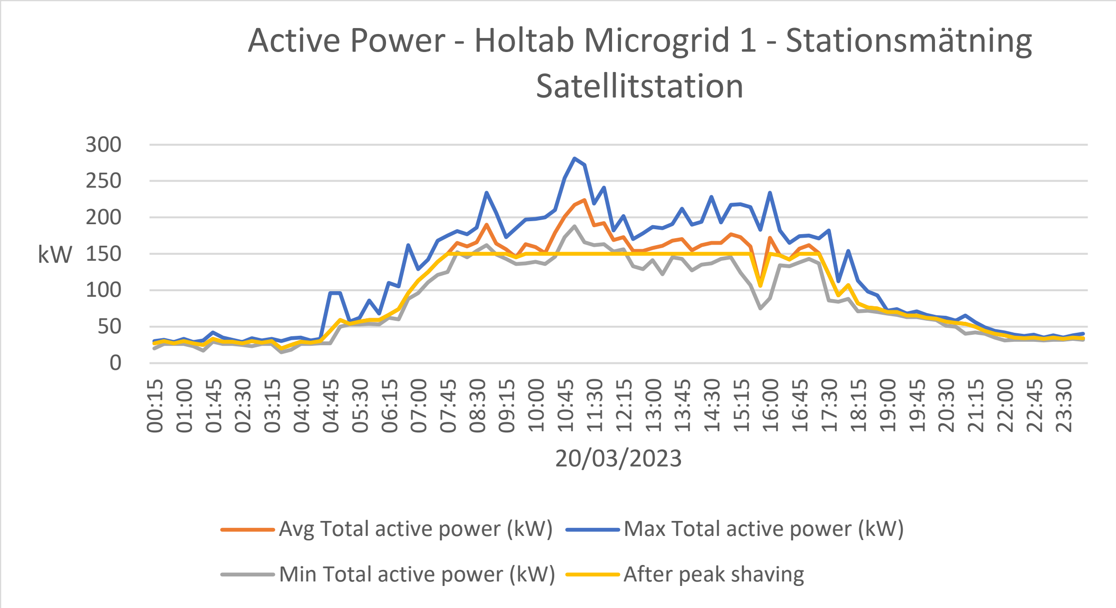


Figure 19: Total active power before and after peak shaving.

From ***Figure 19***, the peak energy consumed has been levelled or reduced by the introduction of Energy Storage System (Lithium-ion battery). This technology helps the end user (Holtab Factory) to reduce cost of production.

4.2.2 Power Factor

The power factor correction is achieved by the utilization of an LCR filter with a MOSFET bridge in the network.

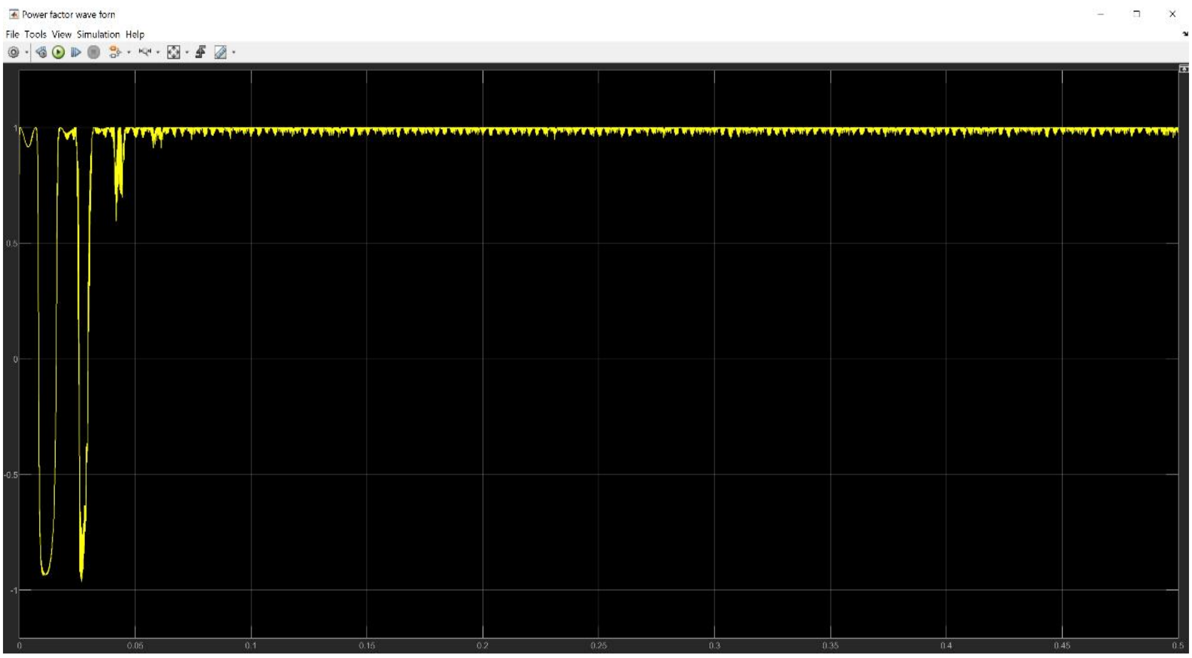


Figure 20: Waveform of Power Factor Correction.

The circuit injects energy from the batteries connected between the line and the neutral. A special type of controller is used for monitoring voltage and controlling the functionality of the MOSFET array. The multilevel inverter and the capacitor bank resulted in the power factor improvement to 0.9773. This will reduce voltage drop and thus enhance the power quality of Holtab AB factory. The result shows that in less than 0.05 second, the power factor is negative because there is much reactive power in the system from the battery which has not been utilized.

4.2.3 Active Harmonics Filtration

The battery system is sensitive to harmonics in the local smart grid. Other non-linear loads also contribute to the total harmonics' distortion.

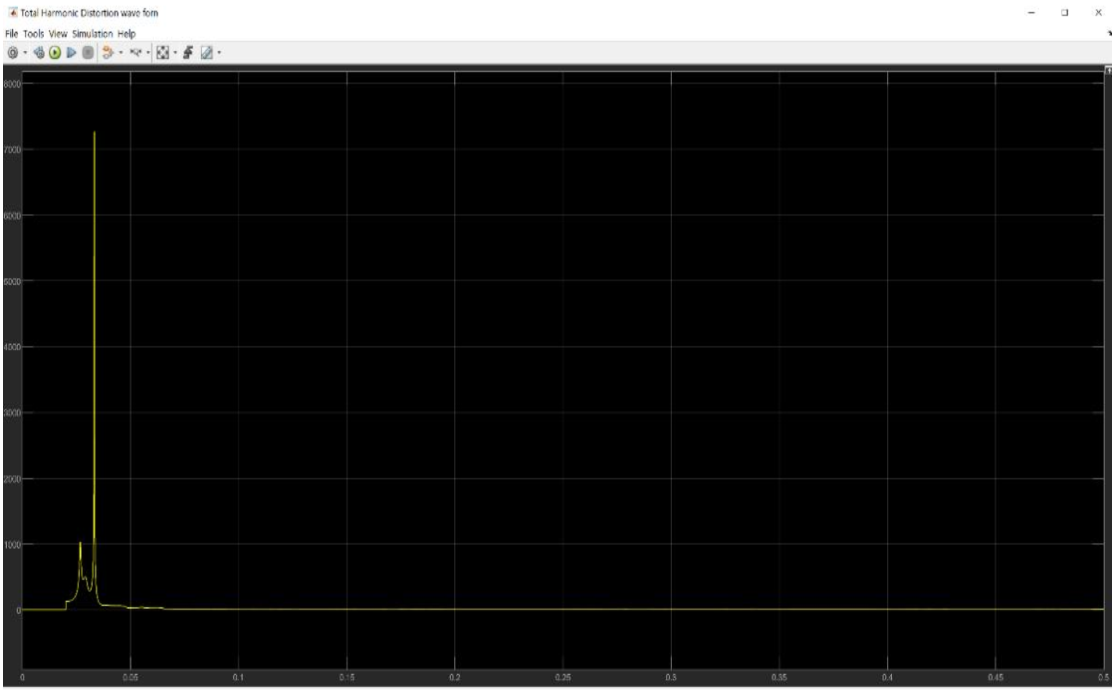


Figure 21: Waveform of Total Harmonic Distortion (THD).

The result shows an initial spike in harmonics within less than 0.05s due to the transient nature of the system and quickly reduces to 16.53; this engenders quality power supply.

4.3 Discussion

The system is simulated in 3 separate modules. The real BESS inverter will utilize all three functionalities in the same circuit with a unified central controller to control the analysis and operating algorithms. However, the three functionalities will not operate simultaneously, but the inverter will operate all three with minimal time intervals to avoid high system complexity and increased design and manufacturing costs. The operation algorithms are still patented by original equipment manufacturers.

CHAPTER 5

5 Conclusion and Recommendations

5.1 Conclusion

The integration of Battery Energy Storage systems into industrial facilities can significantly contribute to energy efficiency improvement and lower the cost of operation. It also helps to increase the lifetime of the infrastructure by lowering the stresses of inductive and non-linear loads.

A typical ROI period of such a system can vary depending on the size of the facility, and the status of the grid (i.e., the power factor, type of loads, and losses in the local system). However, with the increased global energy demand and climate challenges, it is becoming more important to invest in energy efficient systems in the short and long run.

The study has achieved its objectives. The ESS has been able to lower the peak power demand from the grid (peak shaving) from about 275kW to 150kW, the power factor of the system has been improved from 0.5272 to 0.9773 as a result of the installation of multilevel inverter and capacitor bank; and the resulting harmonics which usually accompany the conversion of DC to AC have been greatly reduced as a result of the passive filter circuit in the improved network.

5.2 Recommendations

From the findings arising from this research, the Holtab AB Factory should as a matter of necessity:

Option I: Install an Energy Storage System (ESS) in the existing PV plant as this will reduce much power consumption from the grid during peak production period and thus save production costs. This comes with additional improvements on the power quality and reduction in harmonics according to this study.

Option II: Incorporate a capacitor bank into the network to improve the power factor and hence, the quality of power supplied to loads.

- Install a passive filter into the system to suppress the harmonics arising from D.C. to AC conversion and sometimes, due to inductive loads.

Utilizing option II in Holtab local grid will require less investment but the peak shaving functionality cannot be achieved. The investment in option I will require a larger capital investment, but the financial payback time will be shorter and can be converted into positive commercial investment with higher system reliability and increased redundancy in case of grid outage. A proper ROI analysis is planned to be implemented in a separate study for Holtab's smart grid investment in BESS.

5.3 Future Works

The future works listed below relating to this research can provide a more comprehensive understanding of the benefits and challenges of integrating battery systems into industrial facilities with distributed energy generation, ultimately contributing to the advancement of sustainable energy solutions and improved power quality in industrial settings.

- ✓ Incorporate the necessary control systems for improved results

To enhance the performance and effectiveness of the battery system integration as studied, future research on this work should focus on the development and implementation of advanced control systems. These control systems could include optimized energy management, fault detection and diagnostics, grid interaction control and load shedding and prioritization.

- ✓ Calculate and study the return on investment (ROI)

Conducting a comprehensive financial analysis to assess the economic viability of the battery system integration is also necessary. This should involve cost-benefit analysis, energy savings estimation, ROI calculation and payback period.

- ✓ Pilot project test

Before full-scale implementation, conducting a pilot project to validate the findings in this research and assessing the practicality of the proposed battery system integration is also necessary. Consider the following aspects site selection, data collection, operational challenges, stakeholder feedback, scalability assessment.

References

[1] K. O. Uwho and H. N. Amadi, "Design And Simulation Of 500kw Grid Connected PV System for Faculty of Engineering, Rivers State University Using Pvsyst Software," 2022, Accessed: May 06, 2023. [Online]. Available: www.worldpopulation.com

[2] N. Keilman, "Data quality and accuracy of United Nations population projections, 1950-95," Popul Stud (NY), vol. 55, no. 2, pp. 149–164, 2001, doi: 10.1080/00324720127686.

[3] "Market Report Series: Renewables 2018 – Analysis - IEA." https://www.iea.org/reports/renewables-2018 (accessed Jan. 08, 2023).

[4] K. O. Uwho, H. N. Amadi, and C. O. Ahiakwo, "Loss, Performance and Carbon Analysis of the Grid-Connected PV System, Rivers State University using PV syst," Recent Trends in Control and Converter, vol. 5, no. 3, Dec. 2022, Accessed: May 06, 2023. [Online]. Available: http://hbrppublication.com/OJS/index.php/RTCC/article/view/2802

[5] M. Bortolini, M. Gamberi, and A. Graziani, "Technical and economic design of photovoltaic and battery energy storage system," Energy Convers Manag, vol. 86, pp. 81–92, Oct. 2014, doi: 10.1016/J.ENCONMAN.2014.04.089.

[6] R. S. Bhatia, S. P. Jain, D. K. Jain, and B. Singh, "Battery energy storage system for power conditioning of renewable energy sources," Proceedings of the International Conference on Power Electronics and Drive Systems, vol. 1, pp. 501–506, 2005, doi: 10.1109/PEDS.2005.1619738.

[7] K. Bradbury, L. Pratson, and D. Patiño-Echeverri, "Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets," Appl Energy, vol. 114, pp. 512–519, Feb. 2014, doi: 10.1016/J.APENERGY.2013.10.010.

[8] R. L. Fares and M. E. Webber, "A flexible model for economic operational management of grid battery energy storage," Energy, vol. 78, pp. 768–776, Dec. 2014, doi: 10.1016/J.ENERGY.2014.10.072.

[9] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," Renewable and Sustainable Energy Reviews, vol. 42, pp. 569–596, Feb. 2015, doi: 10.1016/J.RSER.2014.10.011.

[10] J. Leadbetter and L. Swan, "Battery storage system for residential electricity peak demand shaving," Energy Build, vol. 55, pp. 685–692, Dec. 2012, doi: 10.1016/J.ENBUILD.2012.09.035.

[11] A. Berrada and K. Loudiyi, "Optimal Modeling of Energy Storage System," International Journal of Modeling and Optimization, vol. 5, no. 1, pp. 71–77, Feb. 2015, doi: 10.7763/IJMO.2015.V5.439.

[12] M. Beaudin, H. Zareipour, A. Schellenberglabe, and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," Energy for Sustainable Development, vol. 14, no. 4, pp. 302–314, Dec. 2010, doi: 10.1016/J.ESD.2010.09.007.

[13] P. P. Barker and R. W. de Mello, "Determining the impact of distributed generation on power systems: Part 1 - Radial distribution systems," Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, vol. 3, pp. 1645–1656, 2000, doi: 10.1109/PESS.2000.868775.

[14] N. K. L. Dantas et al., "Impact Analysis of a Battery Energy Storage System Connected in Parallel to a Wind Farm," Energies 2022, Vol. 15, Page 4586, vol. 15, no. 13, p. 4586, Jun. 2022, doi: 10.3390/EN15134586.

[15] P. P. Barker and R. W. De Mello, "Determining the impact of distributed generation on power systems: Part 1 - Radial distribution systems," Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, vol. 3, pp. 1645–1656, 2000, doi: 10.1109/PESS.2000.868775.

[16] M. Bojrup, "Advanced Control of Active Filters in a Battery Charger Application".

[17] S. Khan Khadem, M. Basu, M. Conlon, S. K. Khadem, S. Member, and M. F. Conlon, "A Review of Parallel Operation of Active Power Filters in the Distributed Generation System," Conference papers, pp. 1–10, Sep. 2011, doi: https://doi.org/10.21427/D75F9N.

[18] A. M. Oo and P. Phyu Thae, "Power Factor Improvement for Tile Factory," 2019, Accessed: May 18, 2023. [Online]. Available: https://www.irejournals.com/formatedpaper/1701482.pdf

[19] I. A. Adejumobi, O. I. Adebisi, and S. A. Oyejide, "Developing small hydropower potentials for rural electrification.," International Journal of Research and Reviews in Applied Sciences, vol. 17, no. 1, pp. 105–110, 2013.

[20] R. K. Akikur, R. Saidur, H. W. Ping, and K. R. Ullah, “Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review,” Renewable and Sustainable Energy Reviews, vol. 27, pp. 738–752, Nov. 2013, doi: 10.1016/J.RSER.2013.06.043.

[21] A. Kasaeian, M. Feidt, S. Petrescu, and A. Mellit, “Solar Thermal Engineering,” International Journal of Photoenergy, vol. 2017, 2017, doi: 10.1155/2017/7493781.

[22] P. Mercier, R. Cherkaoui, and A. Oudalov, “Optimizing a battery energy storage system for frequency control application in an isolated power system,” IEEE Transactions on Power Systems, vol. 24, no. 3, pp. 1469–1477, 2009, doi: 10.1109/TPWRS.2009.2022997.

[23] Nayagam, V. Senthil. "Design of standalone PV system with Cuk converter." International Journal of Innovative Science and Engineering Research (IJISER) 7 (December (12)) (2020).

[24] Kai, D., et al. "Power quality comprehensive evaluation for low-voltage DC power distribution system." In 2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), pp. 1072-1077. IEEE, 2019.

[25] Pradip, C., et al. "Analysis of energy management in grid-connected residential PV system." International Journal of Innovative Science and Engineering Research (IJISER) 6 (July (7)) (2019).

[26] Mahela, O. P., et al. "Power quality improvement in renewable energy sources based power system using DSTATCOM supported by battery energy storage system." In 2019 Fifth International Conference on Electrical Energy Systems (ICEES), pp. 1-6. IEEE, 2019.

[27] Wu, Z., et al. "Comprehensive evaluation of power supply quality for power sale companies considering customized service." In 2018 International Conference on Power System Technology (POWERCON), pp. 734-739. IEEE, 2018.

[28] Peter, A. G., and K. A. Saha. "Comparative study of harmonics reduction and power factor enhancement of six and 12-pulses HVDC system using passive and shunt APFs harmonic filters." In 2018 International Conference on the Domestic Use of Energy (DUE), pp. 1-10. IEEE, 2018.

[29] R. B. N., V. G. R. M., and S. R. R., “Battery energy integrated active power filter for harmonic compensation and active power injection,” Sustainable Computing: Informatics and Systems, vol. 35, p. 100664, Sep. 2022, doi:

10.1016/J.SUSCOM.2022.100664. [9] Rajesh Babu, N., et al. "A Case Study on Improvement of Power Factor of an Industrial Load."

[30] M.G. Molina, P.E. Mercado, Control design and simulation of DSTATCOM with energy storage for power quality improvements, in: 2006 IEEE/PES Transmission & Distribution Conference and Exposition: Latin America, Caracas, 2006, pp. 1–7.

[31] Anzari M., Meenakshi J., Dr. Sreedevi V.T. "Simulation of A Transistor Clamped H-Bridge Multilevel Inverter and Its Comparison With A Conventional H-Bridge Multilevel Inverter." 2014 IEEE International Conference On Circuit, Power and Computing Technologies (ICCPCT).

[32] Y. Shi, B. Xu, D. Wang, and B. Zhang, “Using Battery Storage for Peak Shaving and Frequency Regulation: Joint Optimization for Superlinear Gains,” IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 2882–2894, May 2018, doi: 10.1109/TPWRS.2017.2749512.

[33] L. Feng et al., “Optimization analysis of energy storage application based on electricity price arbitrage and ancillary services,” J Energy Storage, vol. 55, Nov. 2022, doi: 10.1016/J.EST.2022.105508.

[34] X. Xi, R. Sioshansi, and V. Marano, “A stochastic dynamic programming model for co-optimization of distributed energy storage,” Energy Systems, vol. 5, no. 3, pp. 475–505, 2014.

[35] Guo, Y., & Fang, Y. (2013). Electricity cost saving strategy in data centers by using energy storage. IEEE Transactions on Parallel and Distributed Systems, 24, 1149–1160.

[36] Wang, Y., Wang, B., Chu, C. C., Pota, H., & Gadh, R. (2016). Energy management for a commercial building microgrid with stationary and mobile battery storage. Energy and Buildings, 116, 141–150.

[37] Worthmann, K., Kellett, C. M., Braun, P., Grün, L., & Weller, S. R. (2015). Distributed and decentralized control of residential energy systems incorporating battery storage. IEEE Transactions on Smart Grid, 6(4), 1914–1923.

[38] “Temperature Effects on PHI Batteries vs. Lead Acid | Briggs & Stratton Energy Solutions.” https://simpliphipower.com/company/news/blog/temperature-effects-on-phi-batteries-vs-lead-acid/ (accessed Aug. 17, 2023).

[39] "Battery 101 Three Things Need Know Lead Acid Batteries | Northeast Battery Blog." https://northeastbattery.com/battery-101-three-things-need-know-lead-acid-batteries/ (accessed Aug. 17, 2023).

[40] "Normal Inverters and Solar Inverters: What's the Difference?" https://www.upsinverter.com/normal-inverters-and-solar-inverters-whats-the-difference/ (accessed Aug. 17, 2023).

Appendix 1

_design.m

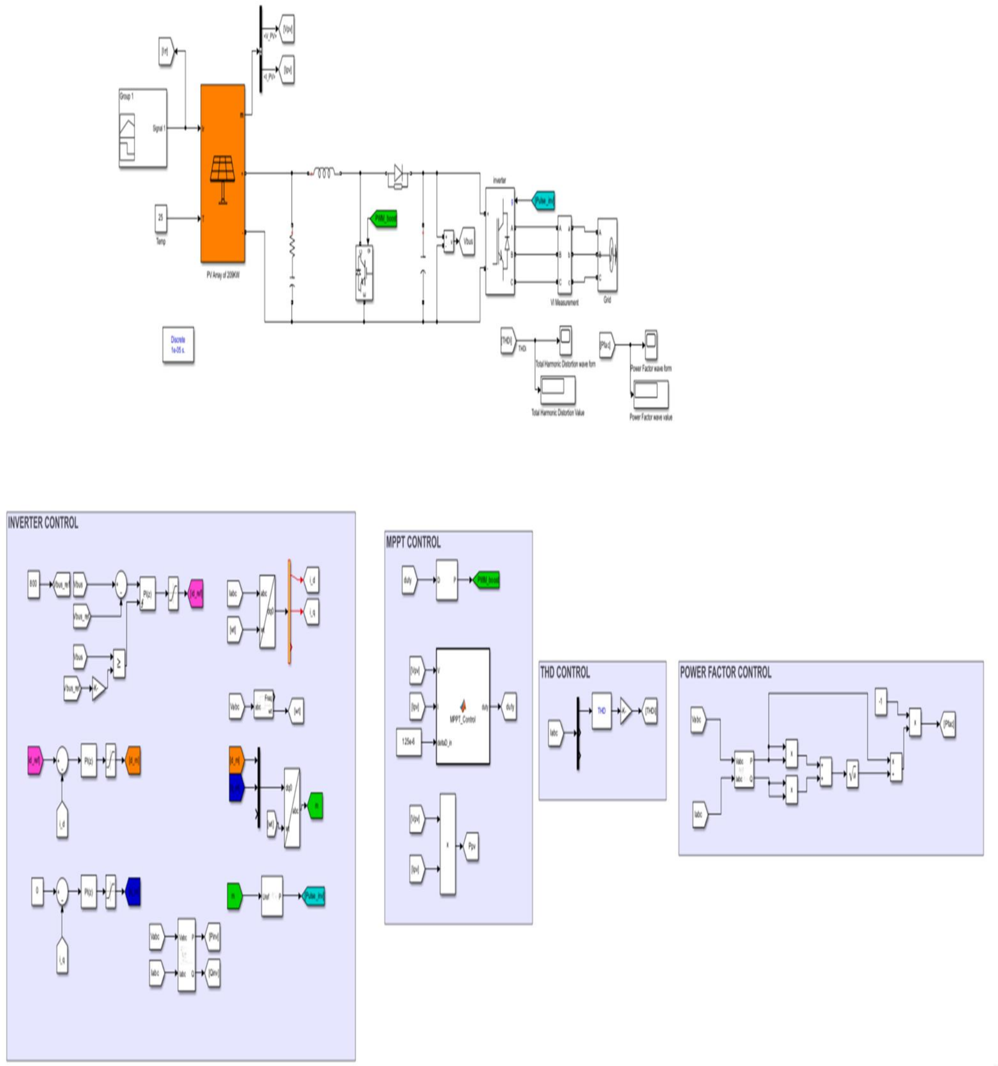
```
%Author: Vitalis & Mulham
clear
clc
Ts=10e-6;   %sampling time
P=209e3;     %Rated Power
U=380;      %inverter phase2phase voltage
f=50;        %grid frequency
fsw=5e3;    %switching frequency

Lf=((0.1*U^2)/(2*pi*f*(P/3)));

%design of boost converter
Vmpp=406;
V_bus_ref=800;
Vin=Vmpp;        %input voltage of boost converter
Vo=V_bus_ref;    %output voltage of boost converter
fsw_boost=5e3;  %switching frequency of boost converter
D=1-(Vin/Vo);
L_bound=((1-D)^2)*D*(Vo^2)/(2*fsw_boost*P);
L_boost=10*L_bound;
C_boost_min=(D*P)/(0.01*Vo^2*fsw_boost);
C_boost=1000e-6;
```

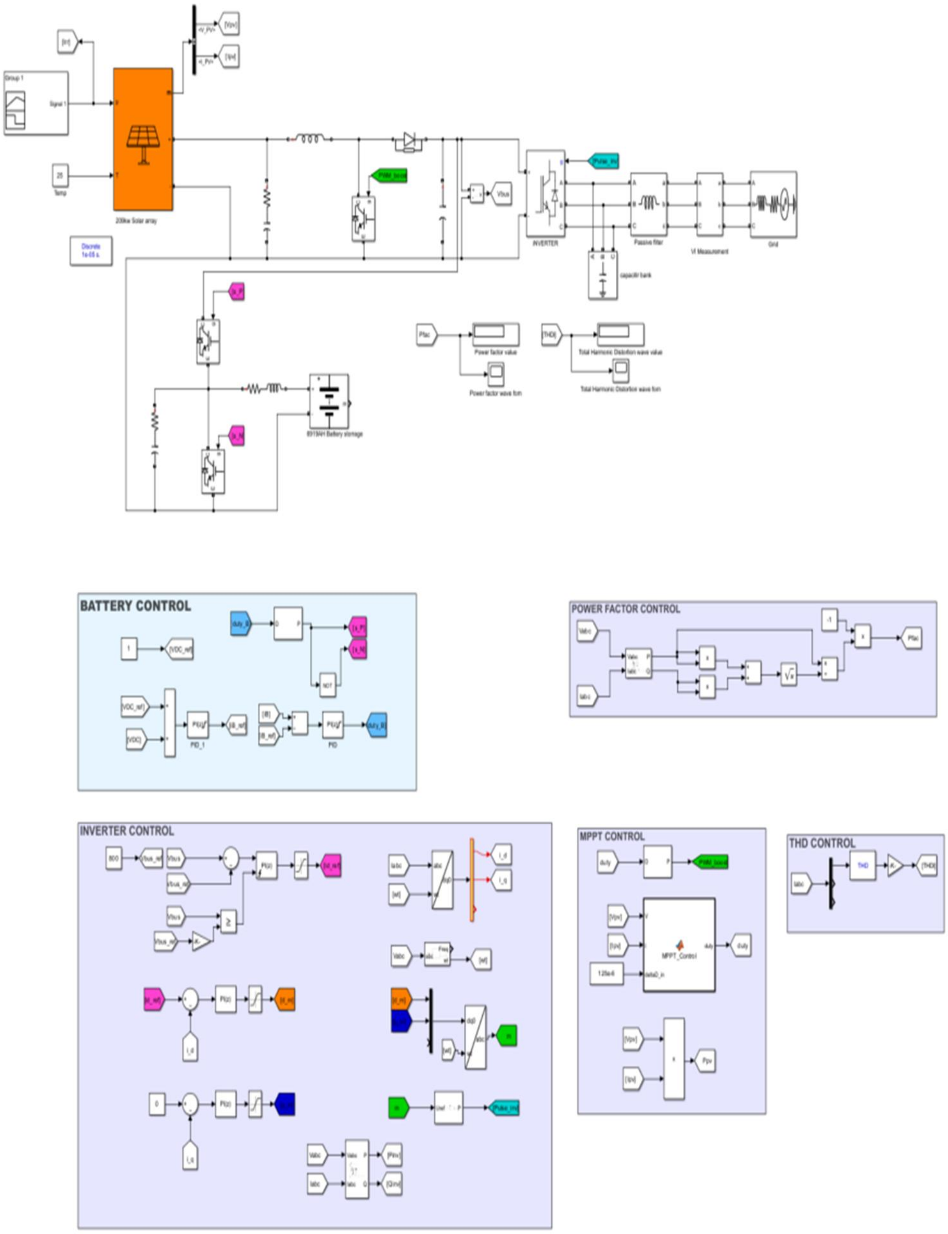
MATLAB filter design simulation

Appendix 2



MATLAB/SIMULINK implementation the power system without battery

Appendix 3



MATLAB/SIMULINK implementation the power system with battery