Technical and Economic Evaluation of a Community based Hybrid Power System

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Abstract

Trends in increasing power production in distributed grids change structure in conventional power systems. Integration of renewable power sources and energy storage solutions in grid-connected energy systems results in the development of hybrid energy systems. Hybrid energy systems implementation is important because of their potential to decrease intermittency, but it has to operate in a clean, economically viable, and reliable manner. This thesis investigates the impact of a hybrid system in the distributed, grid-connected system and the main goal of the thesis is to conduct optimized scheduling of hybrid system to investigate potential techno-economic benefits. Simulating steady-state analysis, optimal scheduling and dynamic stability of the system expands benefits to the plant owners, community, and distribution system operator.

Preface

The Masters' thesis titled "Technical and Economic Evaluation of Hybrid Power System" has been written by Josip Mrcela in the 10th semester at the Department of Energy Technology, Aalborg University in the period of February to May of 2021.

The thesis was supervised by Jayakrishnan Radhakrishna Pillai, Associate Professor at the Department of Energy Technology. Personally, I would like to thank the supervisor for continuous guidance, knowledge sharing, and exceptional motivation throughout the thesis writing.

I would also like to express gratitude towards my parents Anica and Zoran with my brother and sister Ivan and Mia for supporting me to achieve this milestone, I herewith dedicate this thesis to my beloved family.

Student signature - Josip Mrcela

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1 Introduction

In today's conventional electrical energy grid, most of the electricity is produced by large generating units. Large generation plants transmit electricity through high voltage transmission lines where on the other end voltage is decreased from HV to MV. MV levels correspond to the distribution network where power is transmitted to the consumers. Some of the production is generated at distribution levels close to the consumers. This distributed production is called a distributed generation (DG) [1].

Even though distributed generation is small compared to large power generation plants, these technologies play crucial factors in power systems. Some major factors include increasing reliability to the system, emergency capacity, and an alternative expansion to the system. Governmental policies favoring combined heat and power generation, and renewable sources assure that DG will continue to represent more and more impact on the power systems. Figure 1.1 represents future developments expected as distributed generation increases its role in power generation.

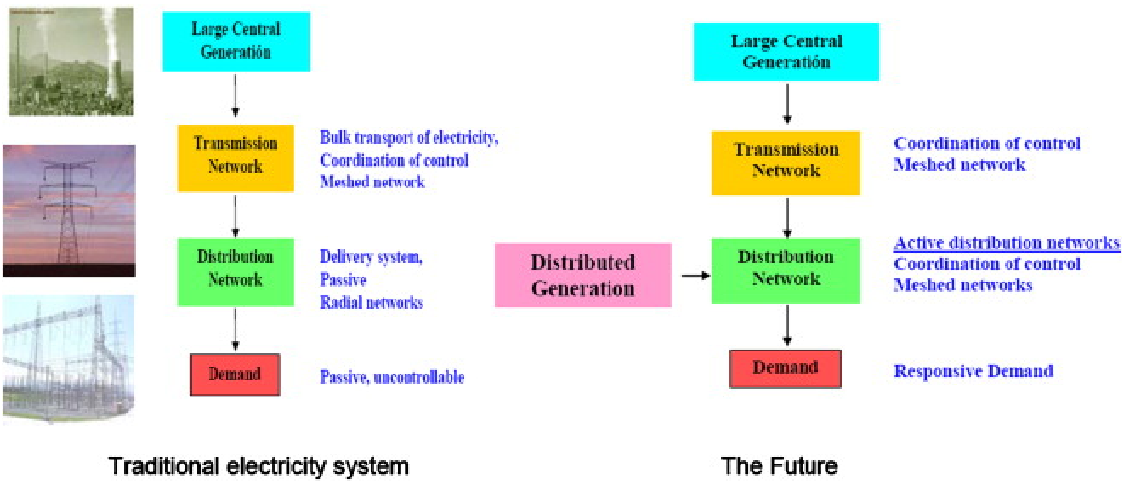

Figure 1.1: Schematics of implementation of distributed generation in the power system [2]

1.1 Distributed generation

The distributed generation does not have a strict definition, but the most widely used definition is as follows: DG is a relatively small generating unit installed close to load centers. For example, installed Croatian HPP has the power of 576 MW and investigated power plant is 500kW hydro and 500kW solar [3]. Technological innovations and changes in the economic and regulatory environment have increased the focus on DG. This is confirmed by IEA (International Energy Agency) which in 2002 published Distributed Generation in Liberalised Electricity Markets and addressed DG implementation in a modern power system [4].

In the published book IEA concludes 5 major factors that contribute to the DG evolution and those are:

- developments in DG technologies
- constraints on the construction of new transmission lines
- increased customer demand for highly reliable electricity
- the electricity market liberalization
- concerns about climate change

If DG is utilized correctly many benefits can be achieved. DG can provide benefits to consumers and utilities as well, most beneficial are systems with unavailability to connect to big generation units. DG allows independent producers to install capacities on a smaller scale and it might improve system reliability and stability.

Major benefits of distributed generation sources are [5]:

- increased penetration of RES and other sources which diversifies energy portfolio
- wide utilization of RES will reduce fossil fuel consumption and greenhouse emissions, consequently benefiting the environment
- efficient CHP and backup peak-load systems increase capacity. Also improving system efficiency by using waste heat
- enables transmission lines to be less congested, therefore lower transmission losses, and also postpone erecting new transmission lines
- production close to consumers can also improve voltage stability to areas where voltage support is difficult

DG can also give some technical problems [6]:

- energy flow can be reversed to the transmission system, therefore power quality and stability can be affected
- DG increases voltage level in the distribution network, this can be beneficial if voltages are low, but also, if voltages are nominal, an increase of voltages due to DG can cause issues
- managing reactive power might be an issue, DG sometimes use asynchronous generators that cannot provide reactive power
- DG can cause protection equipment redundancy issues. Under certain conditions, DG can create difficulty in managing the protection scheme to the overall system. For example, a short circuit

does not flow only from the main power grid, but also from DG units, therefore a more complex protection scheme is required to achieve selectivity [6].

- if power converters are used, power quality can be affected (high harmonics injected into the system) and also, power harmonics do not possess any inertia therefore if rapid power imbalance is present frequency does not have "buffer" therefore drops immediately

Distributed generation has a lot of interest recognized by international agencies. Implementation of distributed generation has many benefits, while also if not implemented carefully can have many drawbacks which must be considered (implementation of BESS, FACTS, hybrid systems, virtual power plants, and others). This project has the purpose of implementing distributed generation as a combination of hydro and solar power generation. Combining more power sources as one production plant is called a hybrid power system. The hybrid system can offer solutions to the challenges stated above. The next section gives insights into these types of power production units.

1.2 Hybrid power system

As already established, DG will have an impact on future power systems. While implementation of DG in the system can be beneficial, trends in using environmentally friendly solutions can offer their drawbacks. The nature of unpredictable generation based on wind and solar irradiation brings more issues in the control of the power systems.

Issues in renewable power sources can be compensated by implementing more than one power source as one generating unit. Combining two or more power sources into one is called a hybrid power system. Hybrid power systems can offer more reliable and convenient production by having a control system that utilizes most of each power production energy. Hybrid energy generating units along with control systems usually have storage systems, this offers robust and safe energy dispatch whenever possible. A general example of the hybrid power plant is shown in Figure 3.2.

Achieving smooth and robust operation of hybrid power plant might be challenging to develop, but with understanding each of the power sources in the system, one drawback of the power source can compensate with another. This is the central idea of having a hybrid power system.

Application of the hybrid power system can be categorized into the following [8]:

- remote ac networks
- distributed generation application
- isolated or special purpose electrical loads (for water pumping, desalination, etc.)

The typical hybrid power system is based on the combination of diesel generators with wind or solar

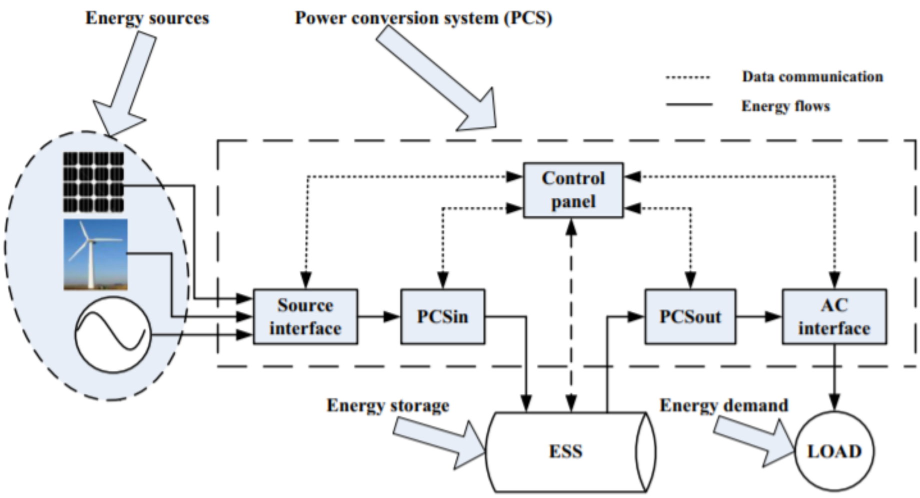

Figure 1.2: Example of a hybrid power system [7]

power plants [8]. The goal of this system would be to decrease fuel consumption as much as possible by producing power from renewable sources. This idea of the hybrid power system in practice would not achieve desired goals if one or more of the following are not implemented: supervisory control system, energy storage, and load management. Only with these technologies, the hybrid power system can work in harmony [8].

As basic principles of distributed generation and hybrid power systems are explained. One major factor including the operability and economic dispatch of these types of systems is the energy market. The energy market which will be investigated only for grid-connected hybrid systems, as for islanded systems different scheme is utilized.

1.3 Energy market in electrical power systems

The development of hybrid power systems as a part of DG largely depends on the financial aspect of the system. Implementing various sources of energy as hybrid power plants has to have economic value to the investing bodies whose goal is to achieve economic profitability while contributing to the decarbonization of the energy system. This is achieved by deregulating the electricity market where electricity suppliers try to find niches in the market, and where consumers consequently search for suitable energy service [4].

Electricity production has to be sold to the energy market at some price. Energy markets can be either regulated or deregulated. The regulated energy market has fixed tariffs based on a unit of produced energy for a fixed purchasing price. Depending on the generation source, different price points are given for the producers, therefore in this scenario individual producer of energy sells energy with a defined price per energy unit (for example, for small HPP (less than 500kW) price is 0.12eur/kWh while for small SPP (less than 30kW) is 0.26eur/kWh). On the other hand, the deregulated market does not have a fixed price for production. This price change is driven by the demand and supply of the commodity. Deregulated electricity market usually has a pattern of highest energy price during peak (afternoon) hours and lowest during the night.

In this project, a regulated market will be investigated first to achieve power production under the stipulated grid code. Further, the implementation of deregulated market structure will be explored to optimize the work of the hybrid power system.

1.4 Problem formulation

Investigation of the small-scale hydro/solar power production is of importance to determine possible benefits of community, investor, environment, and the grid operator. While it can offer many positive outcomes, it is also challenging to develop reliable, safe, robust, and efficient operations. Operating a hybrid power system has to be a combination of different aspects to be able to satisfy all of its constraints.

This project tends to achieve the best performance by following grid code to reliably operate, optimize power production in respect to available energy, scale the system accordingly to be economically viable, and determine dynamic response to keep the grid stable.

1.5 Objective

The objective of this project is to conduct optimized scheduling, economic operation, and distribution grid integration studies of a hybrid power system.

The hybrid energy system comprises a small hydropower plant, solar power plant end energy storage. The optimized integration of the hybrid power system in the local grid ensuring economic scheduling, harmonized operation, and meeting system operation and steady-state requirements are emphasized. The case study applied in this project is based on a partly remote small city located in Croatia, and further, the economic benefits for the hybrid power plant owner and indirect benefits of the community and grid utility are analyzed. Further, this project scope is constituted out of 4 areas:

- State-of-the-art analysis of the technical and economical evaluation of hybrid power systems, operational, control and electricity pricing schemes.
- Modeling of hybrid power systems and local power distribution networks, and grid impact assessment of the hybrid system.
- Develop economic scheduling of the local hybrid power system for the cost-effective and synergy operation utilizing the complementary nature of renewable-based distributed generation units

and flexibility from energy storage options.

- Model and conduct system frequency stability studies to ascertain the reliable operation of the hybrid power system meeting the technical requirements during normal operation.

1.6 Methodology

Methodology in modeling, simulations, data, and software utilized in this thesis is listed as:

- Distributed system production and demand data acquisition and processing using MATLAB software
- Modeling system individual model components for simulation purposes
- Distributed system load flow and quasi-dynamic analysis simulations using PowerFactory - DIgSILENT software
- Data acquisition of electricity price market with supply-demand data from quasi-dynamic analysis
- Optimised scheduling of hybrid power plant using MATLAB software
- Modeling individual components and frequency stability using MATLAB Simulink software

1.7 Limitations

The thesis limitations are given as:

- Load and production data are utilized and adjusted with external sources
- Modeling of individual components are simplified
- Data for river discharge and hydro-generator efficiency production is interpolated
- Optimised scheduling utilizes exact production data and day-ahead market data and their uncertainty is not considered
- Frequency response models consider only hybrid power plant as an energy source

1.8 Outline of thesis

The thesis is grouped into 7 chapters, a brief overview of each is outlined:

1. Introduction - A short outline of the given thesis theme is given, including objective, methodology, and limitations.
2. Trends in the future distributed power system - Investigation on current research investigations on distributed systems, distributed generation. An overview of current/future market schemes, governmental policies, and grid code regulations.
3. Distribution Grid Analysis Involving Hybrid Power Plant - Investigation on effects of the hybrid power plant in an existing grid with modeling and simulations. Addressing distributed system conditions concerning the current electricity market structure and its pros/cons.

4. Optimised scheduling of hybrid power plant - Effects and possible solutions in new electricity market schemes, different scenarios, and scheduling optimization with maximizing profits is conducted.
5. Dynamic stability of HES - This chapter describes and investigates the frequency stability of an islanded hybrid power plant. Intermittency in demand and production is investigated with respect to the grid code.
6. Discussion and future work - brief results and outcome of the thesis, possible further improvements on existing work, problems and solutions in distributed generation, and benefits of hybrid power plants are discussed.
7. Conclusion - Overview of important findings decomposed by each chapter of the thesis.

2 | Trends in future distributed power systems

2.1 Future distributed system

Current trends in increasing importance in DG are already evident as stated in 1, but predicting the degree of DG impact in the power systems is still debatable among the researchers [9]. Based on current estimates possible level DG implementations are shown in Figure 2.1. The figure shows potential scenarios from centralized power systems to fully decentralized where decentralization provides energy locally and utilizes and controls the same energy locally.

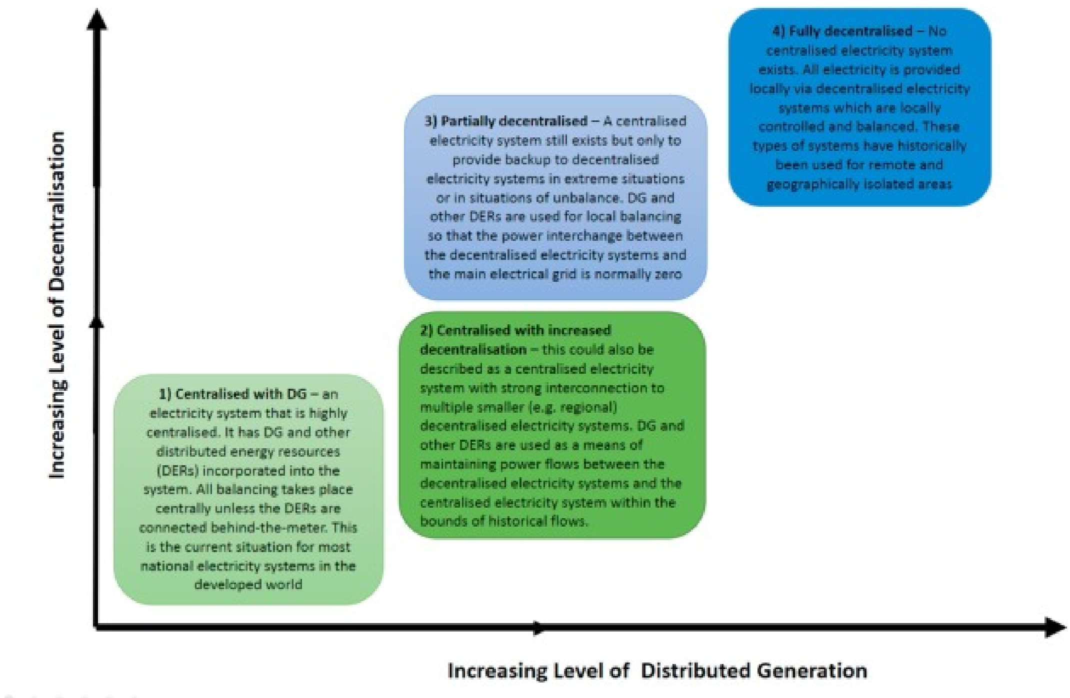

Figure 2.1: Decentralisation of power systems

Further developments of DG is driven by many factors as already mentioned in 1, these factors include higher energy demand [10], governmental policies [11], market liberalisation [12], lower capital cost [13] and regulation [14]. Another type of DG driver is the technical aspect which includes fewer losses since production is close to consumption [15], improved voltage regulation [16], increased reliability of production [17]. This is true only if DGs are installed optimally, higher-level other than optimal or sub-optimal planning can introduce problems in the system all these factors will define future DG implementation.

Prediction on level of DG implementation can be structured in 6 categories, each of them is shortly described [9]:

1. Geographical and climatic considerations and availability of resources - the geographical area will have a significant influence on the feasibility of implementation of DGs. Resource allocation based on climate and terrain will also play crucial factors but, generally, this is already very well understood and investigated therefore is a low level of uncertainty on further developments
2. Existing infrastructure - Existing power system and its reliability will have an impact on DG utilization, in well-established power systems, utilization of DG-s has to be able to transfer power on log distances. In opposition to this, areas with unreliable power systems, stand-alone DG-s make a more suitable case. Other factors include availability to interconnections, communication system between areas, and others.
3. Technological Change and Progress related to heat, Transport, and Storage - Advances in emerging markets such as electric vehicles, heat pumps, changes in transport and heat sectors are predicted to have a high impact on electricity demand. CHP implementation and district heating are highly dependent on population density, therefore its economic value is not justified in all locations.

   Implementing storage devices with DG-s improves system reliability and reduces generation cost and system losses. Therefore the availability of storage solutions will also influence DG implementation. Overall interactions between transport, heat, and electricity are being closely investigated.
4. Social factors and demand response Deployment of DG-s depends also on social acceptance and consumer behavior. Price schemes, type of DG-s technologies will be considered by the community therefore, lower electricity prices, high renewable penetration is current awareness of most of the communities. Deregulation of electricity markets will influence demand response, new more active price schemes are being implemented where consumer price is changed from 2-3 tariff schemes to the hourly scheme. Load demand will, as a consequence be different with a push from peak demand hours at a high price, to lower-priced hours.

Investigation of future decentralized power system based is analyzed in Chapter **??**, where optimum power dispatch is driven by energy market which is fundamentally driven by power demand. Future considerations and market changes are investigated.

With future trends in DG implementation discussed and major driving factors, the governmental law framework has to be considered in order to adhere to current trends.

2.2 Law framework for renewable sources

Investigation on policies and goals of the Croatian government is firmly described in Law on Renewable Energy Sources and High-Efficiency Co-generation - NN 100/2015. A brief overview is given to understand national goals in the renewable sector.

With NN 100/2015 planning and encouragement of production and consumption of electrical energy in production plants that utilize renewable sources and high-efficiency co-generation (in further text ESEC) is defined. Also this document structures system of privileged producers from the same sources, international cooperation on renewable energy sources, and among others questions on the importance of deploying ESEC. Parallel to this law, another important regulatory body that defines guidelines is the grid operator.

The goal of the law is to reach the National plan in penetration of ESEC, decrease the import of energy, efficient usage of electrical energy, decrease fossil fuel consumption, open new jobs in the sector, increase new and innovative technologies with the contribution to the local communities and to diversify energy production.

Framework on which private renewable producer can approach on receiving financial returns by selling renewable electrical energy is by examining given quotas for each renewable sector (on the national level number of possible MW installations per year is defined). Secondly, if the proposed power plant can utilize part of defined quotas, a proposed power plant can apply for receiving privileged pricing per produced kWh. Many technical details and project feasibility is given by the grid operator to address potential problems regarding grid constraints.

After law regulations addressing the implementation of HES, the system has to convey evaluation criteria which subject to multiple points of view of HES feasibility.

2.3 Evaluation criteria

In order to effectively approach to the design of HES evaluation criteria must be conducted. Evaluation criteria can be divided into 4 categories shown in Figure 2.2 [7].

1. Technological factors - are concerned directly by factors of implementation with grid influence of the system. Feasibility, risk, reliability, operation, and performance must be considered.
2. Economic factors - evaluate cost, funds, rate of return, benefit/cost, and others.
3. Socio-political factors - integrating HES has to be accessed by acceptance of community, political acceptance, compatibility with national energy policy, and labor impact. Investigation of this

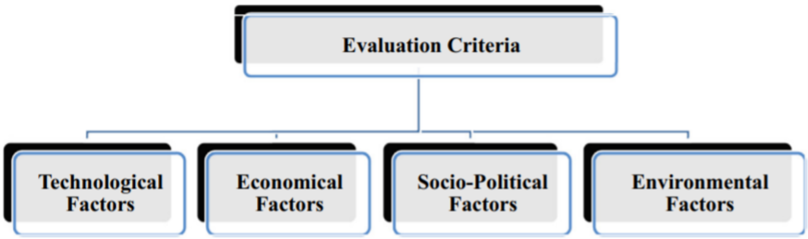

Figure 2.2: Distributed generation [7]

criteria is therefore important to follow current trends and to evaluate the acceptance of the grid operator and community.

4. Environmental factors - address the pollutant emissions, land requirements, and damage to the environment.

The contribution of each of the segments should be considered in acceptance of all criteria to achieve most of all of the aspects, but for purpose of this project techno-economic evaluation is the focus. The proposed hybrid system has to be investigated from a steady-state point of view and this is done by investigating grid code. Grid code defines rules under which power plants must operate to keep the distribution system stable.

2.4 Grid code

A grid code is a law document defining technical specifications of the power plant/consumer to meet requirements of safe, secure, and proper functioning of the subject for connecting to the electric grid. The grid code is given by the grid operator which in Croatia is the HEP group.

The grid code technical specifications for utilized power plant given in NN 74/2018, this law enforces grid code for connection to 0.4/10/20/30/35 kV voltage levels which is under the Distribution system operator (HEP ODS).

Under planning of the connection to the distribution network fundamental factors have to be within certain constraints for electrical variables:

- frequency (under HRN EN 50160)
- nominal voltage (under HRN EN 50160)
- grounding - given by the DSO
- short circuit currents (DSO gives expected SC currents)
- insulation level (given by DSO on voltage level and insulation coordination)
- protection of failure (DSO informs the user of network on protection devices and their settings so that power plant/consumer can set equipment accordingly)

For the purpose of this project, further specifications on voltage and frequency stability are given, all of the parameters are used from EN 50549-2018 norm and parameters are valid under normal operating conditions [18].

- Nominal operating frequency: +/- 0.5 Hz
- Nominal operating voltage: +/-5 % for MV and +/- 8 % for LV
- Power factor range: 0.95 inductive to 1
- Power change at connecting and disconnecting has to be lower than 10% of nominal power per minute

With grid code definitions, further simulations and design will be investigated under these limitations in Chapter 3. A hybrid power plant should not contribute to disturbances in the distribution network more than it is defined. If for some reason distribution network parameters are above-defined conditions, further rules are applied but this is not under the scope of the project.

When steady-state analysis based on the grid code is conducted, optimized scheduling is done by implementing a new deregulated market structure. The market structure depends on the electricity market where electricity is traded, this is of further importance to the economic evaluation of hybrid power plants.

2.5 Electricity market structure

Electrical energy production in Croatia can be sold in two ways. Firstly privileged producers (renewable sources) can contract with DSO to purchase all of the produced energy with a fixed tariff (regulated market), and secondly, energy can be traded on the electricity market (deregulated market).

The privileged system emerged as a governmental subsidy to the renewable energy producers to further accelerate energy transition to more sustainable energy sources. The consequences of this privileged pricing model generated changes in numerous ways. Firstly, the consumer price of electricity was increased by 10% in order for DSO to be able to pay privileged producers, secondly the energy contract is not time-dependent, therefore producers tend to sell electricity in the highest capacity possible. From a power system standpoint, this can generate system regulation issues because the demand/supply of electricity is not met. Lastly, this model is unfeasible because if many producers enter the market with privileged prices, consumer electricity has to rise. This unsustainable market structure will change in future power systems where energy is traded daily and this will, in fact, lead to lower energy prices for consumers, better demand/production, lower system losses, and others.

The second energy arbitrage structure CROPEX [19] will be of interest because it is more focused on private entities willing to trade the market. Currently, there are two energy market schemes active on CROPEX, the day-ahead market, and the intraday market. In the day-ahead market electricity producers/re-sellers bid on the market based on DSO-s predicted model on how much MWh is needed to meet the demand. Energy producers place orders so that they bet on the lowest profitable production that they can achieve, this means that for example, nuclear power plants will bid high prices, and solar power plants low prices. This bidding is shown in Figure 2.3. The figure shows all bids in blue and all ask prices in red for a specific hour in the day-ahead market. Market converged at 29.4 EUR for 240MWh of energy, this means that all of the bidders of energy will be paid 29.4 EUR for each MWh, and all buyers will have to pay for the same price.

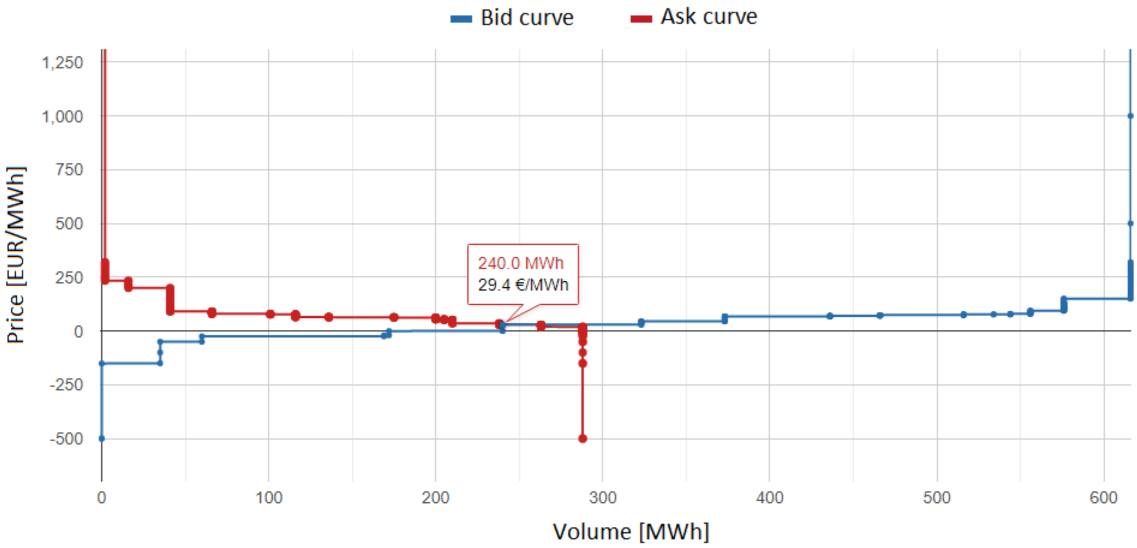

Figure 2.3: Energy orders on CROPEX [20]

With this process of bid/ask for each hour, day-ahead prices are formed. This process starts at 10 to 12 AM each day for prices in the next day to be formed. This means that no market participant knows the price when energy is traded. After 12 AM, the market algorithm allocates energy based on grid constraints and the resulting market is visible as shown in Figure 2.4. Price varies each hour from approximately 50 to 100 EUR/MWh.

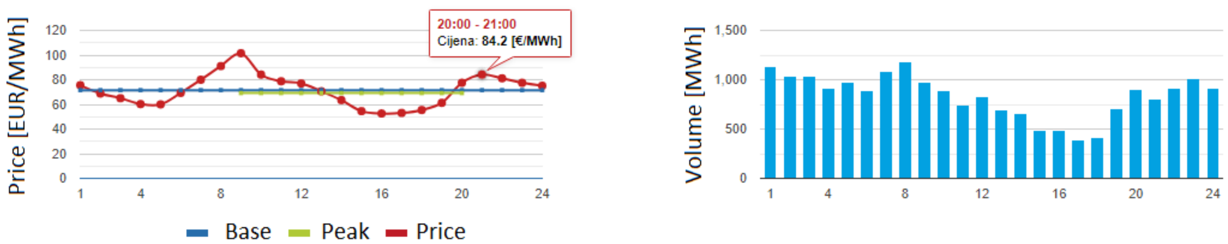

Figure 2.4: Day ahead market on CROPEX [21]

This structure leads market participants to develop complex algorithms on how to predict market price and how to predict power production (for renewable sources weather data) to maximize profits. Power production from the hybrid power plant is also crucial for future power systems because optimal scheduling must be conducted to be efficient on the market.

The second market on CROBEX is the intraday market which focuses on hourly misjudged energy consumption/production, any misalignment due to prediction errors is traded, and participants "fill" the error by payments of participant with the wrong prediction. The intraday market will not be part of the investigation for this project, optimised scheduling based on the day-ahead market is conducted. This way owner of the power plant is being involved in electricity trading where its interest is to earn profit based on predicting day ahead prices.

2.6 Optimised scheduling

Hybrid energy systems constituting of many different components can be difficult to optimize because of many limitations in the means of operability, efficiency, economic benefit, and others. A high level of research is being conducted to optimally operate, control, and schedule HES [22]. Different topics including reviewing the optimal operation, optimization of distributed systems, microgrids optimization, application of artificial intelligence, and optimization of HES have been done [22].

Optimization of hybrid energy systems is an important matter in the means of efficient, economic, renewable, and reliable energy supply. Optimal hybrid energy system designing should convey under multiple goals and therefore multi-objective optimizations are implemented. Current research on optimization of hybrid systems is typically divided into stand-alone or grid-connected systems, number and type of objective functions, renewable or diesel-renewable hybrid systems, and multi-energy systems.

HES with BESS accumulate excess power and release it if required to the grid [23]. In addition, HES can increase the profitability of DGs in grid-connected systems by saving the extra energy at the periods that electricity price is low and sell it back to the main grid at the periods that electricity price is high [24].

In this thesis, the applied objective functions, design constraints, and decision variables in the optimization of hybrid energy systems are developed to optimally schedule hybrid energy system energy dispatch in the day-ahead market.

There are two general approaches on how to optimally schedule the hybrid power system [25]:

- Conventional approach - this approach tends to control power supply according to the demand.

One of the solutions is to generate as much renewable power as possible and different control algorithms are developed for different hybrid systems.

- Using expert system - intermittency in renewable power production cause disturbance in power quality delivered to the load. Power flow management is therefore needed to develop advanced controlling techniques. This is investigated with the implementation of artificial intelligence or expert systems. Some developed control systems utilize Fuzzy logic control techniques, genetic algorithms, a combination of both, etc.

On the mentioned approaches listed above, research is focused on design, operation, and performance analysis. Hybrid system performance is investigated so that individual components are modeled and afterward, their mix is evaluated to meet demand reliably. Voltage variation, frequency, waveform, and power factor must be maintained within the limits according to the grid code, therefore control systems tend to be more and more complex due to many restrictions and optimization parameters [25].

With optimum scheduling of the HES, its impact on the dynamic stability of the system will have to be analyzed in Chapter 5. By the grid code frequency has to stay within a narrow range, therefore the impact of HES must not generate further disturbances in the power system.

2.7 Conclusion

The uprise of DG and hybrid energy systems led to much scientific research being published to maximize its implementation into the grid. Future power systems liberalization is still under researches debate but it is evident that DG will impact power systems more than today.

Promising implementation of DG as a hybrid energy system seems to be able to adhere to problems of intermittency of renewable sources but it is necessary to optimally control the power plant. Due to lower incentives of governments to renewable energy, hybrid energy systems need to adapt to new market structures while following the grid code to be able to operate in a safe and robust manner.

Implementation of many DG-s in the distribution grid can cause drawbacks in the energy quality and can cause unwanted technical problems such as high voltages and power losses. Investigating HES impact in the grid is the goal of the next chapter.

3 | Distribution Grid Analysis Involving Hybrid Power Plant

This chapter describes and investigates an electric distributed system where a hybrid power plant is being implemented. Firstly, system description is given with all of the elements in the system, this includes transformers, generation plants, loads, and cables/over-headlines. Further, hybrid system components, location in the grid, and all essential data are generated. Lastly, static analysis of the electric distribution grid involving a hybrid power plant is done in two ways, power flow, and quasi-dynamic simulation. With simulations, major system bottlenecks, power flow, and power losses are identified.

3.1 Distributed grid specification

Distributed system model under consideration is given in Figure 4.3. System voltage is 20kV and connection with transmission system is via 110/20 kV transformer. The system has a ring distribution structure, this is a typical configuration that offers supply to consumers even if some of the lines disconnect due to fault or maintenance.

The location of the hybrid power plant is shown in Figure 3.1 where busbar BG10 connects solar power plant, storage system, hydropower plant, and self-consumption of the plant. The hybrid system is further connected with 20/0.4 kV transformer TR4. The distributed system has preexisting power plants listed in Table 3.1 below (where the solar power plant is denoted as SPP). Existing power plants include CHP biomass power plants and hydropower plant. CHP power plant operates at installed power at all times according to the Croatian Energy Regulatory Agency [26] [27], this continuous power generation is not environmentally friendly.

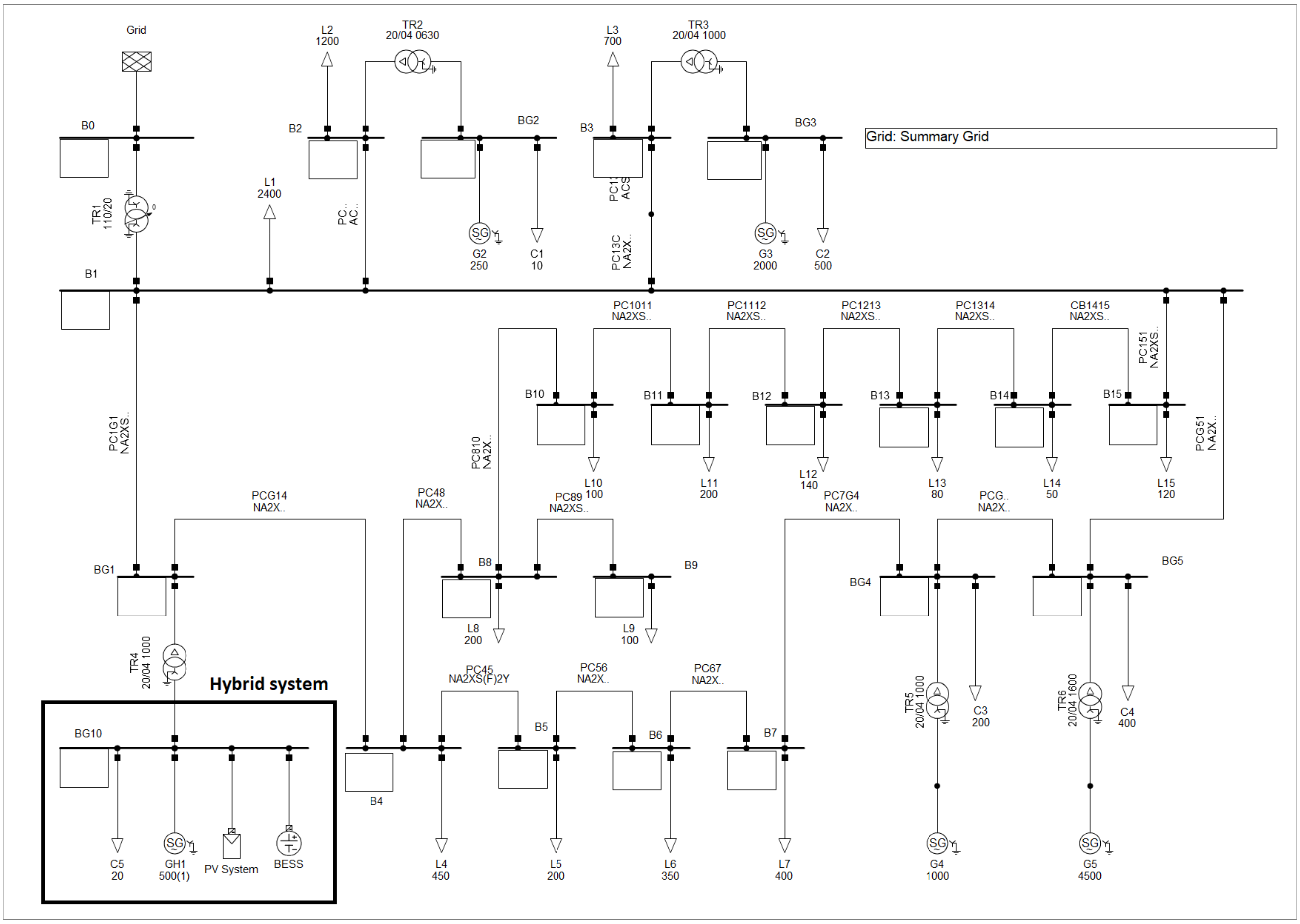

Figure 3.1: Distributed grid model

Table 3.1: Generation plants in distributed network

Number of plant	Model label	Nominal power (kW)	Nominal consumption (kW)	Busbar connection
1	HPP	250	10	BG2
2	CHP1	2000	500	BG3
3	CHP2	1000	200	BG4
4	CHP3	4500	400	BG5
5	Hybrid HPP	450	20	BG10
	Hybrid SPP	500	/	BG10

Transformers and cables/overhead lines are given in Table 3.3 and 3.2 respectively. The distributed system has mostly cables while longer distance conductors are overhead lines. All of the production plants have a low voltage connection to the 20kV system.

Table 3.2: Transformers in the network

Model Label	Connection	Voltage HV(kV)/LV(kV)	Power (kVA)	Impedance Voltage (%)	Vector group
TR1	HV grid	110/20	10 000	11.05	YNyn0d5
TR2	HPP	20/0.4	630	4	Dyn5
TR3	CHP1	20/0.4	2X1000	4	Dyn5
TR4	HYBRID	20/0.4	2x1000	4	Dyn5
TR5	CHP2	20/0.4	1600	4	Dyn5
TR6	CHP3	20/0.4	2x4000	4	Dyn5

Table 3.3: Cables and overhead lines in the network

Number of conductor / model label	Nominal voltage (kV)	Type	Length (km)	Max. allowed continous current (A)
1 / PC12	20	ACSR 3X(1X50 mm2)	11,61	170
2 / PC13C	20	NA2XS(F)2Y 3X(1X150 mm2)	3,3	320
2 / PC13O	20	ACSR 3X(1X50 mm2)	20,4	170
3 / PC1G1	20	NA2XS(F)2Y 3X(1X150 mm2)	1,27	320
4 / PCG14	20	NA2XS(F)2Y 3X(1X150 mm2)	3,4	320
5 / PC48	20	NA2XS(F)2Y 3X(1X150 mm2)	0,8	320
6 / PC45	20	NA2XS(F)2Y 3X(1X150 mm2)	2,32	320
7 / PC56	20	NA2XS(F)2Y 3X(1X150 mm2)	0,2	320
8 / PC67	20	NA2XS(F)2Y 3X(1X150 mm2)	2,13	320
9 / PC7G4	20	NA2XS(F)2Y 3X(1X150 mm2)	0,2	320
10 / PCG4G5	20	NA2XS(F)2Y 3X(1X150 mm2)	0,1	320
11 / PCG51	20	NA2XS(F)2Y 3X(1X150 mm2)	0,87	320
12 / PC89	20	NA2XS(F)2Y 3X(1X150 mm2)	0,31	320
13 / PC810	20	NA2XS(F)2Y 3X(1X150 mm2)	0,46	320
14 / PC1011	20	NA2XS(F)2Y 3X(1X150 mm2)	0,57	320
15 / PC1112	20	NA2XS(F)2Y 3X(1X150 mm2)	0,70	320
16 / PC1213	20	NA2XS(F)2Y 3X(1X150 mm2)	0,79	320
17 / PC1314	20	NA2XS(F)2Y 3X(1X150 mm2)	0,21	320
18 / PC1415	20	NA2XS(F)2Y 3X(1X150 mm2)	0,27	320
19 / PC151	20	NA2XS(F)2Y 3X(1X150 mm2)	1,1	320

3.2 Hybrid power plant purpose and specification

A hybrid power plant has multiple purposes in its implementation. The primary purpose is the owner's point of view. Owner investment in renewable energy is returned by selling electricity to the power system operator. The current market scheme is regulated, but new policies in deregulation of the electricity market will change the operation of the power plants. Future power plants should meet the demand more actively, therefore power production has to be optimally scheduled. Too many DG units can produce many issues in the system as already described in the previous chapter, one of the issues is returning power to the transmission system, therefore, increasing power losses and impacting system redundancy. This issue will be further discussed in static power flow and quasi-dynamic analysis.

Hybrid system purpose other than owner/investor point of view follows current trends in implementation of renewable sources which conveys national goals described in the previous chapter. Further, this hybrid system goal is the trend following DG production which in the future will make distributed systems more self-sustainable. Moreover, the implementation of a hybrid system should tend to keep electricity prices the same for the consumer or in this case community, while increasing power quality for the consumer. Another potential implementation of HES in the future would be replacing CHP plants due to a change in energy policies pursuing more renewable sources. Therefore it's important to analyze the operational and economic benefits of HPP on interacting with the distribution grid and also local benefits to the stakeholders like DSO and communities. With all the purposes and goals of hybrid power plant implementation, the specification of the hybrid system is given.

In this study, a hybrid system consists of a solar power plant, hydropower plant, and battery system. The diagram representing the hybrid system is shown in Figure 3.2. This configuration is chosen fundamentally to compensate for inconsistent production of the solar power plant during the winter months (low irradiation) and hydropower during the summer months (low water flow). Implementation of both sources should compensate to achieve more continuous power production. The battery system is part of the hybrid power plant to meet the peak demand. As for now the market structure is regulated and the battery system does not have economical value, but due to liberalization of the market, energy price will vary throughout the day and therefore battery system will play a crucial role in energy dispatch. The battery system will discharge energy when it is needed for peak demand, while energy price will benefit the owner financially.

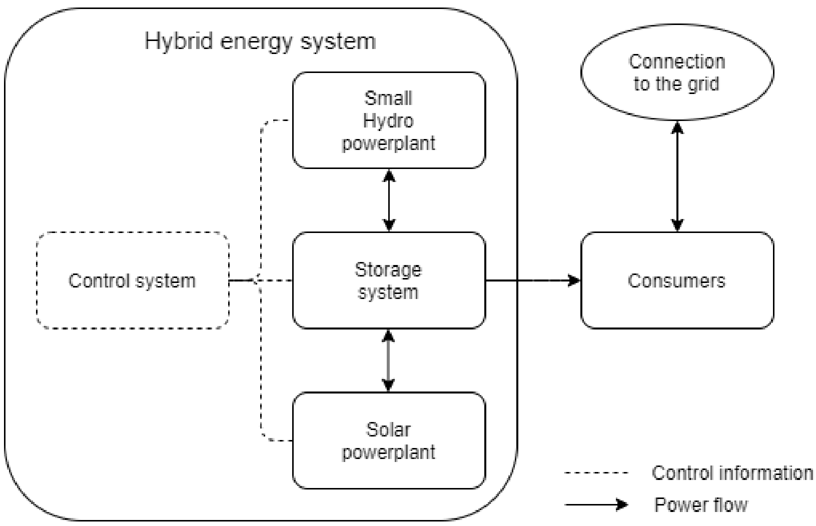

Figure 3.2: Hybrid power plant control system

The hybrid system installed power from the solar plant has a power of 500kW, the same as the hydro power plant. The battery system can produce a peak power of 500kW with 2MWh of total energy, which is sufficient to dispatch during peak hours.

3.2.1 Power generation from hydro power

The designed power plant has a small accumulation lake whose purpose is only to keep water height above turbine constant independent of the river flow, therefore it does not offer any energy storage. Turbine water height can not be controlled for river discharge below 3m/s and above 50m/s. Maximal water flow through the turbine is 20m/s and if water flows over this value, then part of the water is released on the side canal. Therefore the operating mode of the water turbine is from 3m/s to 50m/s where from 20 to 50 m/s turbine flow is 20m/s.

Extracted data from Croatian Meteorological and Hydrological Service [28] is shown in Figure 3.3. Data has a resolution of water readings daily therefore cubic interpolation is used to generate data in hourly resolution. This interpolation will generate an error but it is not considered very significant, and due to lack of data range of error is undetermined. By yearly power production, this hydropower plant is expected to generate 2GWh of energy, and with this interpolation, 1.8GWh is achieved.

Figure 3.3 shows that river oscillations may be significant in rain season and that dry season water flow sometimes goes below 3m/s where turbine does not operate.

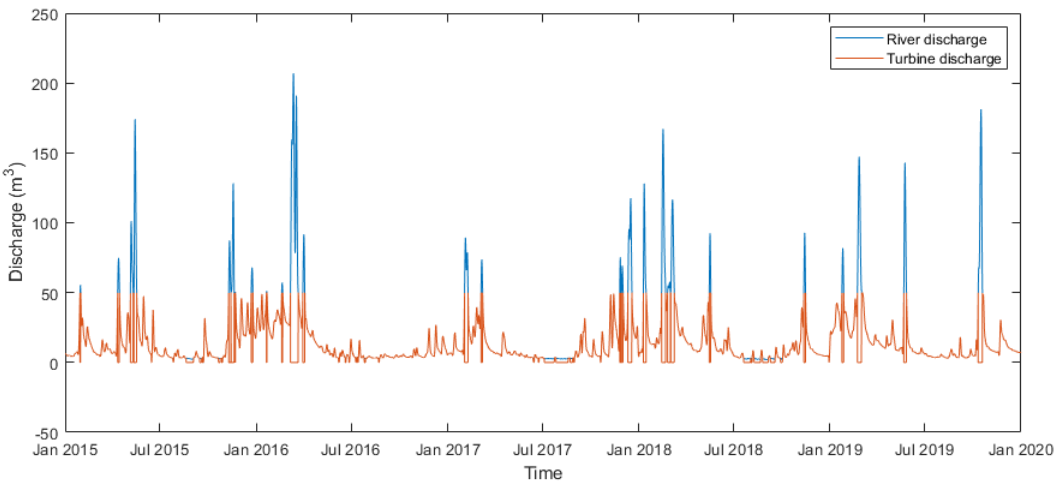

Figure 3.3: River discharge and Turbine discharge

River flow rotating turbine generates power output at the generator. Generator efficiency is not the same throughout the discharge regime, therefore turbine efficiency based on flow is shown in Figure 3.4. Points from the turbine are measured values and with interpolation of points using cubic interpolation, data points are changed to curve with power to turbine discharge dependency.

Representation of river flow vs power production is shown in Figure 3.5. Observations show that power

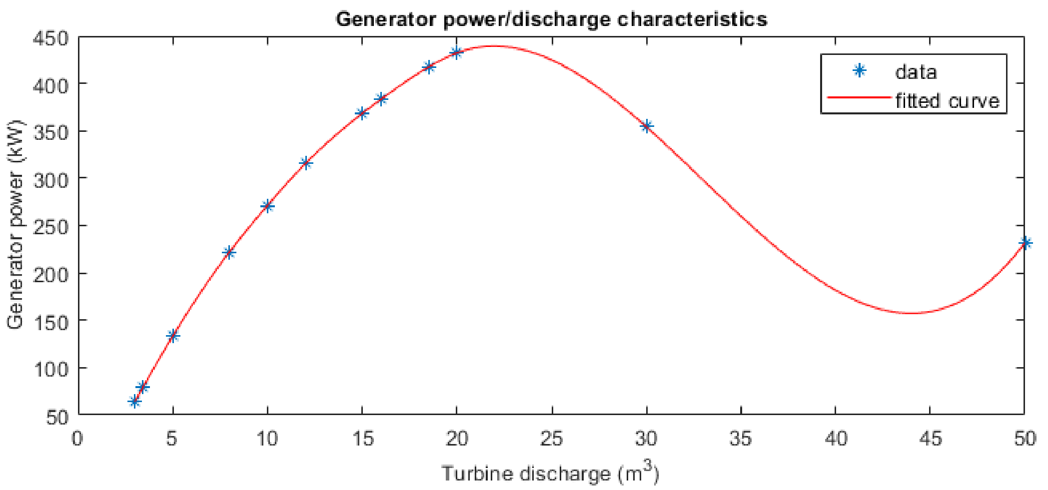

Figure 3.4: Generator efficiency

is instantly cut to 0 if the flow is above or below limits.

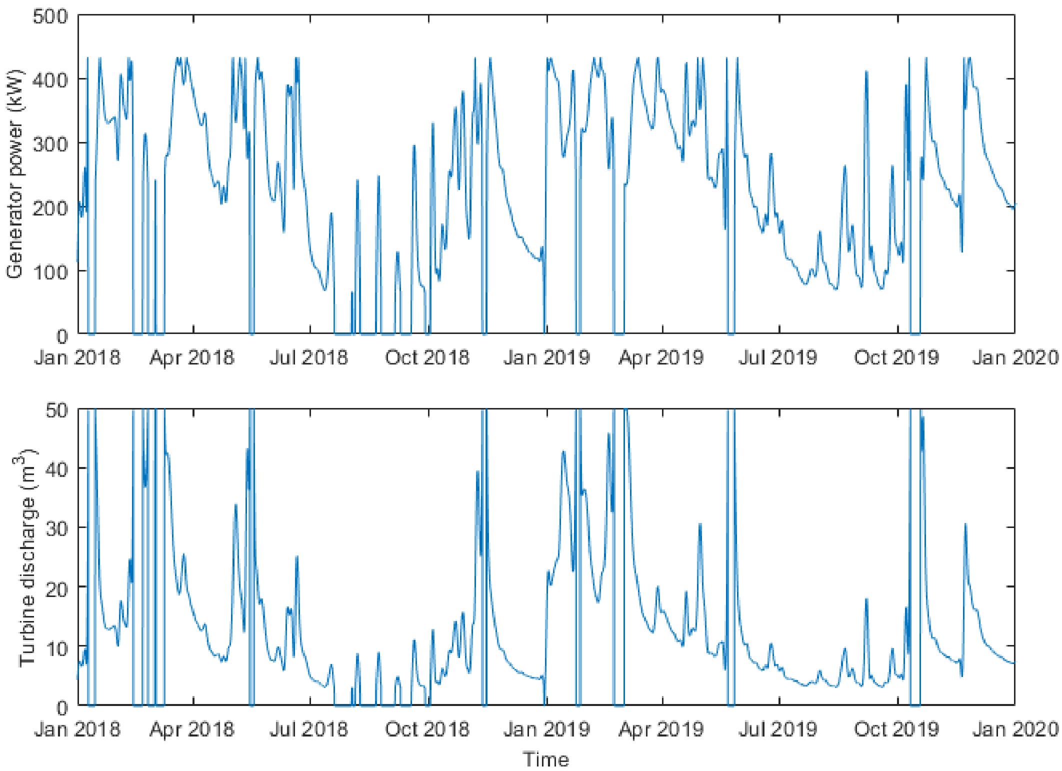

Figure 3.5: Power production and turbine discharge in 2018 and 2019

3.2.2 Power generation from solar power

Solar irradiation data is extracted from The Solcast API Toolkit [29] in the hourly frame. Data taken as irradiation is Global Horizontal Irradiance (GHI). GHI is the total solar radiation incident on a horizontal surface. The data utilized has a fixed tilt for the panels and uses optimum tilt angle for the best performance.

The solar power plant has installed power of 500kW, and the average efficiency of each cell is taken as 15% with converter efficiency as 95%. Power plant production is shown in Figure 3.6, for comparison, hydro production is also plotted. With this comparison, it is visible that throughout cloudy/rainy days hydropower production increases while solar power production decreases. This compensation of solar and hydropower is the main purpose of hybrid power plants: to compensate drawbacks of each of the production units.

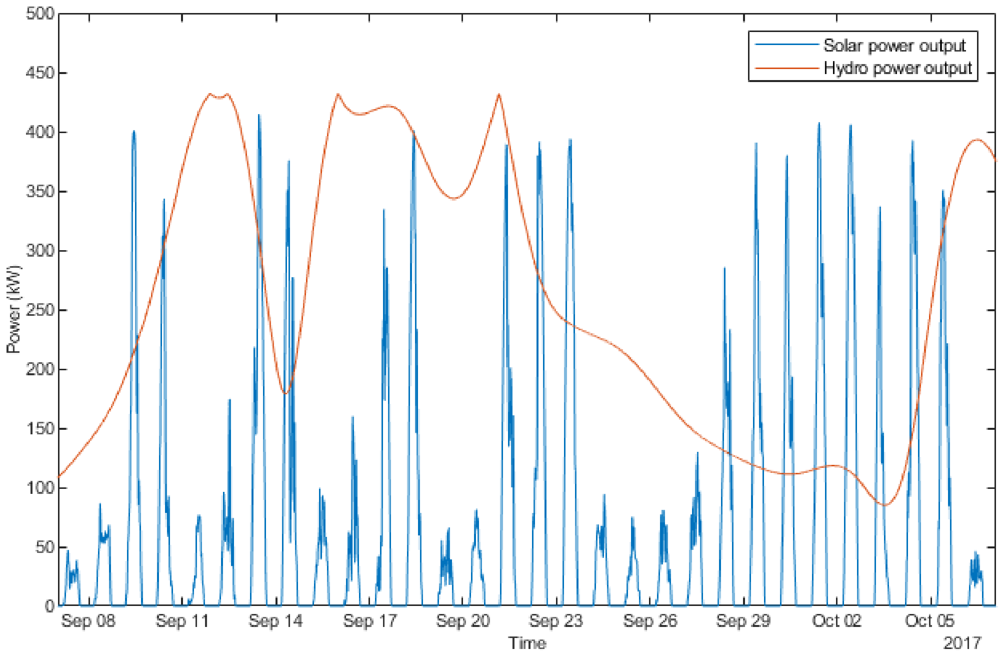

Figure 3.6: Solar power plant production

3.3 Power consumption for residential consumer

Determining residential and industrial power consumption throughout the day depends on the season and the day of the week. Data for load profile is derived as hourly data from OpenEI - U.S. Department of Energy [30]. Residential and industrial data is given for one year period where similar climatic conditions as in Croatia are used for loads within the Californian area. Data is further adjusted to the peak load for consumers in the distributed grid. The list of all consumers is given in Table 3.4 where peak active power is given and reactive power is taken with 0.95 power factor.

Table 3.4: Grid consumers

Number of consumer	Model label	Maximum active power (kW)	Type of consumer
1	L1	2400	Residential/Industrial
2	L2	1200	Residential/Industrial
3	L3	700	Residential/Industrial
4	L4	450	Residential
5	L5	200	Residential
6	L6	350	Residential
7	L7	400	Residential
8	L8	200	Residential
9	L9	100	Residential
10	L10	100	Residential
11	L11	200	Residential
12	L12	140	Residential
13	L13	80	Residential
14	L14	50	Residential
15	L15	120	Residential
16	C1	10	Consum HPP
17	C2	500	Consum CHP/Industrial
18	C3	200	Consum CHP/Industrial
19	C4	400	Consum CHP/Industrial
20	C5	20	Consum Hybrid PP

With the definition of consumers in the network, all of the parameters necessary for the power flow and quasi-dynamic simulations are given. The next section simulates power flow in the system.

3.4 Load flow study

Simulating load flow in the distribution grid is conducted to recognize any potential system issues. The focus of the load flow is to determine system losses, voltage levels, and power outflow/inflow from the main grid (transmission system). This is done by generating 3 cases, and overview of the cases is as follows:

- Case 1 - disconnected HES with production at 25% and consumption at 100%
- Case 2 - disconnected HES with production at 100% and consumption at 25%
- Case 3 - connected HES with production at 100% and consumption at 25%

3.4.1 Case 1

Investigating power flow without hybrid power plant are firstly conducted. Figure 3.7 shows simulation results with consumption at 100% and production of 25% as seen in Table 3.5. It can be seen from the simulation results that system voltages are stable as defined in the grid code (+/- 5%), busbar BG1 for example has a voltage of 0.9669 p.u., which is close to 0.95 allowed. This scenario has under-producing conditions but based on the existing market structure (demand 4 times higher than supply as seen from Table 3.5) CHP producers tend to push as much power to the system. Therefore, a more realistic scenario is generated.

Table 3.5: System conditions - Case 1

Production	25 %
Consumption	100 %
Worst busbar voltage	0.9669 p.u.at BG1
System losses	40 kW/ 50kVAr
Supply/demand	1.93MW/ 7.80MW
External infeed	5.91MW

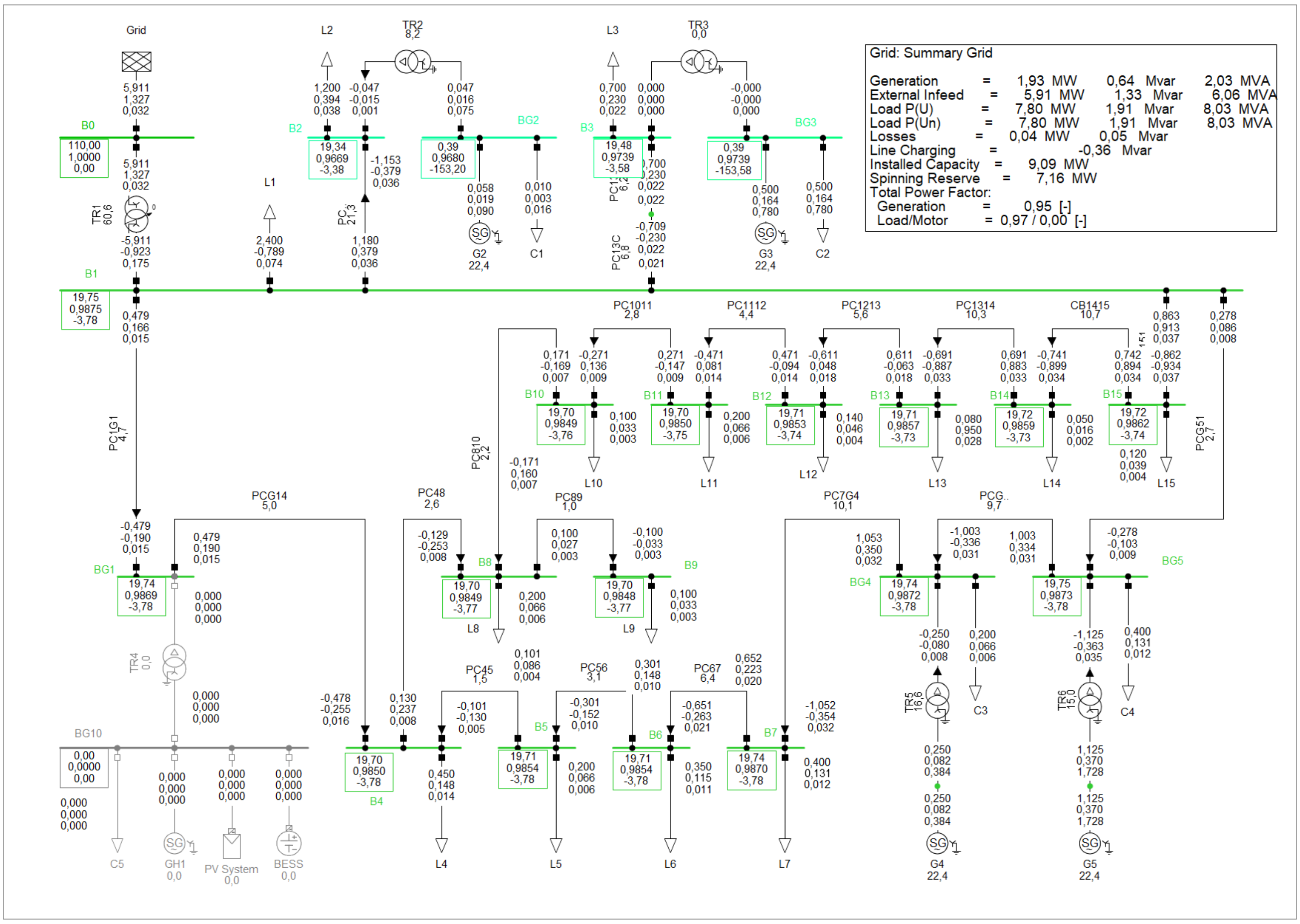

Figure 3.7: Case 1 load flow results

3.4.2 Case 2

In case 2 figure represents the scenario as shown in Table 3.6 with power flow without a hybrid power plant. In this case Figure 3.8 shows loading of 25% and production of 100%. In this simulation voltage, issues occur, BG3 and B3 exceed voltage limits due to overproduction in the system. The current market structure tends to develop this scenario because CHP-s do not have an incentive to follow the demand since their profit is fixed per kWh produced. Therefore rise in system losses (over

50%) and rising voltages are observed.

Table 3.6: System conditions - Case 2

Production	100 %
Consumption	25 %
Worst busbar voltage	1.0603 p.u.at BG3
System losses	70kW / 190kVAr
Supply/demand	7.73MW/ 1.95MW
External infeed	-5.71MW

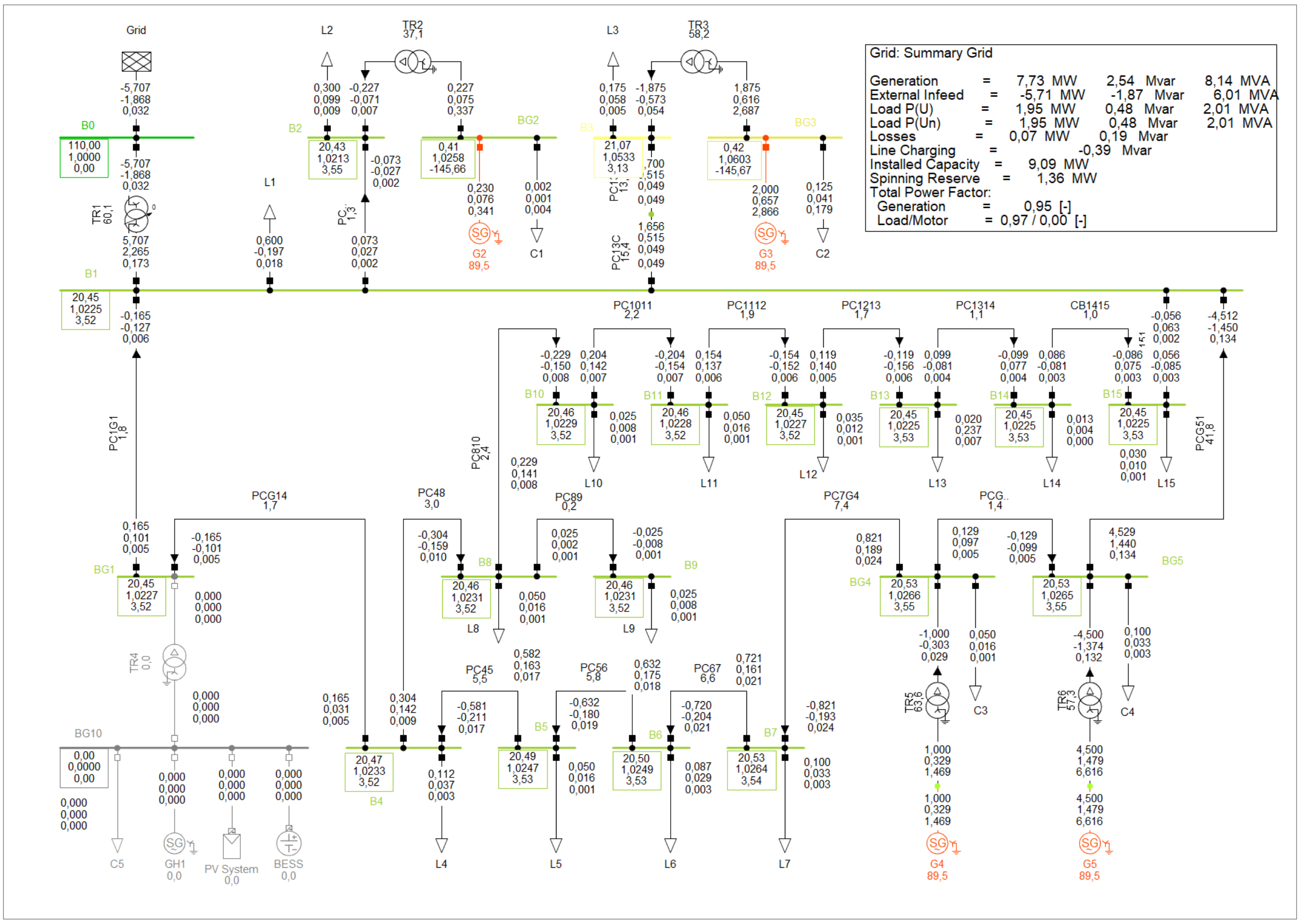

Figure 3.8: Case 2 load flow results

3.4.3 Case 3

Figure 3.9 repeats scenario given from Case 2, while in this case hybrid power plant is connected as Table 3.7. The figure shows that hybrid power plant does not contribute in further grid destabilization significantly. An almost identical voltage problem arises within the system with even higher system losses.

Table 3.7: System conditions - Case 3

Production	100 %
Consumption	25 %
Worst busbar voltage	1.0606 p.u.at BG3
System losses	80kW / 430kVAr
Supply/demand	9.23MW/ 1.95MW
External infeed	-7.2MW

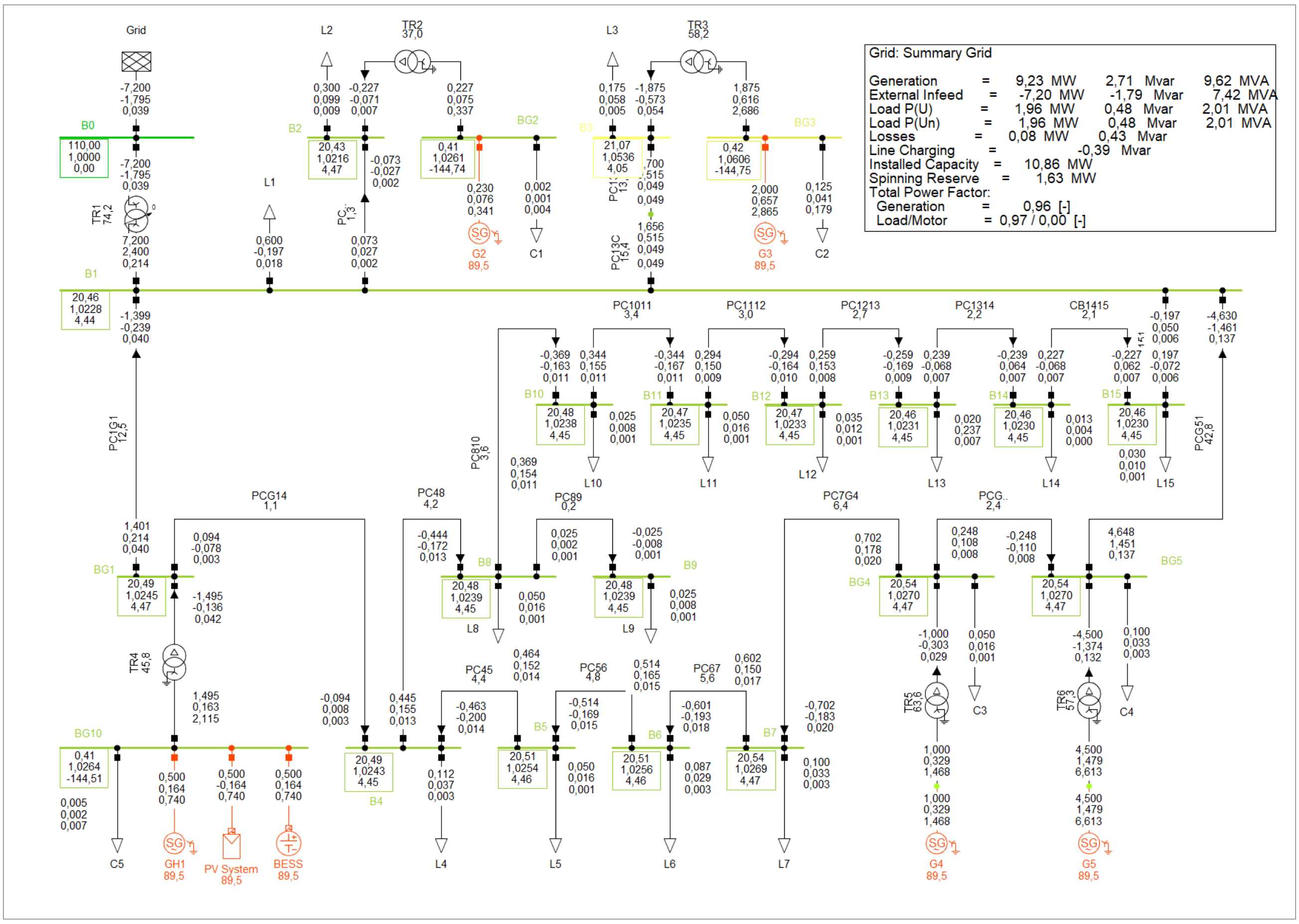

Figure 3.9: Case 3 load flow results

Since the distribution grid has voltage issues in Case 2 3, voltage regulation is introduced as shown in Figure 3.10 which shows results with grid transformer voltage regulation at the 20kV side. Voltage regulation is crucial in this case especially with the possibility to change secondary voltage when a transformer is energized. Changing tap voltages while the transformer is energized is called On-load tap changer (OLTC), setup is done so that voltage is regulated with 2.5% step with a margin of max/min 10%. Simulation shows that voltage levels are well within the limits and that the tap position is changed to -1, meaning voltage is decreased 2.5% from normal levels. With this feature, the system is able to run smoothly in different work regimes with hybrid power plant and load flow satisfies grid code.

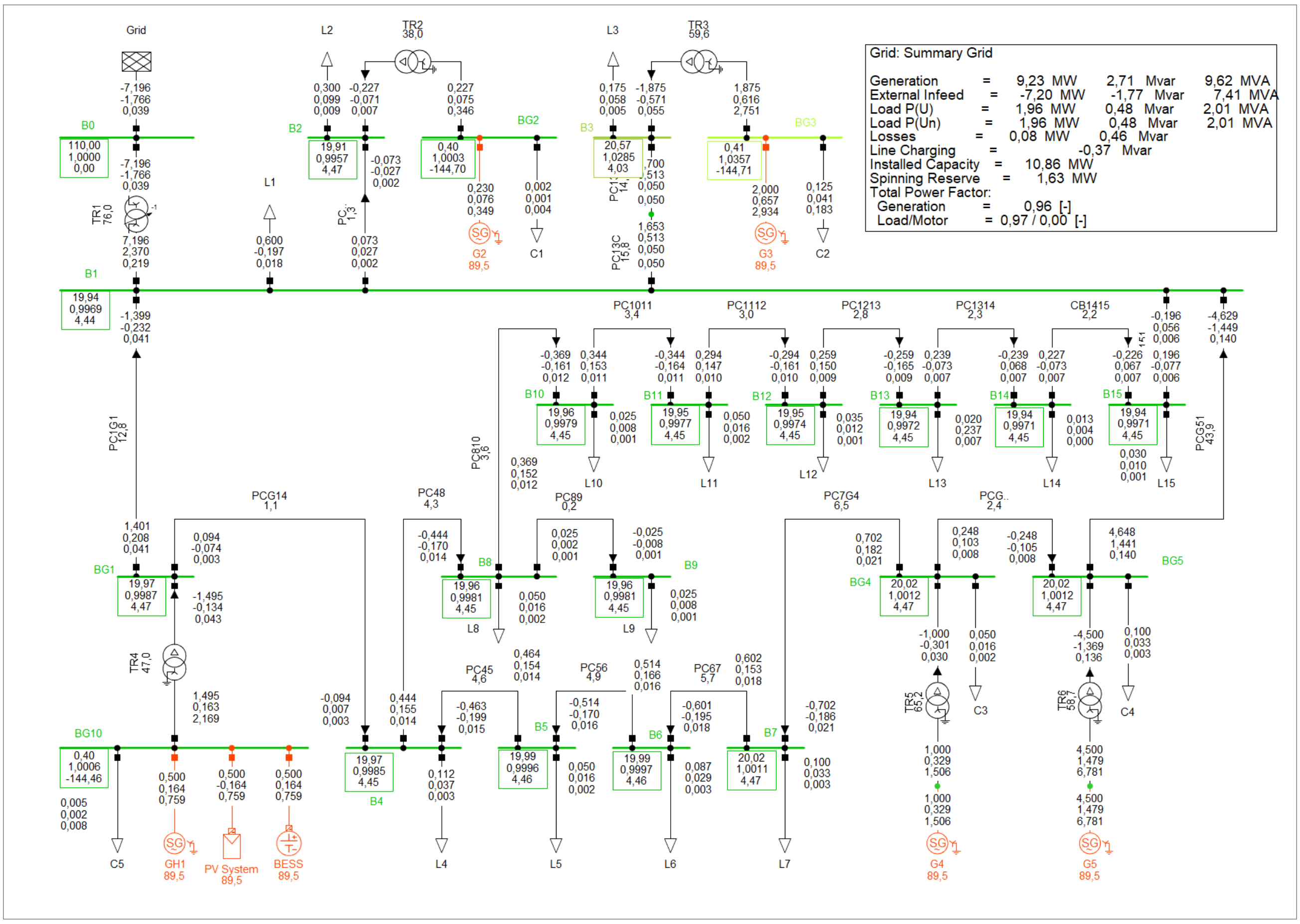

Figure 3.10: Case 3 with voltage regulation

Overview of the important results from the load flow study is shown in Table 3.8. The table shows that in cases with low demand, power production does not follow consumption and therefore losses in the system are higher due to excess power pushed through conductors. Also, critical voltages (voltages with the highest difference from 1 p.u.) show that high production causes over-voltages exceeding grid code limits, which can be regulated with OTLC at transformer connected to the external grid.

Table 3.8: System conditions - Case 3

Case number	OTLC	System losses (kW)	Critical voltage (p.u.)	External infeed (MW)
Case 1	no	40	0.9669 @ BG1	5.91
Case 2	no	70	1.0603 @ BG3	-5.71
Case 3	no	80	1.0606 @ BG3	-7.2
Case 3	yes	80	1.0357 @ BG3	-7.2

After a basic load flow study is conducted, further system simulation is investigated with quasi-dynamic simulation. The need for quasi-dynamic simulation is conducted to further analyze the system in a real-time environment with the defined time period to further observe any potential system problems during its operation.

3.5 Quasi-dynamic simulation

Quasi-dynamic simulation investigates multiple loads flows at a defined time step, therefore the data for each of the consumers and producers must be given in time series in order to conduct the study. Because quasi-dynamic simulation represents multiple load flow calculations, parameters from static load flow will become time-dependent and thus further provides useful data to determine system behavior. Simulation is investigated for one year time period with a time step of one hour. With the quasi-dynamic simulation, grid character can be observed meaning, typical demand, typical power production, power flow to the main grid, and others.

The first result for the quasi-dynamic simulation shown in Figure 3.11. The upper line (red) represents active power production from the DG-s and the lower (blue) line shows demand in the system. It is evident that the system produces excess power at all times. This implies that from a distributed grid point of view voltage and system power losses will rise. Looking from the external grid, power is sent back to transmission lines which generate losses and a more complex selectivity scheme is needed. In peak hours energy consumption is approximately 7.5MW and production 8.5MW, which does not seem to be an issue. But in the night hours, demand is around 2.5MW while production is around the same which shows that production is almost 4 times higher than demand.

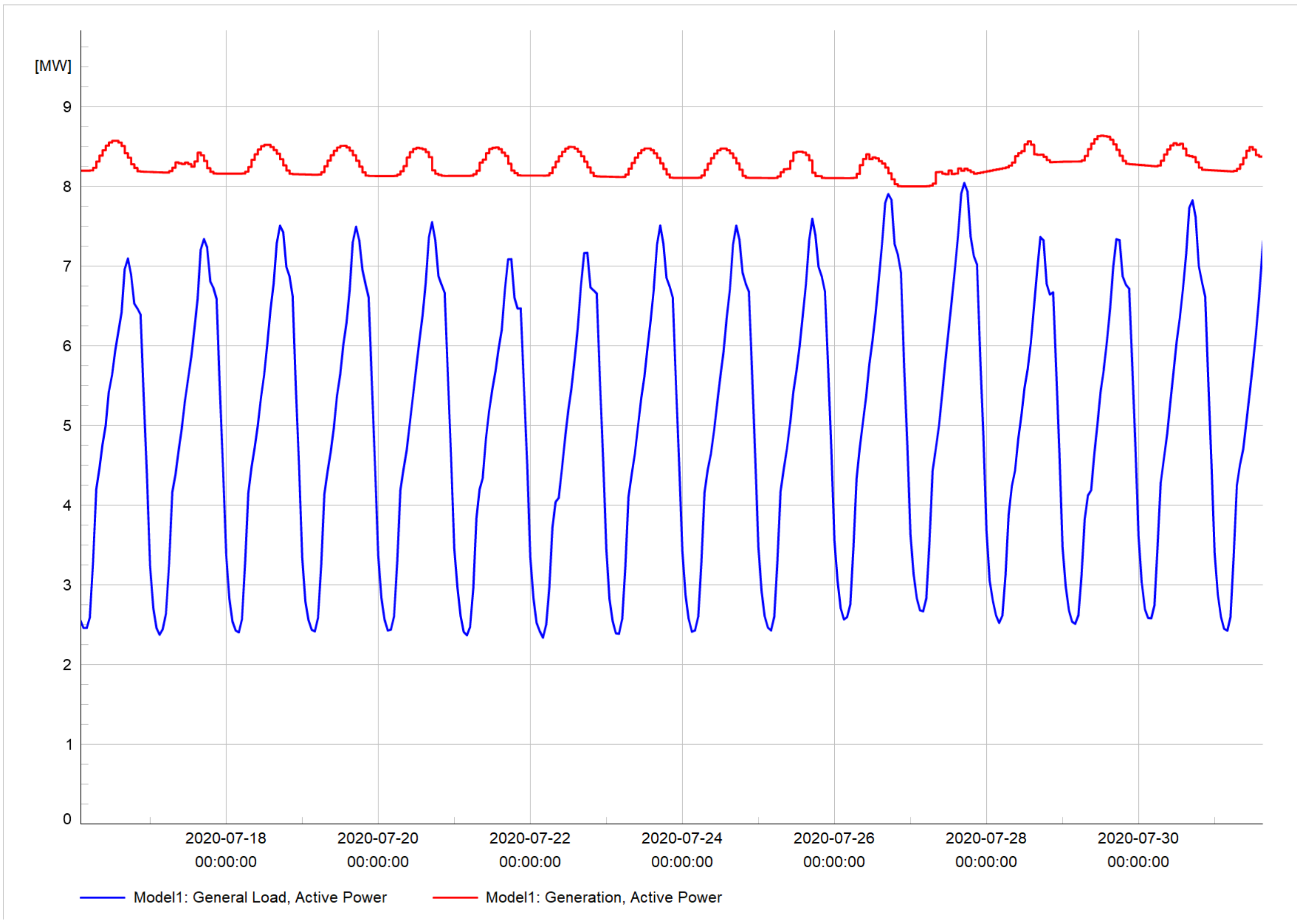

Figure 3.11: Demand and production in the distribution system

Simulation results from Figure 3.12 demonstrate power production of the hybrid power plant during September where production of a hydro power plant is low and solar power plant at peak during the day. While power demand is very high, it can be seen that solar power production follows demand compared to Figure 3.11. This is important because scheduling the solar power as part of a hybrid system will not tend to have issues with demand.

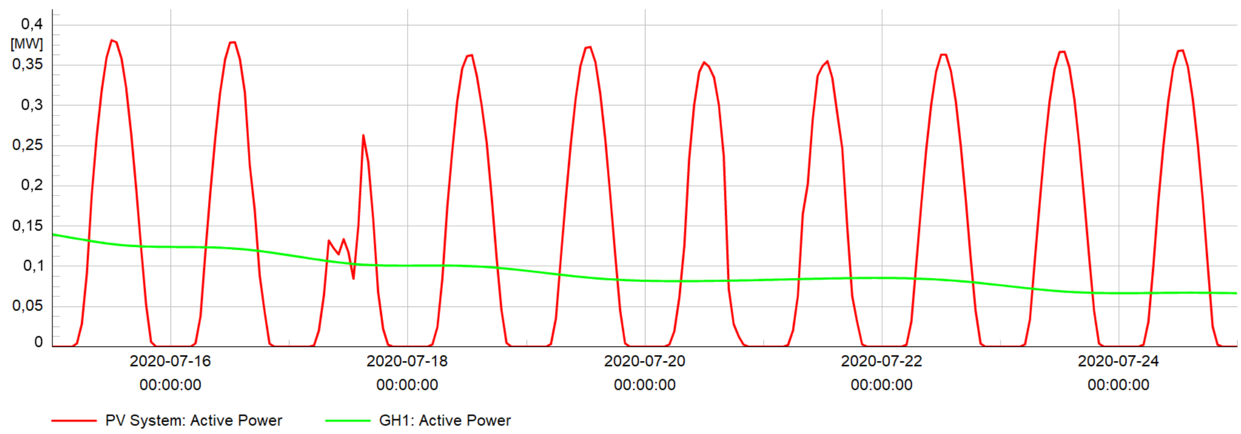

Figure 3.12: Hybrid solar/hydro production graph

Figure 3.13 shows external grid power flow and power losses in the system. As already stated, demand is poorly followed by production and the system returns power to the transmission system at all times. This will cause more power losses to the transmission system because the power is not utilized close to the loads. The lower chart shows power losses in the system itself, losses are higher when demand is not met, in this case, active power losses increase from 50kW to 80kW because existing lines carry much more energy than consumers need. A pattern in system losses is followed by the inverse of system power flow to the grid, the more excess power is produced, the more losses in the system occur. If in this case high voltage overhead lines would be observed, the same effect would be in place. This definitely is not positive for the system efficiency.

From the DSO standpoint power should be more optimized within the local network while minimizing power losses. This would be solved by lowering the price of electricity and operational costs, with these steps, CHP overproducing would be more closely followed by demand. Otherwise, DSO would need to invest in a new reconfiguration to keep the system follow grid rules and to keep efficiency. System reconfiguration would mean possibly new transmission lines to avoid congestion, new equipment to allow power flow bidirectionally, or others.

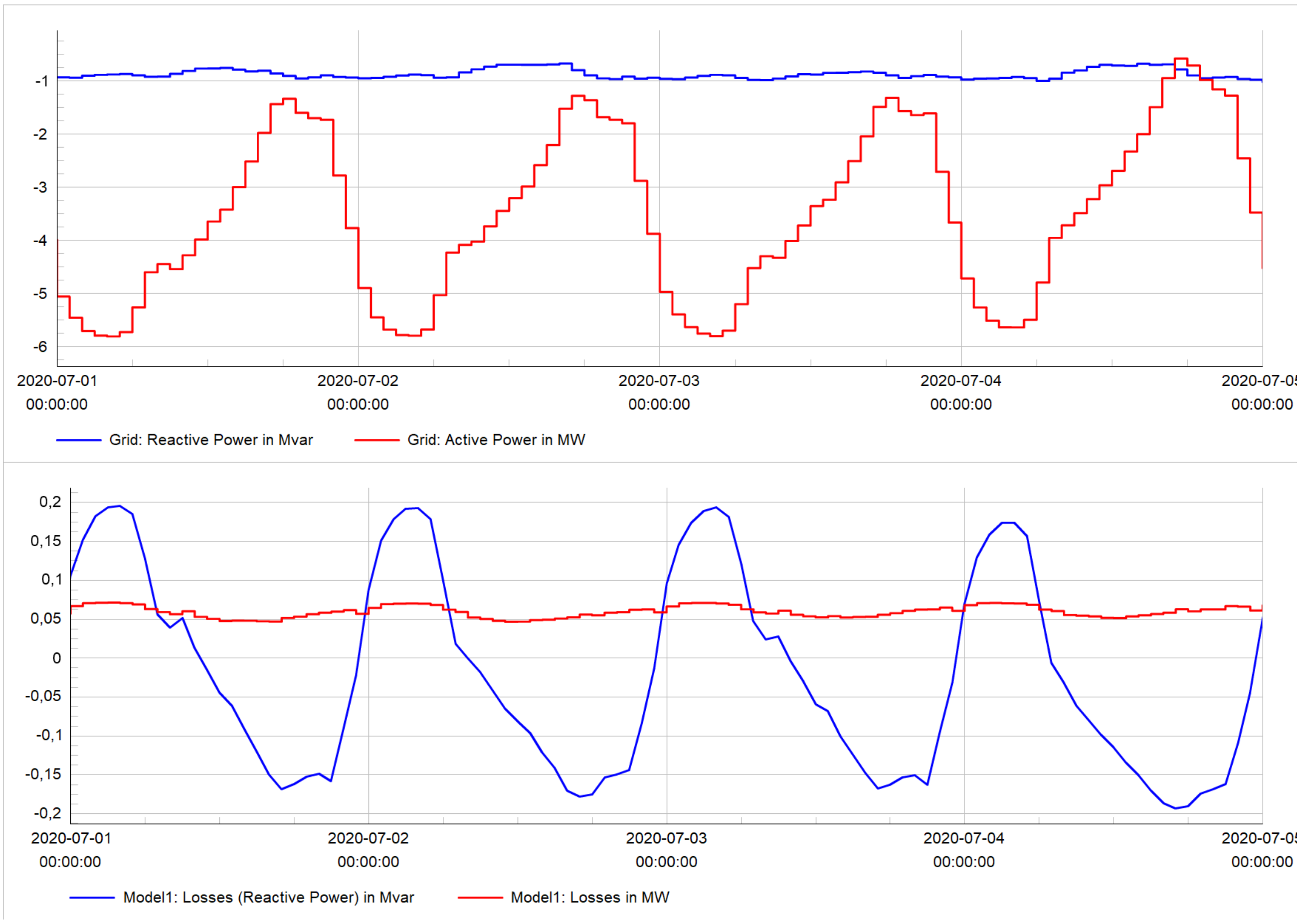

Figure 3.13: External grid power flow and power losses

3.5.1 Quasi-dynamic simulation with OTLC voltage control

Figure 3.14 represents voltage and tap change during 5 days. The upper chart shows busbar BG3 voltage which has the highest voltage issues. With tap change on the grid transformer TR1, BG3 voltage is regulated to keep it under 1.05 p.u., or in other words, the voltage reaches 1.04 p.u. regularly. The Middle and lower graphs show regulation on the TR1, tap change is done daily to keep voltages under grid code regulations, but this is mostly done to regulate the voltage at the BG3 busbar. The effect of tap position shown on TR1 hourly is seen from the lower graph. At higher consumption voltage tap is at position 0 and in lower consumption at 1, change is 1% per tap.

As tap changing is done 4 times per day to keep voltages within limits, this has a consequence of decreasing the OTLC lifetime of the transformer because contacts are frequently used. As the lifetime of OTLC decreases, more maintenance would be needed which generates more costly operations from the DSO standpoint.

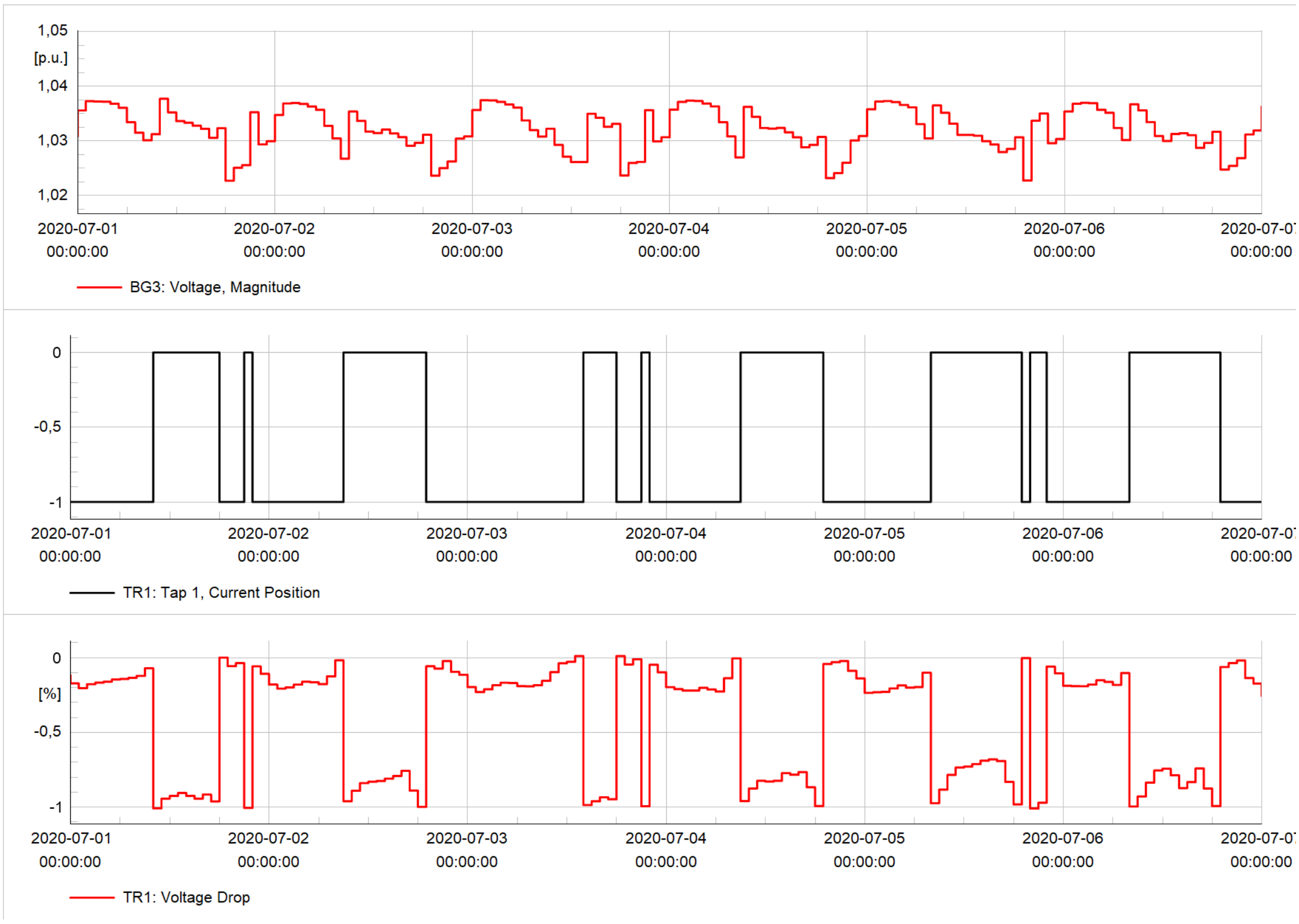

Figure 3.14: Voltage and tap change

Generally, distributed grid showed voltage regulation issues and higher losses in the regulated market scenario. These issues will be even more prominent if more DG-s connect to the system, with consideration of future power systems with more heat pumps, electric vehicles, and big AC units with deregulating electricity market and further replacement of polluting CHP-s system should not have voltage nor losses issues.

3.6 Conclusion

Analyzing distributed systems with static simulation showed concrete problems in the network. Firstly, the system has voltage regulation issues as shown from power flow simulations, and this problem is solved by OTLC at 20kV voltage level of grid transformer. Another issue was observed with the overproduction of the DG in the network. These issues could be enhanced in the future with more plants and loads in the system. If more balanced power flow could be introduced, it would decrease system losses, lower electricity prices, and less DSO reconfiguration would be needed. As an effect of this more green power could be consumed locally and rescheduling generation would be beneficial from a reliable operation, economic and sustainable point of view.

With the current regulated market scheme, producers in the network do not have an incentive to follow the demand for electricity and from an investment standpoint, power plants tend to give maximum power at all times. Maximum power production results in high power flow back to the main grid and also generates losses in the cables/overhead lines. Modern power grids have the tendency to change the market structure from regulated to deregulated schemes, this should positively impact all system stakeholders (power plants, DSO, and consumers). Power plants would need to generate returns based on changing electricity price which typically follows the demand, this means that DSO would benefit with less expensive system upgrades and regulation while consumers would have higher electricity quality with lower prices as DSO cuts expenses.

As done in this chapter, the power flow with different challenges and prospects was essential to study and analyze, to define issues in the current system. In the next chapter, optimized scheduling and economic operation of hybrid power system is investigated to see if future power system brings more efficient and reliable operation.

4 Optimised scheduling of hybrid power plant

This chapter focuses on optimized scheduling of the power plant based on the day-ahead market. Investigation on the current market scheme, new scheme, and different scenarios on optimization is calculated. The sole purpose of optimizing based on the day-ahead market is to generate cost function directly related to the profits of the owner of the plant. This will be compared to load demand and how market pricing is correlated with the demand.

4.1 Optimised scheduling in future distributed power systems

As already aforementioned in Chapter 2, deregulated market is expected to replace current government-subsidized renewable generation. As prices of renewable technologies are decreasing, governmental subsidies diminish over time. The end case of the renewable sources is to cut governmental incentives and therefore all renewable generating units will trade electricity actively.

Current market scheme is shown in Table 4.1. It can be seen that wind, solar and CHP plants have the same rate of 70.67 EUR/MWh while hydropower plants are more subsidized. The hydropower plant utilized in this project is 500kW, therefore, the rate is 124 EUR/MWh which is almost double that of the solar power plant.

Table 4.1: Privileged pricing for plants with less than 5MW installed

Type	Installed power range	EUR/MWh
HPP	300kW < $P_{installed}$< 2MW	124.00
HPP	2MW < $P_{installed}$< 5MW	117.33
WPP	0kW < $P_{installed}$< 5MW	70.67
CHP	0kW < $P_{installed}$< 5MW	70.67
SPP	0kW < $P_{installed}$< 5MW	70.67

Fixed tariff per MWh does not provide any demand into consideration therefore power plants tend to sell energy as produced. With this scheme, any battery storage system would not make economical sense and as already discussed in Chapter 3 and issues in the grid may occur.

With market deregulation, privately-owned power plants will tend to sell energy at the best market price, where power plants with energy storage systems can dispatch energy even more flexibly dependent on the market. Implementation of storage systems will have to be scheduled according to the market predictions and available power.

This project tends to focus on optimal scheduling based on ideal market predictions and ideal weather forecasts. The goal of optimized scheduling is to generate the highest possible profits for the hybrid power plant. This will be investigated in multiple case scenarios where profitability and optimization techniques will be observed.

Cases considered are listed as follows:

- Case 1 - Current pricing scheme vs. day ahead market: investigates price difference between current market scheme and day-ahead market scheme where hybrid power plant consists of only solar and hydro sources (no BESS).
- Case 2 - BESS system in the day-ahead market: generates strategy of energy dispatch based on market prices in two ways. Firstly solar and hydro energy is sold to the market as it is produced, and secondly, BESS interacts with the day-ahead market in an optimized manner, so that it buys energy if it is more profitable to buy, and sells otherwise.
- Case 3 - power system in the day-ahead market: With the last study case, a hybrid system is completely optimized to generate electricity based on prices on the day-ahead market. This means that energy from HESS can be utilized to BESS without purchasing energy from the market, and further dispatches energy as prices arise.

All of the cases investigated are discussed and modeled in three month period, January, February, and March. The total energy available in three months from hybrid power system is the same for all of the cases and values are:

- Hydro energy 551.75 MWh
- Solar energy 81.53 MWh

The reason for comparison and different optimization procedures is to investigate the influence of current and future power systems from a techno-economic point of view. Technical point of view oversees aspect of energy dispatch and how closely it follows the demand, and economical aspect includes maximizing profits for the hybrid system.

4.1.1 Case 1 - Current pricing scheme vs. day ahead market

In the first case, the profitability of the power plant is generated as represented in Figure 4.1. The flow chart from the figure represents data flow and pricing calculation, hourly data, and efficiency are transformed to power, and afterward, different tariffs are multiplied by each hour pricing. After prices of each source are calculated, the sum of both profits represents total HES profit.

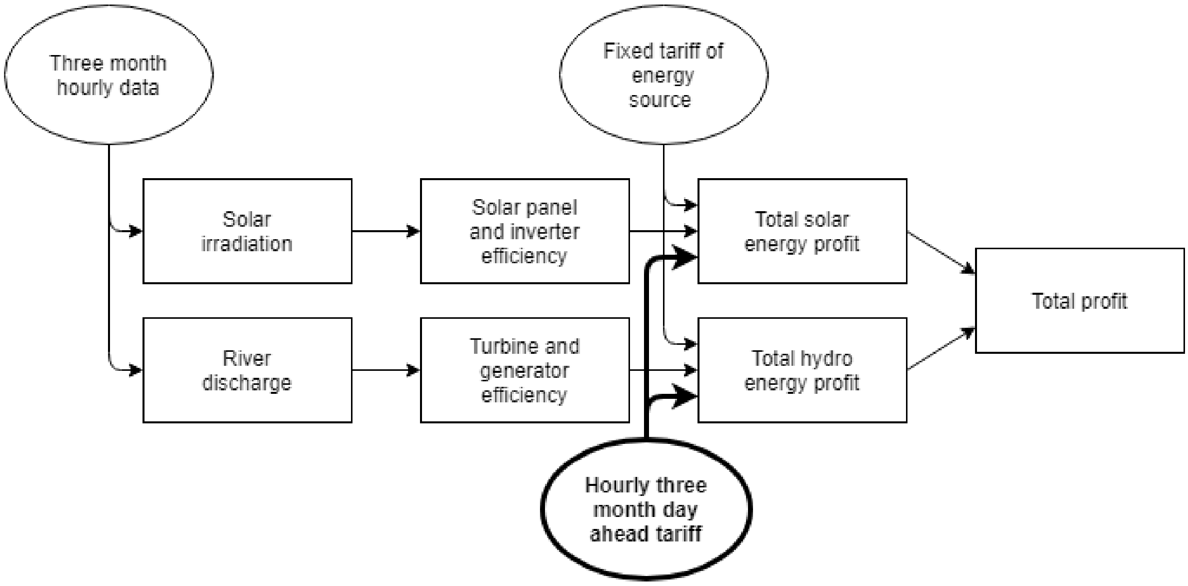

Figure 4.1: Pricing tariffs - fixed regular line, day ahead bold line

Table 4.2: Privileged pricing for plants with less than 5MW installed

Type	Pricing (EUR/MWh)	Profit (EUR)
Fixed tariff		
Hydro energy Solar energy	124.0 70.67	68 418 5 761
Total		74 179
Day ahead variable tariff		
Hydro energy Solar energy	Variable with mean 40.99 Variable with mean 40.99	21 675 3 096
Total		24 771

Table 4.2 shows results of different pricing schemes during the first three months of 2020. It is obvious that the current pricing scheme is much more profitable than the day-ahead market. This subsidized scheme is paid from consumers of electricity where all of the consumers pay 13.33 EUR/MWh which is forwarded to privileged power producers. It can be concluded that energy will get more expensive the more privileged power plants are in the system since this energy is bought for three times its market value in the day-ahead market. Therefore this pricing scheme is unsustainable and since renewable technologies become cheaper, ODS is gradually decreasing pricing for the privileged producers, for example, CHP pricing in 2016 was 124 EUR/MWh while in 2121 is 70.67 EUR/MWh [31]. Tendency leads to completely cut subsidizing the power plants as technology gets cheaper. An example of completely cutting subsidies is the first wind power plant that is not subsidized in Croatia, wind power plant Korlat with installed 95MW power with no governmental subsidies operating from 28.04.2021.

[32].

With changing price scheme in Croatia, it is important to develop economic scheduling for the power plants in order to achieve profit for the owners of the plants in the day-ahead market. Higher energy dispatch freedom can be achieved with storage systems, and for this hybrid power plant, BESS is utilized.

4.1.2 Case 2 - BESS system in day-ahead market

The first approach in economic scheduling of hybrid power plat where BESS utilizes market pricing deviations to schedule to achieve best returns.

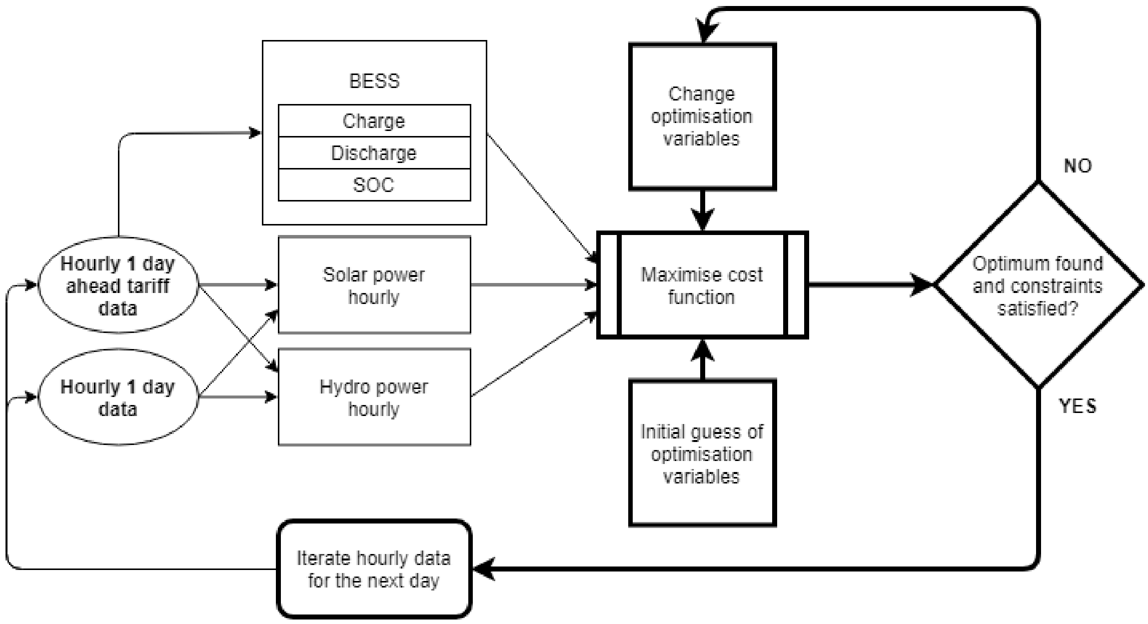

Figure 4.2: Case 2 flowchart

Representation of optimization process is shown in Figure 4.2. Firstly data for 24 hours of the day-ahead market and production data is fed to cost function directly, meaning that hydro and solar power is sold as it is produced. BESS system utilizes price difference in order to charge and discharge optimally, optimisation then feeds all initial guess values and searches for the optimum. The optimization is iterative where maximum profit is to be found, if not new iteration starts, otherwise new day data is looped in the same process. This optimization algorithm is done each day for three consecutive months.

Optimised scheduling of the BESS is achieved with function fmincon in Matlab software. Cost function maximises profit for one day which is given as:

$$max\,[f(P_{hi}, P_{si}, P_{di}, P_{ci})] = \sum_{i=1}^{24} M_{pi} * (P_{hi} + P_{si} + P_{di} + P_{ci}) \tag{4.1}$$

With constraints:

$$0 \leq P_{di} \leq 0.5 \tag{4.2}$$

$$-0.5 \leq P_{ci} \leq 0 \tag{4.3}$$

$$0.2 \leq SOC_i \leq 0.8 \tag{4.4}$$

$$SOC_i - P_{di}/2 - P_{ci}/2 - SOC_{i+1} = \begin{cases} 0.2 & \text{if i = 1,24} \\ 0 & \text{otherwise} \end{cases} \tag{4.5}$$

$$P_{di} * P_{ci} = 0 \tag{4.6}$$

Where:

M_{pi} - Market price at i-th hour

P_{hi} - Available hydro power at i-th hour

P_{si} - Available solar power at i-th hour

P_{di} - Discharge power at i-th hour

P_{ci} - Charge power at i-th hour

SOC_i - State of charge at i-th hour

Cost function equation 4.1 consists of a sum of hydro, solar, BESS charge, and BESS discharge. The Sum of total power each hour is multiplied by the market price for the same hour, and lastly, a sum of 24 hours profits is generated to calculate total daily profits.

Constraints 4.2, 4.3 and 4.4 limit charge, discharge and SOC, equations 4.2 and 4.3 limit discharge from 0MW to 0.5MW and charge from 0 to -0.5MW respectively. Limiting SOC from 0.2 to 0.8 means that SOC can be in the range of 20% to 80%, this ensures that BESS does not charge nor discharge fully to increase its lifetime. Constraint 4.5 is responsible for keeping track of SOC, in the first and last hour of day-ahead market SOC is limited to 20% this ensures that for each day BESS is completely discharged and prepared to charge the next day. For hours that are not beginning and end of the day, equation 4.5 tracks the SOC each hour. SOC for the next hour is equal to the previous hour SOC added with charged or discharged energy in percentages. Energy percentage is calculated as charged/discharged power in an hour divided by the total MWh of BESS which is 2. In this way, previous SOC is increased or decreased in percentages and equalized with SOC for the hour ahead. For example, if SOC is 0.2 (or 20%) or energy-wise 0.4MWh, charging occurs with the power of -0.5MW for one hour, energy increases for 0.5MWh which is 25% more of total energy in BESS, this has a consequence of next hour SOC to be equal to 0.45 (or 45%). Lastly, constraint 4.6 ensures that charging and discharging cannot occur in the same hour if a product of charge/discharge is equal to 0, this means that either charge or discharge has to be 0 to fulfill the constraint.

Optimization based on market price is therefore only done by the interaction between the market and the battery, in this case, energy from hydro and solar power is directly sold to the market. Figure 4.3 represents system behavior based on the market prices. A middle graph in Figure 4.3 shows energy charge and discharge with battery SOC, BESS charging occurs in lowest price hours while discharging is highest. Since the market had 2 peaks in power prices, BESS optimization managed to charge and discharge twice a day. With this method, BESS managed to contribute 11.69% more profit than in no BESS HES as seen from Table 4.3.

The lower graph in Figure 4.3 shows constituents of total energy dispatch, it is seen that for this day, hydro and solar power was not close to the peak and that BESS played a crucial role in the amount of energy given, this BESS energy is also represented as an absolute value in 4.3. Bess energy sum is 0, but absolute value shows involvement in a hybrid system, BESS was therefore very active during these 3 months. The upper graph shows power dispatched multiplied by 100 to fit into the day-ahead price graph, and it is seen that energy is dispatched more closely with price, and therefore with overall demand to the system.

Table 4.3: Day ahead market: HES with and without BESS

Type	Profit (EUR)
Case 1	
Hydro energy	21 675
Solar energy	3 096
Total	24 771
Case 2	
Hydro energy	21 675
Solar energy	3 096
BESS	2 896
Total	27 667

Table 4.3 shows improvement in profits from previous HES without BESS. Improvement is 11.69% which is contributed only by BESS involvement in the market. By optimizing HES with BESS by utilizing in-house production for charging and dispatching power by energy market prices, higher returns should be expected, and this is the next case scenario.

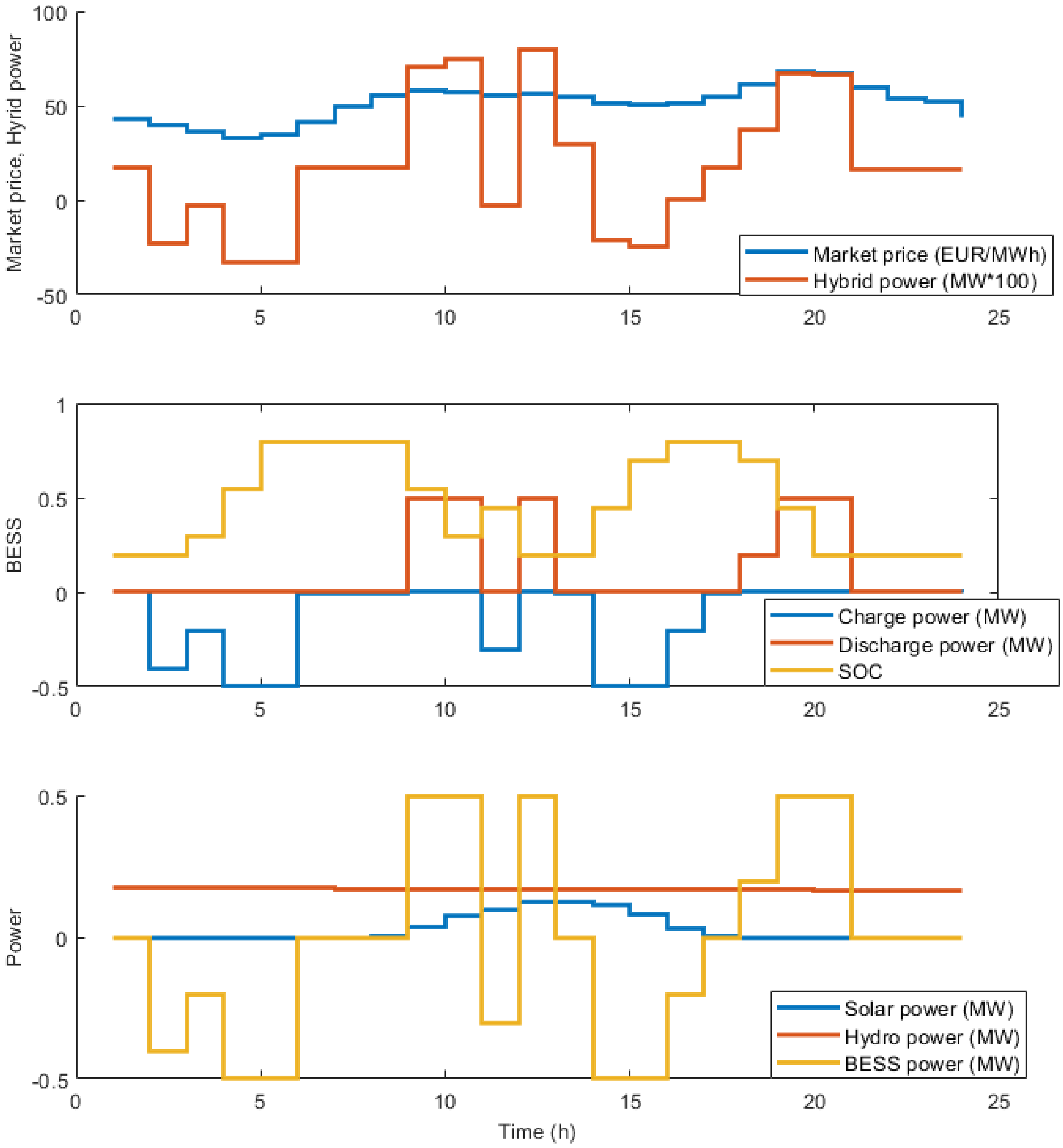

Figure 4.3: Case 2 optimised power dispatch

4.1.3 Case 3 - Hybrid power system in day-ahead market

Case 3 optimization is similar to case 2 with the addition of charging BESS from power generated inside the powerplant itself. The optimization process becomes more complex ad its flowchart is shown in Figure 4.4. The figure shows that after 24-hour data from the day-ahead market and production from renewable sources is generated, hydro and solar power is split into two ways. The first power split of hydro and solar is used to charge BESS and the rest of the power is sold to the electricity market. This ensures that optimization utilized HES power to charge BESS without any cost, which decreases the cost of charging the BESS. All optimization variables are fed to cost function and as in case 2, an iterative process of determining maximum profit is conducted. If the maximum is found and constraints are satisfied, the process is repeated for a subsequent day for a total of three months.

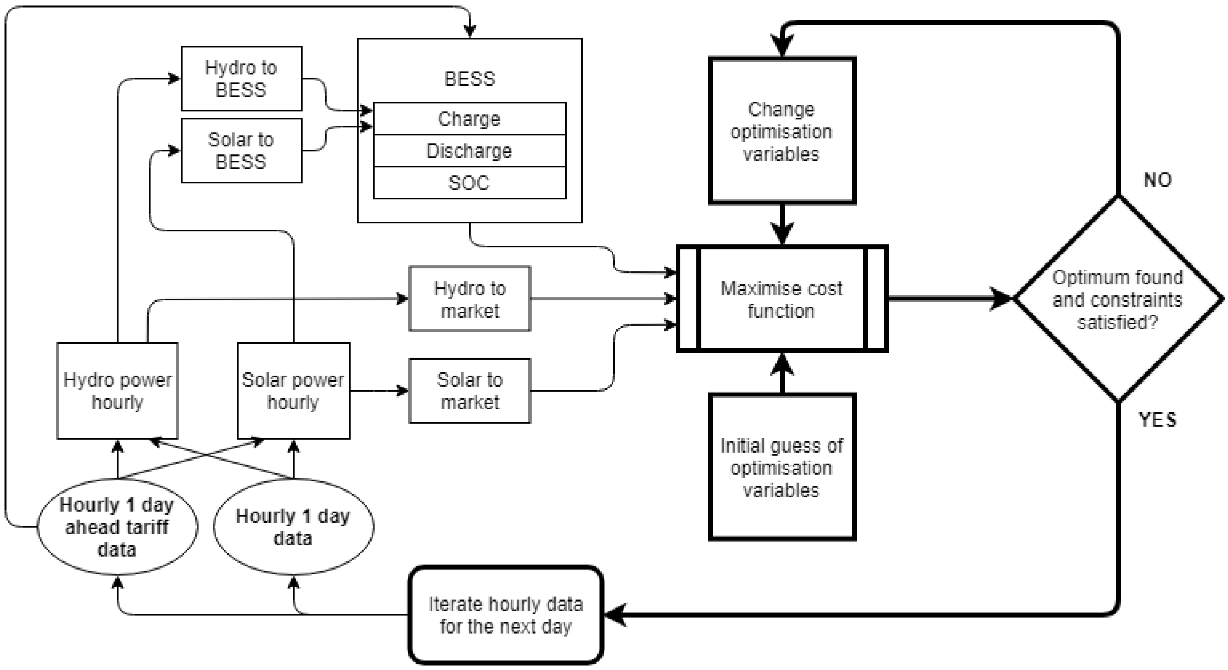

Figure 4.4: Case 3 flowchart

Optimisation of HES with utilisation of energy from power available in HES itself, and buying rest of BESS energy from the market and dispatching accumulated energy on high market prices is the goal. Cost function for optimised scheduling to achieve maximum profits is:

$$max\,[f(P_{hi}, P_{si}, P_{di}, P_{ci})] = \sum_{i=1}^{24} M_{pi} * (P_{hi} + P_{si} + P_{di} + P_{ci}) \tag{4.7}$$

With constraints:

Bound constraints:

$$0 \leq P_{di} \leq 0.5 \tag{4.8}$$

$$-0.5 \leq P_{ci} \leq 0 \tag{4.9}$$

$$0 \leq P_{hpi} \leq 0.5 \tag{4.10}$$

$$0 \leq P_{spi} \leq 0.5 \tag{4.11}$$

$$-0.5 \leq P_{cpi} \leq 0 \tag{4.12}$$

$$0.2 \leq SOC_i \leq 0.8 \tag{4.13}$$

Linear equality constraints:

$$SOC_i - P_{di}/2 - P_{ci}/2 - P_{cpi}/2 - SOC_{i+1} = \begin{cases} 0.2 & \text{if i = 1,24} \\ 0 & \text{otherwise} \end{cases} \tag{4.14}$$

$$P_{hi} + P_{hpi} = P_{Hi} \tag{4.15}$$

$$P_{si} + P_{spi} = P_{Si} \tag{4.16}$$

Linear inequality constraints:

$$P_{hpi} + P_{spi} \geq -P_{cpi} \tag{4.17}$$

$$-0.5 \leq P_{cpi} + P_{ci} \leq 0 \tag{4.18}$$

Non-linear equality constraints:

$$P_{ci} * P_{di} = 0 \tag{4.19}$$

$$P_{cpi} * P_{di} = 0 \tag{4.20}$$

$$(P_{hpi} + P_{spi}) * P_{di} = 0 \tag{4.21}$$

Where:

M_{pi} - Market price at i-th hour

P_{hi} - Hydro power sold to market at i-th hour

P_{si} - Solar power sold to market at i-th hour

P_{di} - Discharge power at i-th hour

P_{ci} - Charge power at i-th hour

P_{hpi} - Hydro power charging to BESS at i-th hour

P_{spi} - Solar power charging to BESS at i-th hour

P_{cpi} - Charging power to BESS from HE S at i-th hour

P_{Hi} - Total available hydro power at i-th hour

P_{Si} - Total available solar power at i-th hour

SOC_i - State of charge at i-th hour

Cost function 4.7 is the same as in the previous case, but new variables within constraints are introduced. Firstly, P_{cpi} is the power used for charging the BESS from the HES, which is further divided into solar and hydro charging P_{hpi}, P_{hpi}. This way 8 variables are in total in the constraints for each hour, which makes sure that HES can store energy from itself rather than buying from the grid if it is more cost-effective.

Firstly bounded constraints (4.8, 4.9, 4.10, 4.11, 4.12, 4.13) are fairly simple, all of the variables have upper and lower limitations to make sure power plant operates within nominal ranges. Three linear equality constraints are generated, first constraint 4.14 is the same as in the previous case which calculates SOC for each time step, next two constraints 4.15 and 4.16 limit the power generated from hydro/solar sources to be equal to the sum of power sold to market and power charged to BESS. The next type of constraints are linear inequality constraints where 4.17 limits power plant charging to be equal or less to the power provided from solar and hydropower, other constraint 4.18 makes sure that overall charging from market and power plant is within BESS max charging power capability. Lastly, all of the non-linear constraints (4.19, 4.20, 4.21) do not allow any charging and discharging to happen at the same time.

One day optimisation results are shown in further figures 4.5, 4.6, 4.7. Figure 4.5 represents available power from hydro and solar sources with respect to how much power is given to the grid and to BESS. As seen from the figure, the total power of hydro and solar is equal to power given and power to BESS. These power changes are market-driven and the benefit of charging the BESS from the plant is because the energy price is equal to 0.

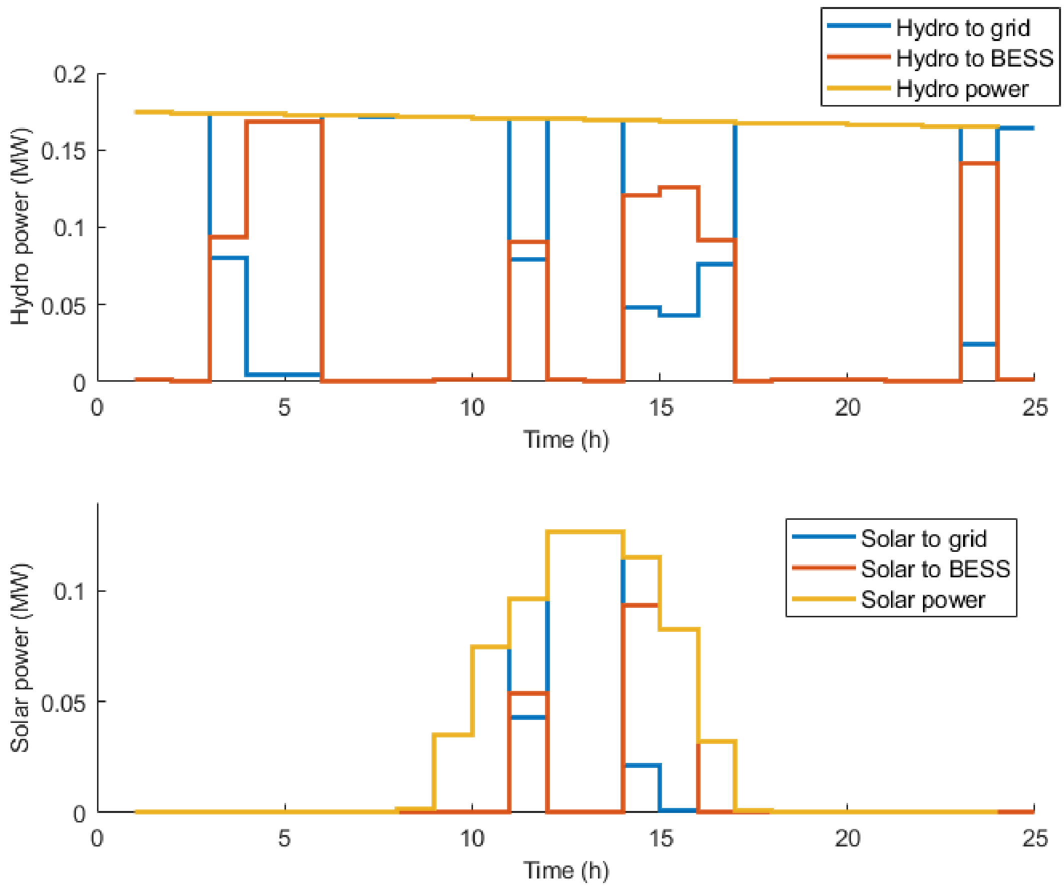

Figure 4.5: Power distribution to grid and to BESS

Figure 4.6 represents BESS characteristic. It is evident that charging and discharging did not occur at the same time and that BESS completes 2 cycles in a day for the best profit. It can also be seen in the lower graph that BESS is being charged from internal HES sources to utilize its available energy when there is economic benefit in doing so.

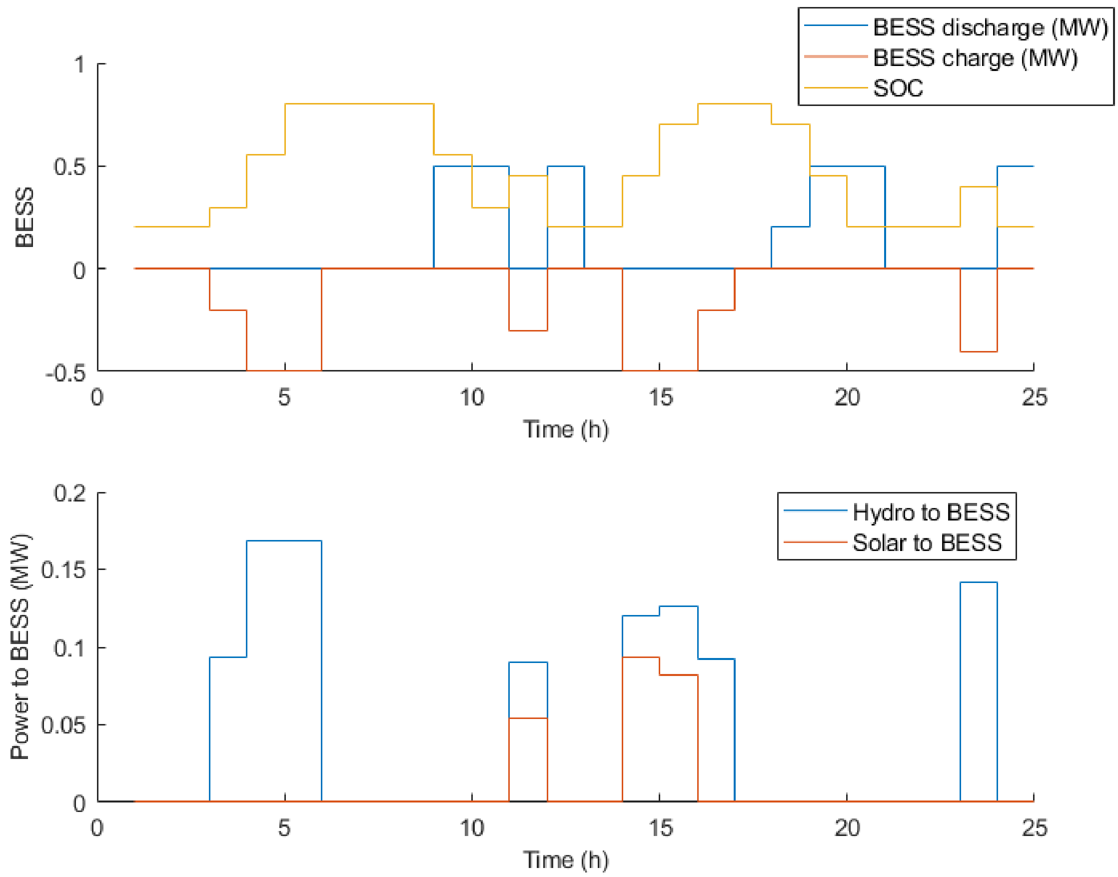

Figure 4.6: BESS operation

The last Figure 4.7 shows overall power plant power dispatch in relation to the market prices. It can be seen that HES takes power from the system at low market prices to utilize it to the high prices. This power dispatching will be further investigated in relation to the actual load demand to see if the power plant follows demand more closely.

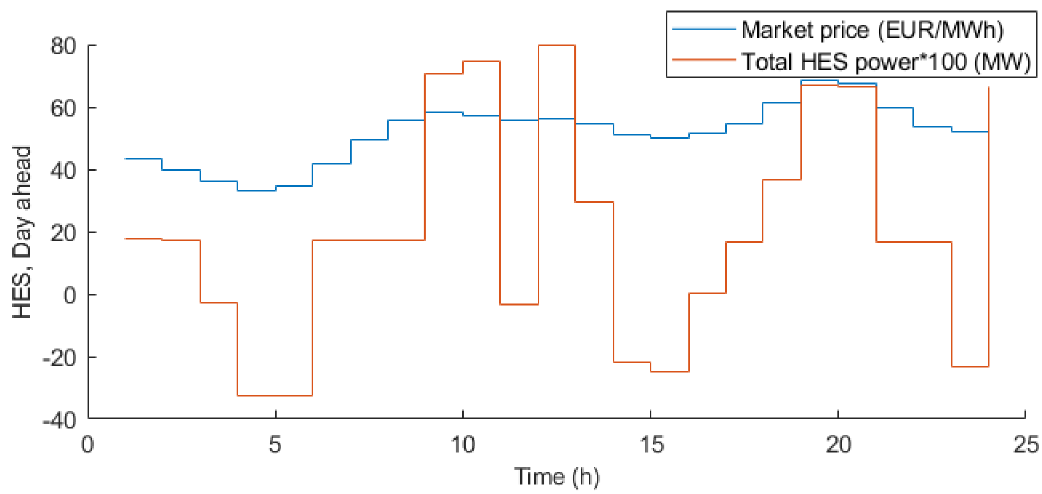

Figure 4.7: HES power and day ahead market prices

Profitability results in case 3 for three months are shown in Table 4.4, as seen from the table, Case 3 optimization resulted in an increase of 4.63% more profits in three months with the utilization of HES available power to charge BESS.

Table 4.4: HES performance - Case 3

Type	Profit (EUR)
Case 2	
Hydro energy	21 675
Solar energy	3 096
Total	24 771
Case 3	
Hydro energy	18 245
Solar energy	2 520
BESS	8 184
Total	28 949

4.2 HES optimized scheduling results and demand performance

Overall cases are composed in Table 4.5. Results from Case 3 optimization show overall better performance than in Case 2 with an increase of 4.63% in profits, and compared to Case 1, overall 16.86% more profit is generated. This optimal scheduling is therefore the best way to utilize power in comparison with the rest of the cases. It can also be seen that in Case 3 less hydro and solar power profits are generated while BESS profits are increased, due to HES charging itself. BESS absolute energy dispatched is also generated, because total energy is 0, the absolute value shows BESS involvement in the power dispatch. BESS absolute energy in Case 3 is shown to increase from Case 2 by 7.8% meaning that BESS is more active in power dispatch.

Table 4.5: HES performance

Type	Energy (MWh)	Profit (EUR)
Case 1		
Hydro energy	551.75	21 675
Solar energy	81.53	3 096
BESS	0	0
Total		24 771
Case 2		
Hydro energy	551.75	21 675
Solar energy	81.53	3 096
BESS	|509.33|	2 896
Total		27 667
Case 3		
Hydro energy	551.75	18 245
Solar energy	81.53	2 520
BESS	|549.40|	8 184
Total		28 949

HES optimal scheduling is done from an economic aspect and a significant increase in profits generated from the day-ahead market is shown. The question that arises is that how would HES perform in the technical aspect more related to load demand. Figure 4.8 is therefore generated. The figure shows per unit values in HES generation and demand, it is important to note that values are not to scale because HES is not scaled enough to compensate the whole distribution grid. This figure only represents a follow-up to the demand, but it is justified by fact that future power systems will have a larger generation share than current systems. In Case 1 with no BESS, HES dispatches energy as produced and therefore demand is not followed by any means, but case 2 and case 3 reveal interesting results. Firstly it is important to note that electricity price in day-ahead market does not necessarily follow distribution grid demand because prices are determined by the whole transmission power system and investigated cases are the only fraction of the overall system. HES power dispatch in cases 2 and 3 show higher power deviations but power dispatch is relatively dispatched when system demand is higher. Since HES power deviation is increased, it is important to conduct an effect on system frequency to show if HES is negatively affecting stability, this is conducted in Chapter 5.

Following the current renewable policies, it is expected that number of CHP polluting plants will be decreased and this opens new areas for renewable plants to replace production units with clean energy. If more renewable is implemented with different combinations of systems like solar, hydro, wind, and energy storage, it is expected that a diversified renewable energy portfolio will generate more consistent power throughout the day or night when demand changes. For example, the future system could have more wind and hydropower which could serve as base power, and energy systems would buy produced power in low demand because of lower prices. In this way goal of utilizing power close to the demand is achieved which decreases DSO financial and technical involvement in the system.

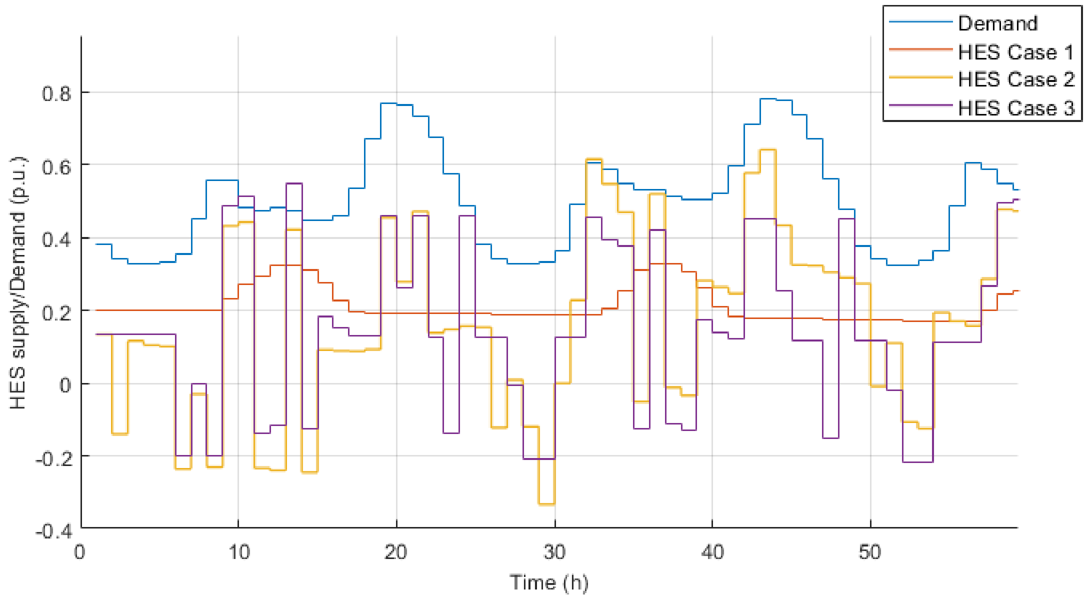

Figure 4.8: Demand vs. HES supply

4.3 Conclusion

After an investigation of optimal scheduling of HES in the day-ahead market, obvious profits from energy dispatch are observed. But deregulated market scheme still has to be implemented, and to implement deregulated electricity market government should play a crucial role. With observed results of showing negative consequences of the current market scheme as shown in Chapter 3, and positive more self-sustainable deregulated scheme conducted by this chapter, it can be concluded that governmental policies in the market scheme are eminent.

While the optimization process in the day-ahead market resulted in more profits, the current market scheme for payments to the DGs is provided directly from the consumers. In the deregulated market the fees of compensating power plants would be eliminated. This means that from a consumer point of view, electricity prices would be lower while maintaining the safe and robust operation of the power system where power plants would be paid in direct correlation with demand in the day-ahead market.

Although benefits are observed with optimized scheduling, Figure 4.8 revealed very high power changes in HES dispatch throughout the day, this could negatively affect system stability and this is the underlying reason why frequency stability will be investigated in next Chapter 5. Further simulations and effects are therefore developed and discussed.

5 | Dynamic stability of HES

Investigating frequency control is crucial for every power system. Frequency deviation is dependent on power demand and supply [33] . If a power system experiences sudden power changes in supply or demand, frequency changes but as already explained in Chapter 2 grid code defines strict rules in which frequency range has to be maintained.

Frequency response in grid-connected power systems is regulated with large power plants which can provide enough inertia and reserve power for regulating purposes. In the MV system investigated in this project, the system is connected to the main power grid, and therefore it is assumed the impact of HES frequency control in the connected grid would be unobserved because of the low power output of HES relative to large grid power plants. But trends as already stated trends in higher DG implementation tend to allocate power near consumers and therefore more self-sustainable systems will emerge [9], this means that investigating islanded systems without grid support is necessary to conduct. Also trends in development in virtual power plants and aggregated zones (more self-sufficient generation and flexible demand loads) have the tendency to provide ancillary services. This justifies the need for hybrid power systems which in future power systems will deliver system services such as frequency and voltage control, especially with decommissioning large power plants and implementation of RE sources. With this said, more resilient DG systems to load change will be needed.

Hybrid power system regulation in a distribution system can be justified with two aspects, first aspect would be system support if transmission level fault occurs so that DG could provide system regulation. The second consideration is the resilience of the system in respect to natural disasters, on 29 December 2020 nearby city of investigated HES was hit by an earthquake of 6.4 magnitude on the Richter scale which left thousands of people with no electricity [34] . In this special case, undamaged parts of the power system could operate in islanded mode and self-regulate grid constraints to keep supplying consumers when most needed. Other than earthquake scenarios where natural disasters occur in different forms and are more common due to climate change [35].

Because of these reasons, system frequency stability in the islanded case will be conducted. Firstly, short background and system parameters are analyzed and further system scenarios and their performance is investigated.

5.1 Generator and Load frequency response

A study of the frequency stability of the hybrid power system will be conducted in order to investigate responses to supply/demand deviations. The simplified control system is developed to understand coordination between power sources and system changes and events.

Implementation of frequency regulation starts with swing equation of synchronous machine that evaluates change in rotor speed with change in mechanical and electrical power shown as [33] :

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \tag{5.1}$$

Where:

H - normalized inertia constant

ω_s - the rotor synchronous speed

δ - the change in the rotor angle

$\Delta P_m - \Delta P_e$ - the difference between the electrical and the mechanical power.

Further equation Equation 5.1, in terms of small deviation in speed and with speed expressed in per unit with $\frac{\omega}{\omega_s} = \omega$ becomes:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \tag{5.2}$$

And in Laplace form of Equation Equation 5.2:

$$\Delta\Omega(s) = \frac{1}{2Hs}(\Delta P_m - \Delta P_e) \tag{5.3}$$

After the synchronous generator equation is obtained, electrical loads are looked into. Electric loads can be divided into loads that are independent of frequency (resistive load character) and dependent on frequency (motor loads). Load frequency sensitivity is obtained from speed-load characteristics which for simplicity is further characterized as one load. The composite speed-load characteristic is given as:

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{5.4}$$

Where ΔP_L is the frequency-independent load component and D $\Delta\omega$ is the frequency sensitive load change. D is expressed as the percent change in load divided by change in frequency. With this equation system can be drawn as shown in Figure 5.1, this means that some of the change in power generated and load will change the frequency with respect of systems sensitivity to frequency.

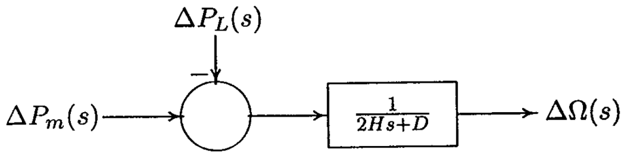

Figure 5.1: Block Diagram for the combined generator-load model [33]

So far the system is shown in Figure 5.1 does not have any control system and therefore its response to load change will generate a non-stable system, this is solved by implementing a control system that uses the change in frequency to generate a signal to manipulate system power production and therefore control frequency deviations.

5.1.1 Frequency Regulation Control

Any system disturbance in production and demand generates frequency change and it is crucial to keep frequency deviations within grid code margin. To mitigate high-frequency deviations, primary and secondary frequency control is implemented. Primary control or also called droop control and is responsible to keep frequency within certain levels and it is implemented as part of the governor, the primary control has a faster response time and it serves as a damper to the frequency drop. Primary control regulation after reaching steady-state generates error from nominal frequency and for this reason, secondary control or load frequency control (LFC) must be implemented. In investigated case PI controller is utilized as shown in Figure 5.2. Primary control of the synchronous generator stabilizes frequency and further LFC (also called automatic generation control (AGC)) corrects frequency error with the PI controller.

Another layer of control is called the regulation participation factor show in 5.2 which determines which power source is more prevalent in controlling the frequency. The participation factor decides the regulation to be the contribution from individual units participating in LFC. The participation factor to each unit is determined based on the economic scheduling of the units (it could also be decided on fast response, ramping, and others) participating in frequency regulation. The Sum of both participation factors is 1 and different levels will be investigated.

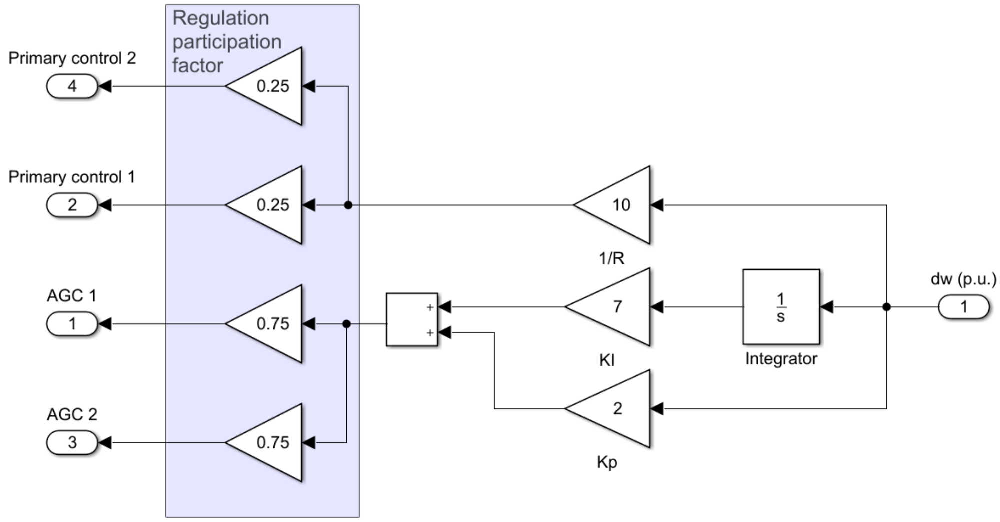

Figure 5.2: Simulink model for the control feedback for AGC and primary control

5.1.2 Hydro turbine model

Simulating frequency response is done via governor-turbine block utilized from [33]. Governor transfer function regulates turbine output level and therefore changes the mechanical output of the hydropower plant which further upon disturbances stabilizes turbine speed to some steady state. The turbine transfer function is responsible for following turbine output as mechanical power to generate electrical power. Figure 5.3 represents governor-turbine in simulation.

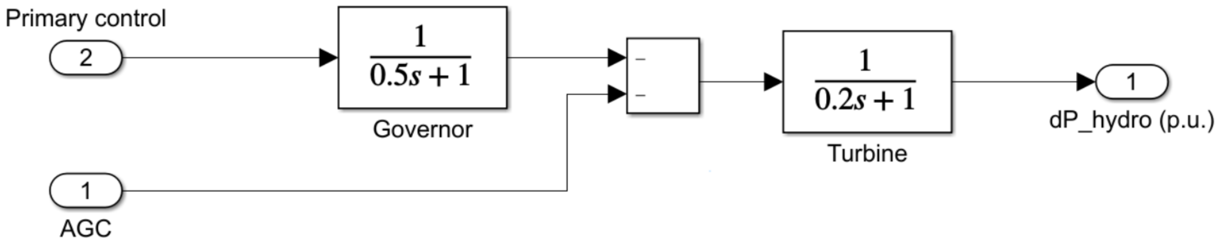

Figure 5.3: Governor-turbine model in Simulink

5.1.3 BESS model

Battery model utilised is taken from [36], and its transfer function from [37]. BESS work principle is very simple and Figure 5.4 represents the simulation of BESS used. Firstly control commands are forwarded into BESS and the first limiter determines maximum and minimum power output, the first comparison block checks if SOC allows discharging and the second comparison block allows discharging. BESS system starts as 50% SOC at the beginning of the simulation and it can BESS can provide maximum power up to 2.5 hours. Integrator block in BESS loops energy dispatched to follow

SOC and this is divided by maximum SOC to exit as a variable in further simulations.

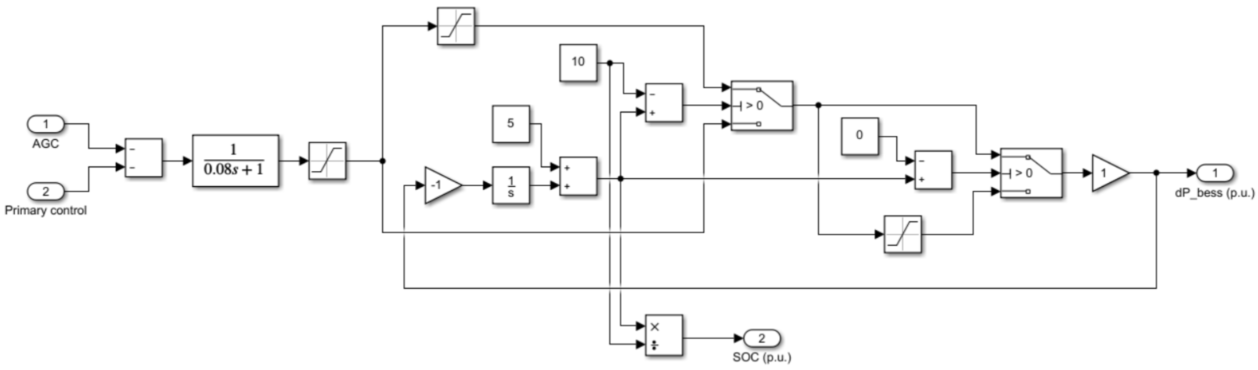

Figure 5.4: Simulink battery model

5.1.4 PV production and load demand

In order to simulate power disturbances in the system PV and load, deviations are generated as shown in Figure 5.5. Load and PV generation changes are taken from [36], and further two deviations are added to simulate higher changes. Firstly load changes at 10th second with load rise event of 0.3 p.u. where this simulates sudden load increase, and secondly 0.2 p.u. increase at 5th second represents sudden PV production change. This allows simulations to stress test high load change and PV production change to observe system behavior with a different setup.

Figure 5.5: Load and PV power deviations

5.2 HES simulation models and scenarios

A simulated HES isolated system is shown in Figure 5.6. As seen from the figure, all of the units are per unit and all powers represented are power changes, not power outputs. This means that the system starts as a stable closed-loop and power changes will generate frequency instability and units responsible for compensating are hydro generator and BESS. Power units are added to one with summation block and further system inertia and load response generate frequency change also as per unit value. Changes in frequency are forwarded to the Feedback control block which generates input signals for BESS and hydro generator. The feedback loop should be able to control frequency within grid code which is +/- 0.5Hz or 0.01 p.u..

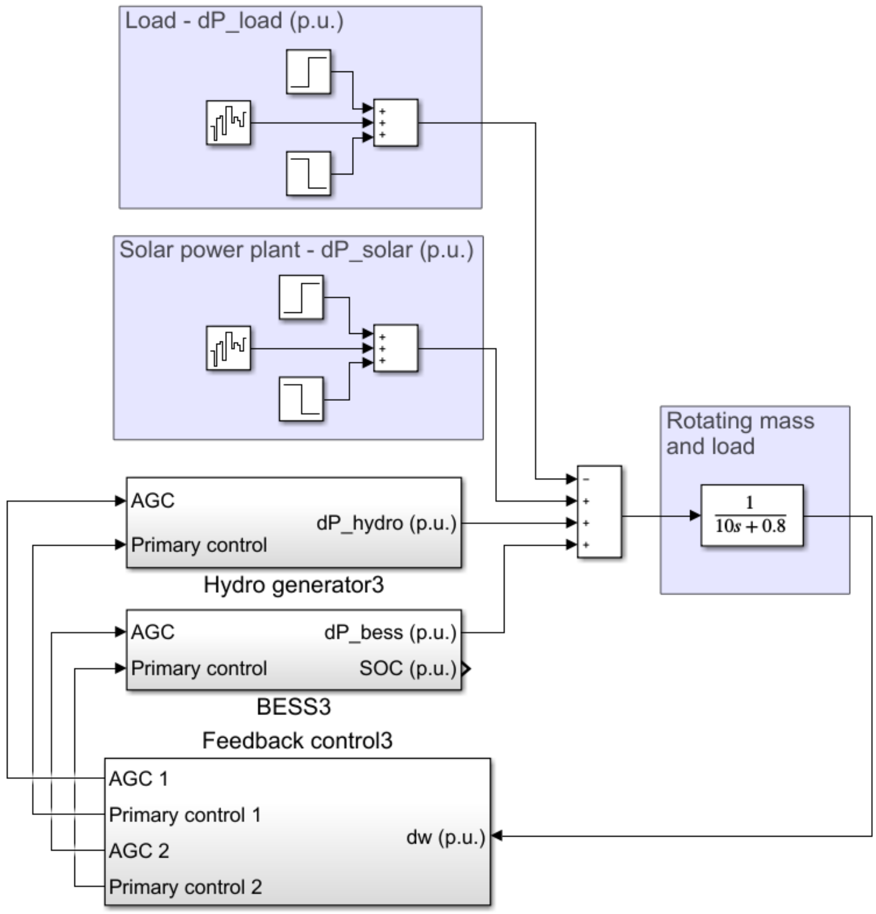

Figure 5.6: Simulink model for diesel scenario

Simulation constants are given in Table 5.1. Constants are taken from [33].

Table 5.1: Constants used in simulations

Model	Description	Value	Symbol
Inertia and load response	Inertia constant	10	2H
	Load damping constant	0.8	D
Control feedback	AGC pi-controller P	2	Kp
	AGC pi-controller I	10	Ki
	Speed droop	10	$\frac{1}{R}$
Hydro generator	Time constant for prime mover	0.2	τ_T
	Time constant for governor	0.5	τ_G

Simulations under investigation are divided as follows:

- Case 1 - Single area HES without BESS and different regulation participation factor
- Case 2 - Single area HES with BESS and different regulation participation factor

For regulation participation factor 3 scenarios are generated as shown in Table 5.2.

Table 5.2: Primary control and AGC participation factors

Control	Hydro generator	BESS
Control scheme 1		
Primary	0.25	0.25
AGC	0.75	0.75
Control scheme 2		
Primary	0.5	0.5
AGC	0.5	0.5
Control scheme 3		
Primary	0.75	0.75
AGC	0.25	0.25

5.2.1 Case 1 - Single area HES system without BESS

In the first case HES does not utilize BESS. System used in simulation from PV and load changes from sub-chapter 5.1.4 is shown in Figure 5.7, and simulation results are represented in Figure 5.8.

As seen from Figure 5.8 every power disbalance destabilizes frequency and compensating hydro unit increases or decreases power output in inverse to the frequency change. If the frequency drops hydro generator increases power output and vise versa. This system does not have a participation factor because only one source of energy is used to stabilize frequency. Case 2 investigates scenarios when BESS is included as a HES system.

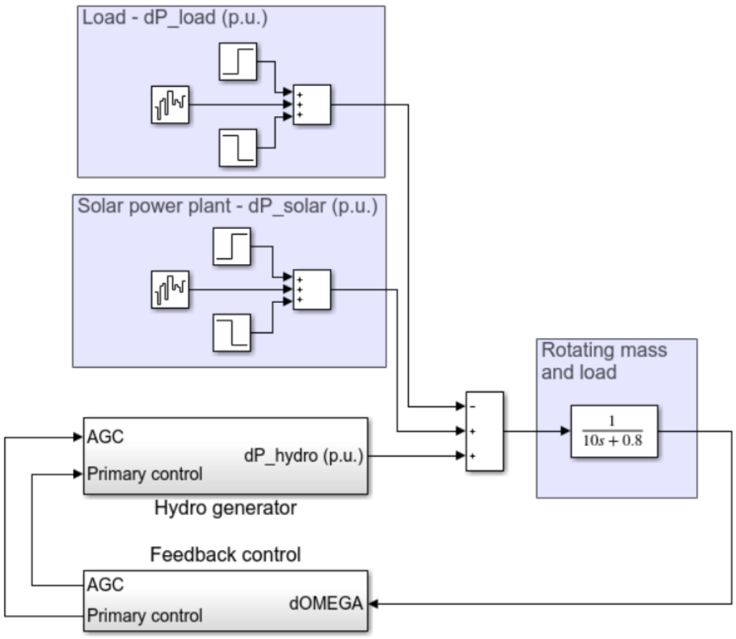

Figure 5.7: Simulink model for HES without BESS

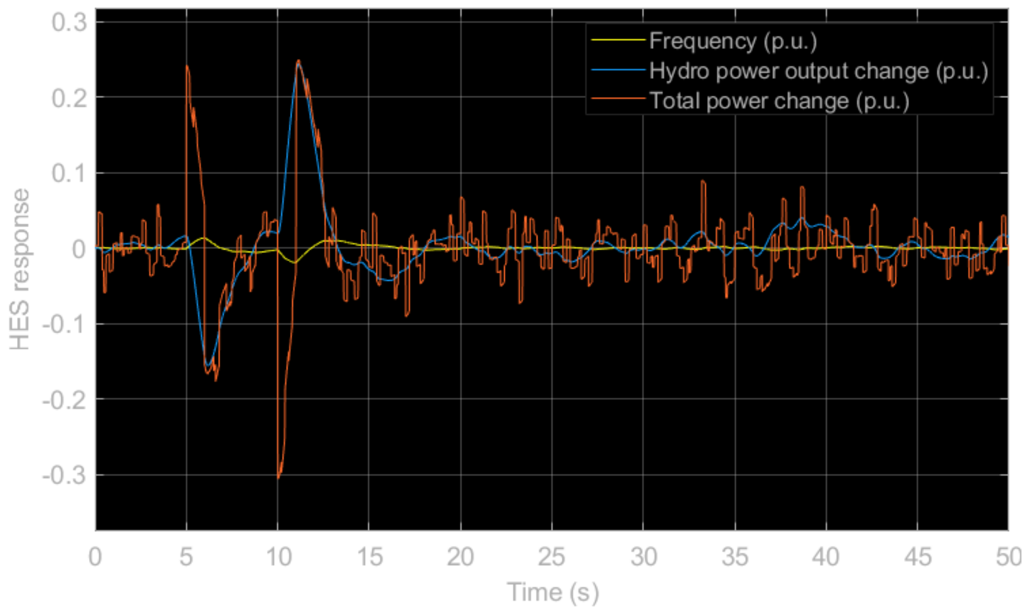

Figure 5.8: Simulink simulation of frequency response - Case 1

5.2.2 Case 2 - Single area HES system with BESS

In scenario 2, the same load and PV disturbances are generated, with the same participation factors included in the Feedback control system with BESS as part of the hybrid energy system. Simulation model used from Figure 5.6 generates results seen on Figure 5.9

Investigation for best participation factors is demonstrated in Figure 5.9. Figure 5.9 shows Case 2 results with participation factors shown in Table 5.2, as seen from the figure, control scheme 3 has

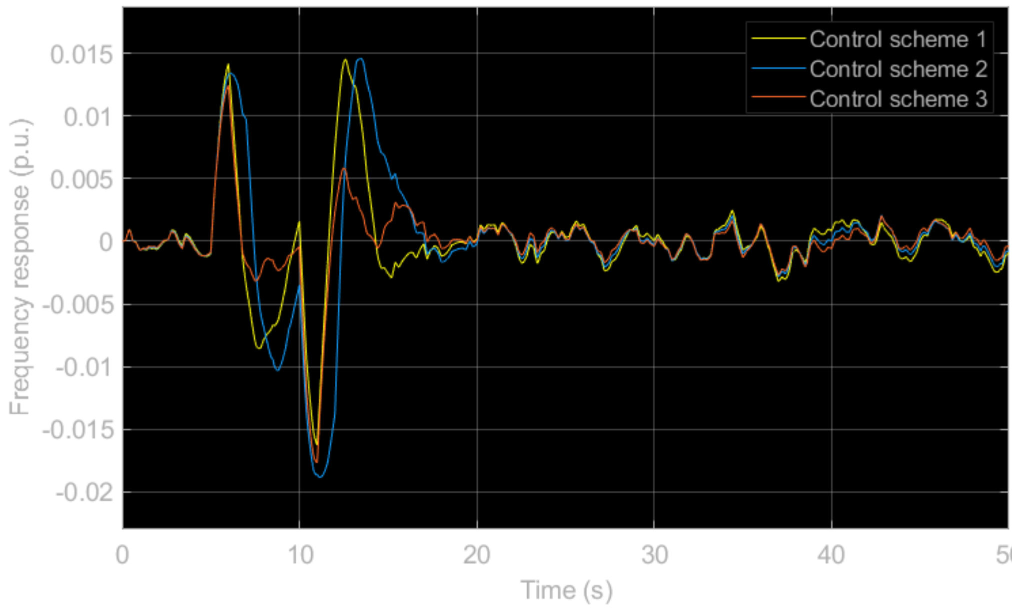

Figure 5.9: Simulink simulation of frequency response - Case 2

the best performance compared to the other two cases. The participation factor in control scheme 3 favors primary control with a factor of 0.75, and AGC participation of 0.25 frequency oscillations is lower. In control scheme 3, both instantaneous load and PV changes generate approximately 0.015 frequency deviations. The significant performance increase is frequency overshoot once deviations are decreased, this occurs at 7s and 12s in the figure, overshoot is significantly less impactable compared to other cases. Because of better performance, control scheme 3 will be further compared with HES without BESS to observe any potential benefits.

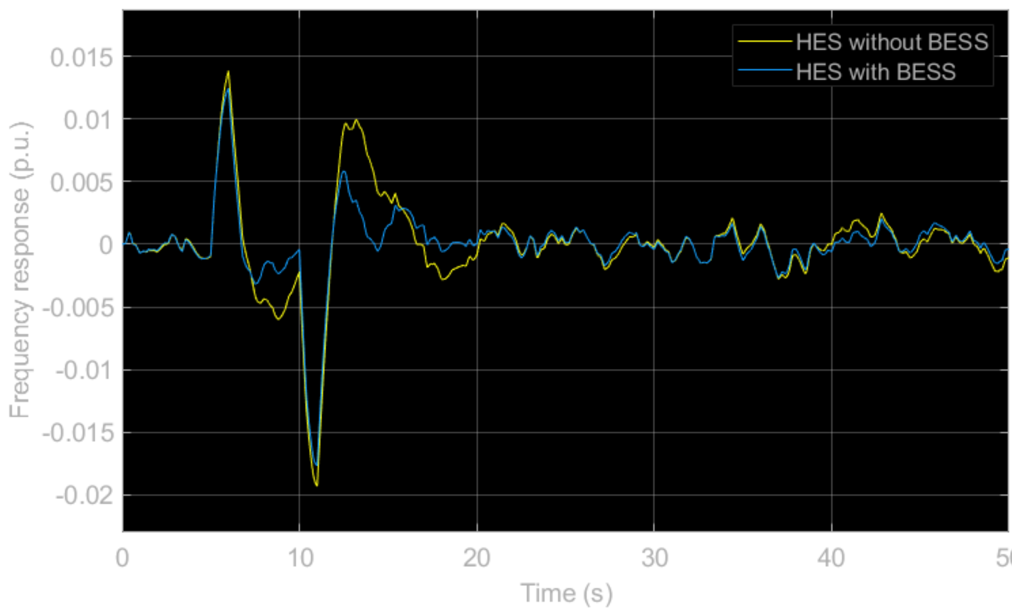

Figure 5.10: Simulink simulation of frequency response - Case 1 and 2

Comparing the best-simulated control scheme from case 2 with case 1, Figure 5.10 is simulated. Simulations show that implementing BESS into the system decreases sudden load change for approximately 0.002 p.u. and frequency overshoot after load change at 7s and 12s for about 0.004 p.u.. This frequency response improvement is significantly better, but the bottleneck is that according to the grid code, frequency has to stay within +/- 0.01 p.u. but in case of too high load or PV change, this is not the case.

Further observations are shown for best performing case with BESS shown in 5.11. It is seen that BESS SOC increases when PV generates power difference as excess energy and also that load change of 0.3 p.u. utilizes BESS power and therefore SOC decreases rapidly.

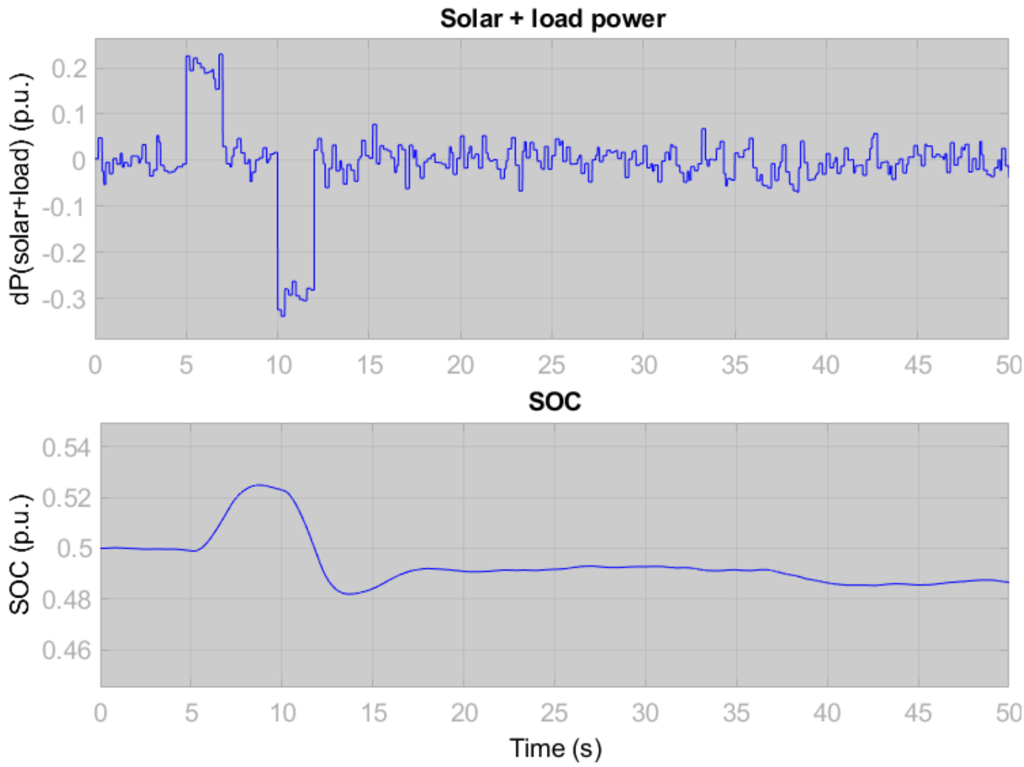

Figure 5.11: Simulink simulation of SOC in Case 2

Lastly, Figure 5.12 represents total power change probed after summation block seen at 5.6. Sudden total power change with system inertia and load demand is responsible for frequency deviations and compensation of hydro generator and BESS power output difference is shown. Power output difference between sources is very similar but BESS slightly outperforms hydro generator in power output difference, or in other words, BESS can slightly faster response to the frequency deviations, and therefore it is very useful in system stability control.

It should be noted that BESS and hydro generators have limits in power output which can be the bottleneck if any of mentioned is already running at full power, or if hydro energy is not available

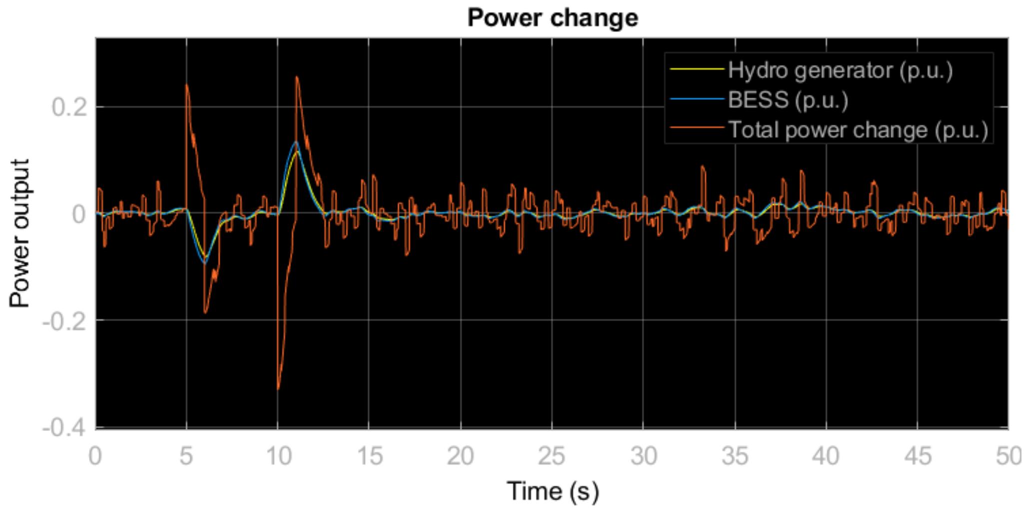

Figure 5.12: Simulink simulation of power output in Case 2

in such quantities, the system is unable to contribute to frequency stability. BESS also has SOC limitation and therefore it should be properly scheduled independence of SOC but this is out of the scope of the investigated project. Therefore HES could provide system support but it cannot follow demand at all times, especially if BESS is discharged.

5.3 Conclusion

System stability conducted is gradually explained through background and main equations explaining basic phenomena. Further for the control system, primary control utilizes proportional control and AGC PI controller, different control parameters are investigated and pest performing ones discussed. Observations show that participation of PI controller has to be decreased because it generates higher oscillations in frequency deviations.

Considering the grid code regulations, frequency has to be maintained within +/- 0.01 p.u. and HES is able to satisfy these criteria if the power that has to be compensated is lower than 0.2 p.u.. Load change on 0.2 p.u. would be observed in Chapter 3 if one of the high consuming loads would disconnect, meaning that for MV system modeled in islanded mode, would be able to maintain frequency-stable if HES would provide enough power. Since future DG-s are expected to increase renewable sources this scenario where HES is able to provide much more power is definitely possible. Overall dynamic frequency study showed that in special case if the system would be islanded, the frequency would be stable according to the grid code.

6 Discussion

Future power systems will change in many ways from conventional power systems. Integration of new technologies, renewable sources, and intelligent synergizing many power systems will further try to achieve better performance, lower operational costs, power quality, and green power. Future trends tend to reverse typical power systems where big powerplants dispatch large amounts of power to long distances to the consumers. Current power grids are gradually changing where power is produced in smaller units closer to the consumers. These trends have already begun with private entities investing in DG where governmental subsidies are provided to speed up the process of implementing renewable energy. However, governmental subsidies are decreasing as renewable technology gets cheaper over time and this causes power producers to trade electricity in the electricity markets.

Hybrid power plants offer a significant improvement in continuous energy dispatch, system stability, and economic profitability. HES in distribution systems can easily adapt to new policies with the implementation of optimization techniques which showed to achieve many benefits to both DSO and investor. Renewable energy systems also can adapt to change their function as system frequency control in special cases, so it makes the system more resilient to abnormal conditions. However, further investigations on effects in the system must be conducted if energy is dispatched based on the day-ahead market since HES tends to switch power output based on profitability. This can be addressed if investigating more active loads are part of the system and also if consumers would be based on changing market prices. These effects on future power systems would generate more concrete solutions to HES optimization.

As far as the technical aspect of the implementation of HES is considered. A lot of current research is being done to optimize HES sizing, operation, increase efficiency, and others. The contribution of different renewable sources has been shown to complement power production units inefficiencies, for example in this thesis, hydro and solar energy are inversely produced as the rainy season blocks PV production but increases hydro production. But other challenges arise with a higher level of HES implementation, combining load supply, DSO regulation and system efficiency can cause more problems than solutions. This could be overcome by close work of DSO and HES owners so that careful planning does not cause more issues in the distributed system.

Regarding economic challenges and potential solutions HES has shown to have a great opportunity in the profitability of the plant. HES typically has an energy storage system and different technologies can be utilized, with cheaper battery storage and emerging hydrogen solutions, more system control will be able to provide a continuous and more reliable power supply. Although these technologies are being implemented, their economic investment is still questionable. Further implementation of these solutions will cut prices so that energy storage systems will be able to generate economic profitability.

The relatively new frontier in intelligent systems is virtual power plants. Virtual plants tend to include small generating units to have more reliable power dispatch. Virtual power plants are somewhat similar to HES but their energy source location is dispersed over the area. This type of plant further optimize economic scheduling with modern techniques and develop more sustainable energy areas. Virtual power plants could in theory replace large-scale power plants to provide system services such as voltage and frequency support.

An expected change in future power systems is an integration of more flexible loads that are able to store energy for later consumption. Examples of flexible loads include residential air conditioners, water heaters, commercial HVAC systems, and others. With flexible loads, more coordination will be needed with HES in order to actively react to each others demands. Coordination will also be needed to avoid peak hours and keep nighttime demand higher, which will flatten the power curve and generate fewer system issues.

The last consideration in future power systems is discussing all of the power system stakeholders who are power plant owners, consumers, and DSO. Satisfying all of the mentioned technical constraints, usually economic behind all of the system contributors must be considered. DSO would prefer cheaper system maintenance, lower losses, and simpler control while power plant owners prefer higher electricity prices which is contrary to consumers. With the liberalization of markets, electricity will be more similar to a traded commodity where demand and supply dictate the price. This approach gives a more efficient and reliable power system, where each system stakeholders would benefit.

7 | Conclusions and Future work

7.1 Conclusion

The objective of this project was to conduct optimized scheduling, economic operation, and distribution grid integration studies of a hybrid power system. This thesis shows that individual aspects of the system have to be investigated, such as steady-state simulations, optimized scheduling, and frequency control to see all potential effects of the hybrid energy system integration. The goal of the project is achieved through different chapters and the findings of each are summarised below.

Starting with Chapter 2 it is evident that the uprise of distributed generation will change future system grid layouts, even though there are many benefits to have production closer to the loads there have to be market changes to incentivize this type of generation. Implementation of DG will be affected by governmental policies and, therefore, the law framework will determine the level of integration will be crucial from an investment standpoint, from a technical standpoint the grid code is determining operability and limitations of the plants. Lastly deregulated electricity markets are being implemented as governmental compensations decrease for renewable sources, this brings optimization techniques of different powerplants in order for it to generate higher returns.

In Chapter 3 investigation on the effects of the current distributed system showed that implementation of HES would not affect system stability in steady-state simulations. The current distributed system has large CHP plants which are not incentivized to follow the demand which causes voltage regulation issues, unnecessary grid losses due to overproduction, and return power back to the transmission system. This would be changed if the new market structure was implemented and DG owners would be prone to dispatch energy as they try to generate profits whenever possible based on the price.

A study of optimal scheduling based on the day-ahead market was conducted in Chapter 4. Different cases were generated to maximize profits generated from the day-ahead market. It is shown that HES could be optimized so that it utilizes as much energy possible and BESS to exploit price differences to have the best results. Cost functions and different constraints were subjected in order to optimally schedule the plant. Also with deregulating markets it is safe to say that consumer prices will decrease since current consumer market prices are developed so that consumer pays for privileged pricing of distributed generator owners.

System stability conducted in Chapter 5 showed that investigating frequency response is improved if the system was under abnormal conditions where HES is responsible for frequency control. As stated, current large power plants are responsible for frequency stability but in case of fault, natural disaster, or future power system without large power plants, frequency control has to be considered. An important finding is that HES has its limitations in the means of maximum load change that can be controlled with grid code limitations.

Overall, the conclusion can be made that the objective was successfully achieved with multiple simulations and system investigations. Implementation of HES in the distribution grid will not destabilize the system from a steady-state point of view, it will achieve better returns if optimally scheduled in respect to the day-ahead market, and in special conditions, it brings more stabile frequency control to the system.

7.2 Future work

Future research on integrating hybrid energy systems is revealed to have many potential positive outcomes from multiple standpoints and these include, consumers, power plant owners, and DSO. Following current research trends future work could include the following:

- investigating future more active load demand
- research new consumer pricing schemes
- developing optimal scheduling with grid constraints
- developing prediction models for day-ahead market and weather
- simulating active voltage control with HES
- optimizing parameters for better frequency response
- effects of implementation high level of renewable sources as DG
- impact on transmission level with high renewable sources in a distributed grid

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