ELECTRIC VEHICLE BASED BATTERY STORAGES FOR LARGE SCALE WIND POWER INTEGRATION IN DENMARK

By

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Abstract

In the recent years, the electric vehicles (EVs) have drawn great attention world wide as a feasible solution for clean transportation. The electric vehicle technology is not new as it was introduced in the mid 19th century. The low battery capacity, driving range and superior gasoline cars had resulted in the demise of electric cars in the 1930s. However, with the advancement of new high density battery technologies and power electronic converters, it is now viable to produce electric cars of higher efficiency and driving range. The performance and durability of the battery technology is improving on a rapid scale and the battery cost is also reducing which could enable the electric cars to be competitive in the market. The electric vehicles could also benefit the electricity sector in supporting more renewable energy which is also one of the most important driving forces in its promotion. In Denmark, there are many hours of surplus wind power production every year. This could be consumed locally through demand side management of electric vehicles by controlled charging of their batteries. Also, the EV batteries could discharge the stored electricity to the grid on demand, which is collectively termed as the Vehicle-to-Grid (V2G) concept. Thus, the EV storage could operate as a controllable load or distributed generator to minimize the power fluctuations resulting from increased variable wind power. The 2025 Danish Energy Policy plans for fifty per cent wind power production replacing most of the conventional generators. This is not desirable for a reliable and safe power system operation and control. The strategies like wind power regulation or increased cross-border transmission capacity may not be sufficient enough to realize the power system balancing. The former strategy spills the clean wind energy and latter could be expensive and limited as the neighbouring countries are also installing more renewable energy across their borders. One of the other alternative solutions lies with the local distributed storages which could be provided by the flexible, efficient and quick start solutions like the Vehicle-to-Grid systems. They could be aggregated as a large energy storage which could be an attractive alternative to the conventional generator reserves being replaced by the wind power.

The role of electric vehicles as a provider of active power balancing reserve is analysed here as a PhD study, where large amount of wind power are being installed in Denmark. This PhD thesis is organized as different case studies which are analysed as steady state or dynamic simulations on selected wind power dominated Danish power and distribution systems. Some of the worst case scenarios of power system operation, like coincident demand and wind ramp periods, days with high and low wind, reduced power balancing reserves, loss of generation etc. is applied in the case studies. The aggregated models of battery storage representing Vehicle-to-Grid systems, generation units and loads are used in these simulations. A generic model of Vehicle-to-Grid systems which can represent the storage constraints and duration is developed for the use in long-term dynamic simulations. Different control strategies are applied to integrate the Vehicle-to-Grid systems in isolated and interconnected power system operation. The operation strategies of conventional Load Frequency Control and generation models are modified to validate the grid power regulation services from the Vehicle-to-Grid systems. The simulation results from the case studies demonstrate the flexibility of Vehicle-to-Grid systems in operating as a generator or as a load to improve the frequency stability of large wind power integrated distribution networks. It provides smooth, robust and faster power system frequency regulation than the conventional generators in providing active power balancing. This superior performance of the Vehicle-to-Grid systems is also verified for an interconnected power system operation where the power exchange deviations between two control areas are significantly minimised. The extent of electric vehicle penetration in the power distribution systems also depends on the support of smart control strategies to facilitate the safe operation of the power system. This research work shows that the overall operation and control efficiency of power systems can be improved by introducing the Vehicle-to-Grid systems as a future grid regulation ancillary service provider substituting the conventional generation reserves.

Abbreviations

AMI	Advanced Metering Infrastructure
BEV	Battery Electric Vehicle
CEESA	Coherent Energy and Environment System Analysis
CHP	Combined Heat and Power
CPP	Condensing Power Plant
DPL	DIgSILENT Programming Language
DSL	DIgSILENT Simulation Language
EV	Electric Vehicle
ICT	Information and Communication Technology
LFC	Load Frequency Control
PHEV	Plug-in Hybrid Electric Vehicle
ROCOF	Rate of change of frequency
SCADA	Supervisory Control and Data Acquisition
SD	Standard deviation
Soc	State of charge
TSO	Transmission System Operator
UCTE	Union for the Coordination of Electricity Transmission
WTG	Wind Turbine Generator
WDK	West Denmark
V2G	Vehicle-to-Grid

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Chapter 1

Introduction

1.1 Background and Motivation

The global challenges of climate change, energy security and environmental pollution have made renewable energy increasingly significant in the energy system. In 2009, renewable energy holds one-fourth of the total global installed power capacity and it has supplied 18% of the global electricity supply [1]. The national policies in many countries have set ambitious targets for the promotion of renewable energy. In the European Union (EU), goals are set for 35% of electricity generation from renewable sources in 2020 and one-third of the renewable electricity is estimated to be produced from wind energy [2]. The wind power is one of the fastest growing renewable energy technologies, especially in the offshore sector. The onshore wind is a commercially proven-technology which is quite popular as distributed generation units. In 2009, the share of renewable energy in the new power installations was 62% in Europe, out of which 38% was from wind power [3]. Similarly, there was an increase of 32% in wind power capacity worldwide during 2009 [2].

In Denmark, the wind power supplies 20% of the annual electricity demand, which is the highest among other countries in the world [4]. In power generation, wind power is currently the most important source of renewable energy in Denmark. The total installed capacity of wind power in Denmark had reached 3730MW by the end of September 2010, including 868MW of offshore wind capacity [5]. Denmark has always promoted renewable energy and decentralized generation as part of its liberal energy policy. Denmark has also set targets for integrating more renewable energy in the years ahead. A 30% share of renewable energy is targeted in the Danish energy supply by 2020 and almost double the present wind power capacity is planned for 2025 [6], [7]. As a result, the renewable energy will be one of the major sources of energy production which has to be integrated smoothly to ensure that the system continues to function in a reliable manner. The renewable energy sources like the wind are characterised by the uncertain and variable energy production which demands for more balancing resources and larger investments. The situation becomes more challenging in the long term when the conventional fossil-fuel generators are phased-out of the energy production. Therefore, local energy solutions like new flexible energy consumption, storage and energy sources must be introduced to ensure an efficient use of energy resources and infrastructure. In the following subsections, a broad overview of the current features of the Danish power system, future energy policies, power balancing challenges and solutions due to high wind power penetration in Denmark are given.

1.1.1 The Danish Power System

Denmark has experienced a vast growth in distributed generation since the late 1980s. Fig. 1.1 shows two maps which illustrate how the Danish power system has evolved during the last two decade from a classical centralised system to a decentralised system of power generation [8]. The centralised power system is characterised by large steam turbine based combined heat and power (CHP) units which is shown as red dots, feeding power into 400kV and 150kV levels. The orange and green dots represent small gas-turbine based CHP units and wind turbines respectively which are dispersed throughout the distribution system at 60kV and below. About one half of the electricity production capacity in West Denmark is equally dominated by these two types of dispersed generation units [9]. Three-fourth of the total wind capacity is installed in the Western part of Denmark.

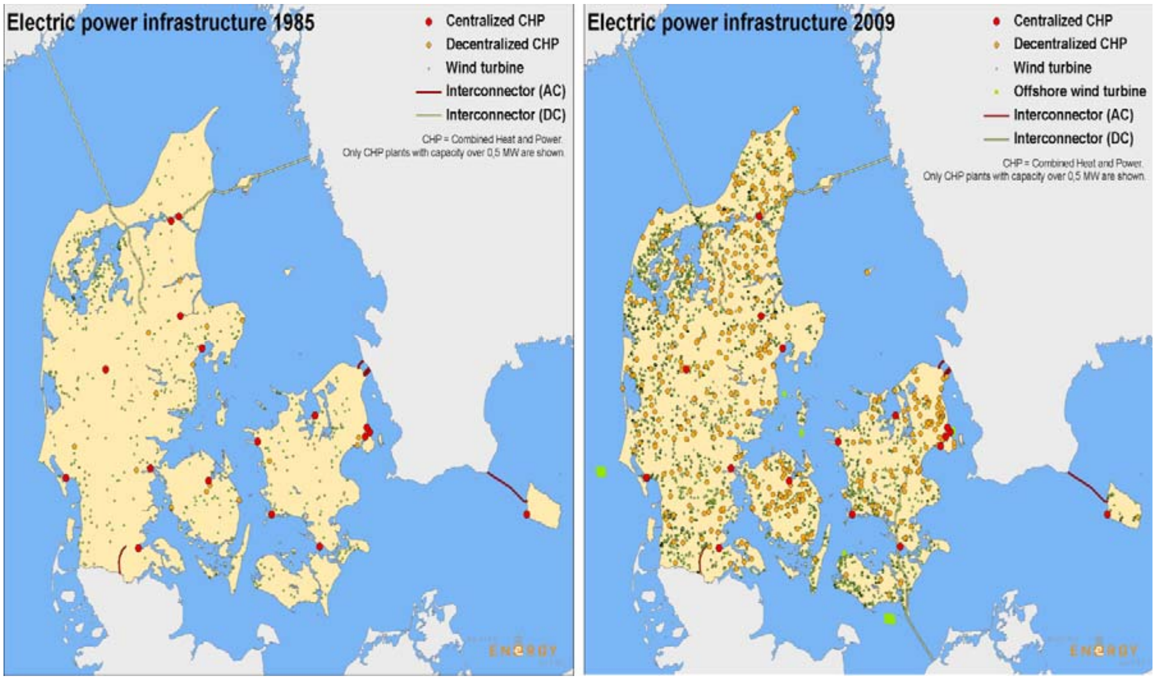

Fig. 1.1 Maps of Denmark showing interconnectors and growth of dispersed generation [8]

The geographical location of Denmark is on the border between continental Europe and Nordic countries. It is a part of the Nord pool electricity market and is electrically connected between the hydro power dominated Nordic system and the thermal based power systems of Europe through Germany. The Western part of Denmark is interconnected through AC lines with Northern Germany, and through HVDC links with Sweden and Norway. Mean while, the Eastern part of Denmark has ac connections to Sweden and HVDC link to Germany. These strong interconnections with its neighbouring countries are one of the important factors that enable the stable and reliable operation of the Danish power system with large amounts of wind power production. The Great Belt HVDC Link was commissioned in August 2010 which directly connects the West and East Denmark for the first time. This will enable both areas to share more power reserves and improve trading in the electricity market [10].

1.1.2 Future Danish Energy Policies and Planning Projects

The renewable energy target of 30% to meet the energy consumption is part of Danish obligation to the EU 2020 targets (20-20-20 targets) [6], [11]. The other key objectives and targets for 2020 in Denmark include 10% renewable energy in transport sector, annual energy savings of 1.5% in the annual consumption levels of 2006 and reduction of greenhouse gas emissions by 20% relative to 2005. As part of the long-term energy policy, “A visionary energy policy 2025” proposed by the Danish government aims for 50% of the electricity consumption which must be met by wind power alone [12]. Therefore, the distribution of electricity generation capacity for 2025 includes 6500MW of wind power plants (4000MW from distributed onshore wind farms and 2500MW from offshore wind farms), 4100MW of central power stations and 2300MW of local CHP units [7]. This represents double the wind power capacity and a reduction of more than 40% of the central power plant capacity from the present installed levels. The locations selected for the future offshore wind farms are shown in Fig. 1.2 [13]. The two new offshore wind farms commissioned in the recent period include Horns Rev 2 in September 2009 and Rødsand 2 in October 2010 which has total installed capacities of 209MW and 202 MW respectively. The estimated power capacities of the future offshore wind farms are available in the 2007 Danish Energy Authority Committee report [14].

The interdisciplinary energy planning projects like CEESA (Coherent Energy and Environmental System Analysis) aims to extend these targets further by studying the feasibility of a self-sustainable Denmark, utilizing 100% renewable energy by 2050 [15].The CEESA project is divided into five work packages which include scenario development, renewable energy in transportation, future power system, market development and environmental assessment of the scenarios. Fig. 1.3 illustrates the energy flow diagram of a 100 percent renewable energy system based on the energy scenarios formulated in the CEESA project [16].

This is represented as a flexible energy system where large amounts of renewable energy are effectively integrated across the heat, transport and electricity sectors. The domestic energy balancing solutions like energy storages, electrolysers, heat pumps and flexible demand are used to negotiate the intermittency of the renewable energy sources.

This PhD project is part of the Work Package 3 (WP3.1) of the CEESA project where static and dynamic power system simulations are conducted to investigate the use of local distributed electricity storages to support large scale wind power production in Denmark.

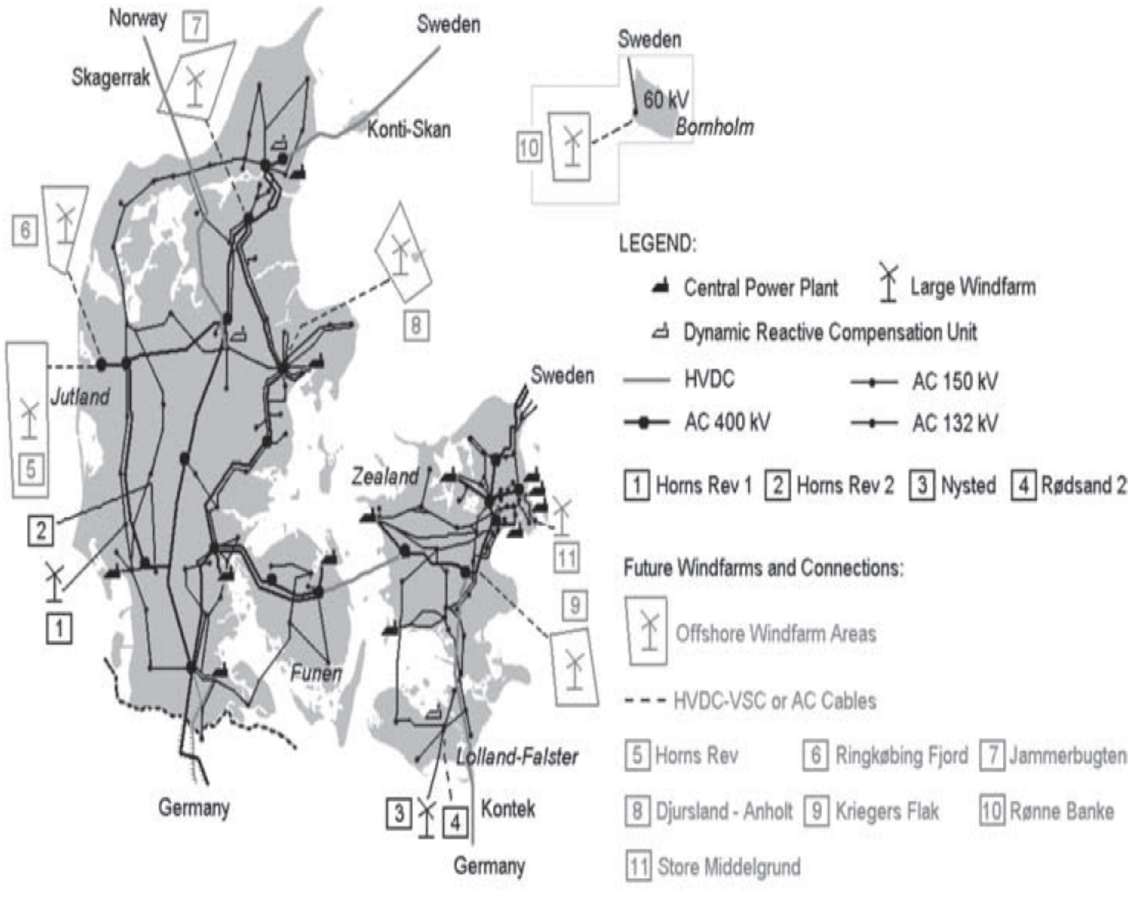

Fig. 1.2 Future offshore wind farm locations in Denmark [13]

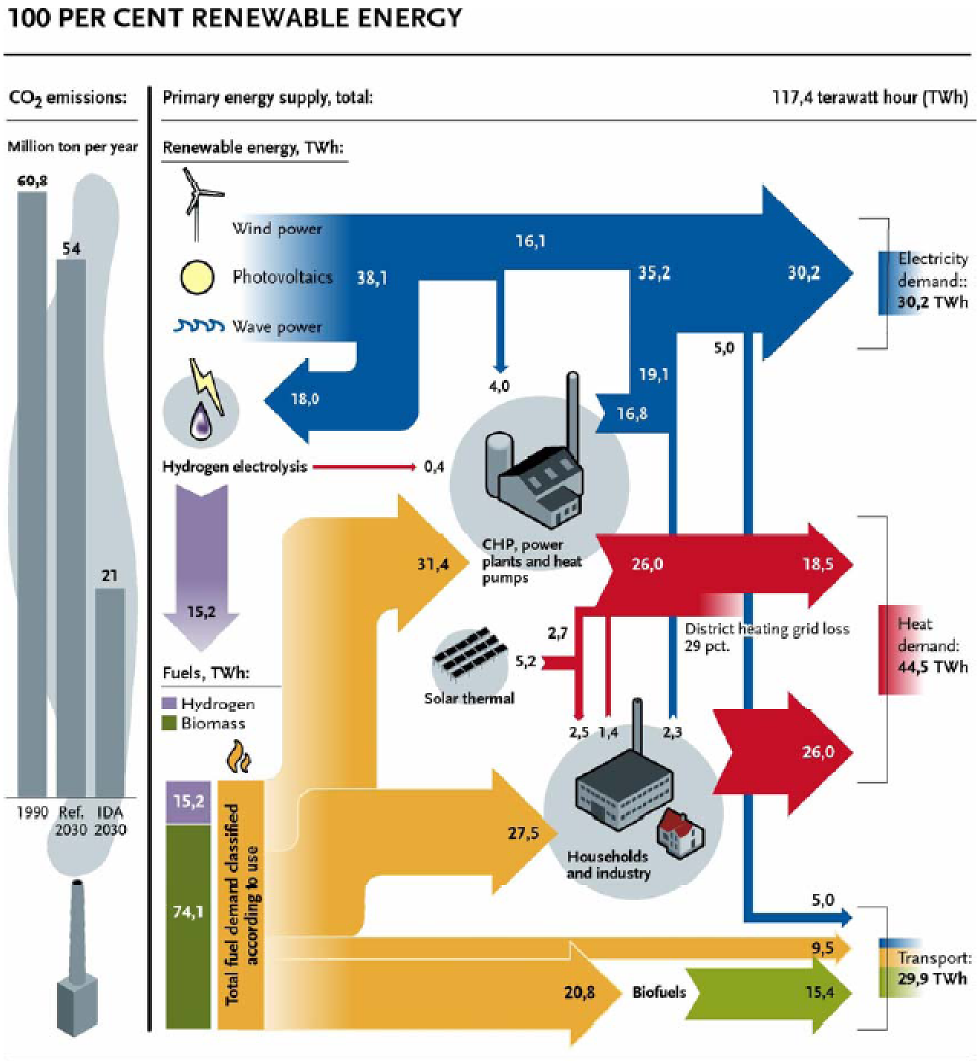

Fig. 1.3 Energy flow diagram of 100 percent renewable energy [16]

1.1.3 Power balancing issues with high wind power penetration

The increasing share of wind power is accompanied by an increasing need of reserve power capacity, which is necessary to balance the electricity system. This regulating power is currently supplied by the central and local power plants in Denmark and abroad. In the present Danish power system, more than half of the imbalances are from the wind power, where 70% are caused by the wind prediction errors [17].

The addition of 3000MW wind power as part of the 2025 plans will introduce additional uncertainty and variability to the power system operation. Fig. 1.4 gives an example illustrating the effect of integrating an extra 3GW of wind power to the power system when compared to the present situation [18]. This simple illustration shows a trend that the future wind power could exceed the system demand in more than thousand hours which is currently less than two hundred hours. This implies the need for further additional balancing resources and larger interconnections to the neighbouring countries. As the central power plant units will be gradually phased-out, the need for alternate quick and flexible regulating units in both generation and consumption must be adopted to accommodate large proportions of wind power. The present cost of power balancing and other ancillary services is about one billion DKK which will be significantly increased with the future wind power installations [18].

1.1.4 Future power system balancing solutions

In view of the Danish energy policy 2025, one of the important measures for an effective integration of wind power is the need for stronger cross-border transmission lines. The Transmission System Operator (TSO), Energinet.dk in Denmark has proposed several plans for new interconnections as well as increasing the capacity of the existing lines to the neighbouring countries [6]. However, the future enhancements on the interconnectors may be limited due to the larger costs involved, longer commissioning time and similar increasing amount of renewable energy penetrations in the neighbouring countries. Germany has planned large development of wind power in the North bordering West Denmark by the year 2020. It is expected to commission 30GW of wind power, mostly offshore wind farms in the North Sea and the Baltic Sea [19]. All these new wind farms are installed at the expense of displacing central power plants which are currently the main source of power system ancillary services. Similarly the Nordic neighbours, Sweden and Norway, targets new wind power installations of 3000MW and 4500MW respectively by 2020 [20].

The regulation of wind power production is another method that could be employed for system balancing. It may be economical to reduce the wind power production during periods of surplus wind power production, higher congestions in the lines and very low prices. A reduction in wind power production also enables the wind turbines to provide up-regulation. The regulation strategies for wind turbines are enlisted in the Danish grid codes which are mandatory controls for new wind power installations [21]. The regulation of wind turbines which spills the “clean” electricity are only attractive if the costs of other means of achieving system balancing exceed the value of the lost generation from wind turbines.

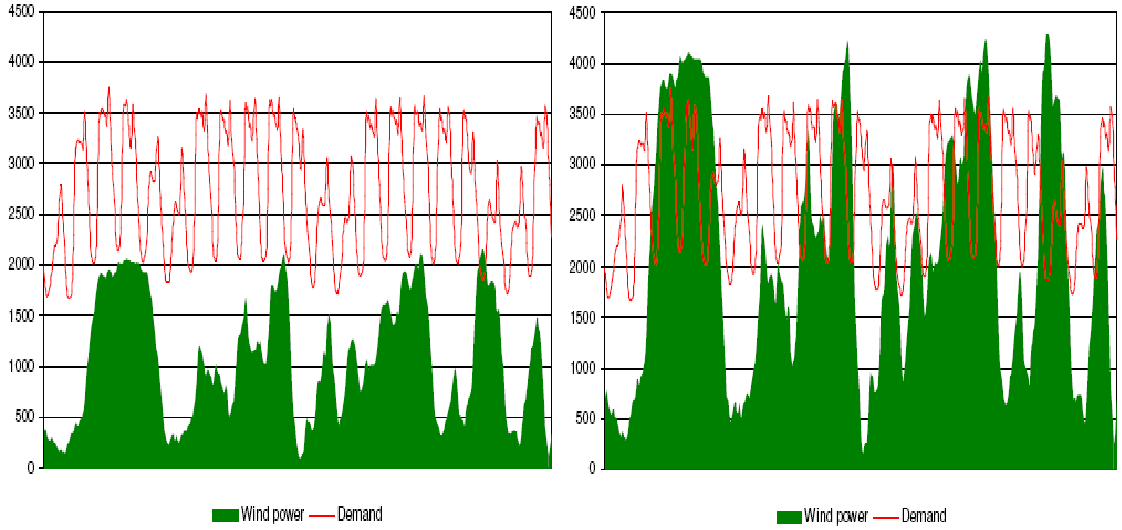

Fig. 1.4 An example illustrating the wind power and system demand for few weeks in West Denmark for two cases 1) Jan. 2008 and 2) Jan. 2008 + 3000MW [18]

In order to effectively integrate larger volumes of wind power, a paradigm shift is thus essential in the Danish energy system where the power system is the central point of this change. The future power system must be intelligent, flexible and efficient in which the electricity produced by the wind power must also contribute to other energy sectors. An intelligent or smart grid infrastructure can facilitate energy balance with a higher degree of interaction across the electricity, heat and transport sectors. This can be realised by advanced control and measurement in consumption, generation and storage technologies using the latest information and communication technology (ICT) which can increase reliability, efficiency and security of the system. The consumption and generation of electricity can be made more flexible by the two-way communication possible in the smart grids [22]. The consumers will become ‘active’ elements where they can manage their loads intelligently for proactively controlling their energy cost. The smart meters which are the important components of intelligent grids could enable demand response, where the consumers can shift the electricity consumption of appliances like heating, ventilation, drying etc., from periods of high price and peak loads to periods of low loads and low prices. The smart grid infrastructure also allows the consumers to deliver power back to the grid for earning revenue by participating in the energy market. The “Cell Project” and “EcoGrid Europe” are the two major projects in Denmark to test and demonstrate the smart grid elements [6].

The heat pumps and electric boilers equipped with smart controls could be one of the best solutions for utilising the electricity from the wind power in the heat sector. The district heating plants and household could benefit from the heat pumps and electric boilers by converting electricity to heat, during periods of low electricity prices where the generation exceeds demand from excess wind power production. The use of thermal storages at the district heating plants will add more flexibility and attractiveness to this strategy. In the transportation sector, a significant flexibility in electricity consumption can be obtained by utilising plug-in hybrid and pure battery electric vehicles as the demand response. This can be realised by controlling the charging of the electric vehicles connected to the distribution system with the use of efficient communication and smart controls. In Denmark, many pilot projects are currently being initiated or executed to analyse the intelligent interaction of heat pumps and electric vehicles with power systems as a part of the smart grid initiative [6], [22]. In the long run, the fuel cell technology may also become an acceptable solution for utilising excess electricity from wind power to produce hydrogen fuel for the transportation, electricity and heat sectors. However, this technology is still in its conceptual stages and the commercial success is currently limited by difficulties in hydrogen storage and low round-trip efficiency [23], [24].

The energy storages are excellent solutions to compensate for the intermittent generation of wind power. The energy storages can store surplus power produced in the grid and can release the electricity into the electricity grid on generation deficit. This property of energy storages can smoothen the short-term as well as long-term variations of wind power and could also provide power quality control functions and other major utility ancillary services like power system balancing and reserves. Fig. 1.5 gives a comparison of various electricity storage technologies based on their power rating and storage duration [25].

The Pumped Hydro Storage (PHS) and Compressed Air Storage (CAES) are the large-scale storage technologies in terms of power and energy capacity. However, the Danish flat landscape is not suited for PHS installations [26]. Currently the Nordic hydropower reservoirs of Norway and Sweden acts as a “virtual storage” to buffer the excess wind power produced in Denmark. It is reported that the CAES technology in Denmark is possible to support large volumes of wind power [7]. However due to the limitations in geographical suitability of the installation site for large underground caverns, the technical and economic feasibility are yet to be proved [27]. The flow batteries like vanadium redox and zinc-bromide are characterised by longer storage duration time compared to typical electro-chemical batteries.

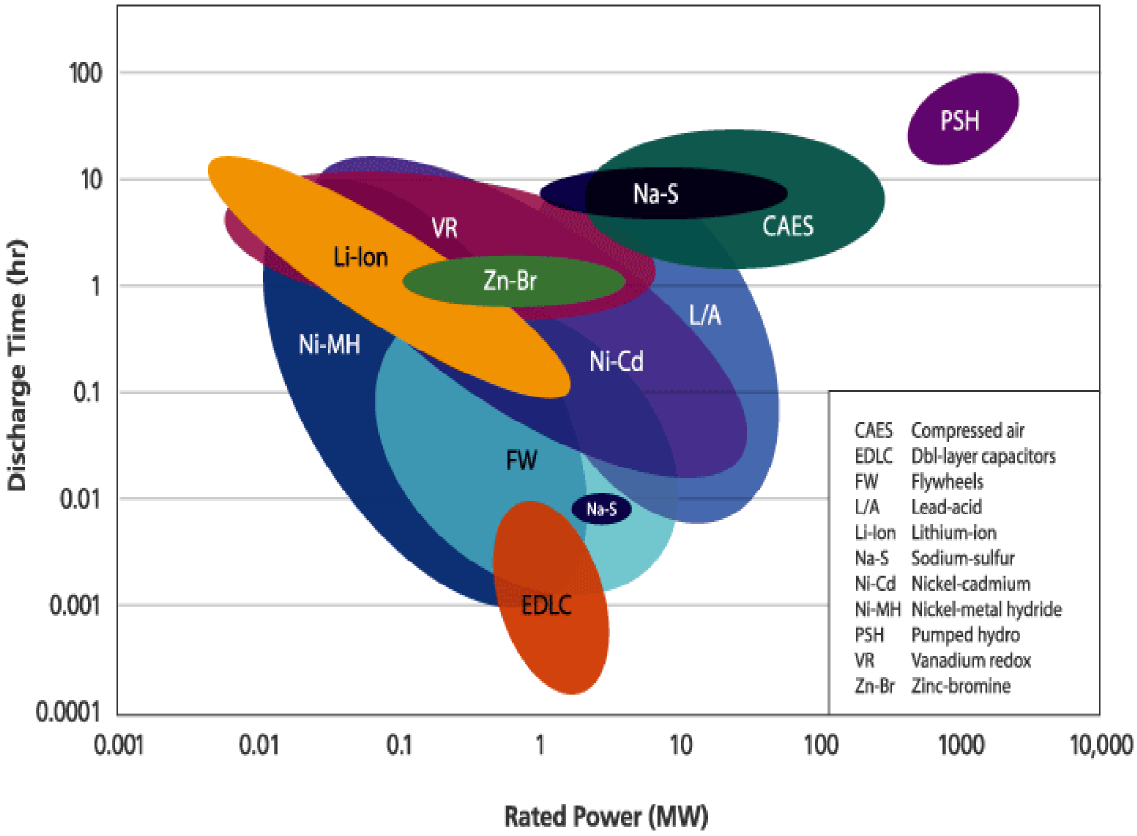

Fig. 1.5 Comparison of electricity storage technologies based on rated power and storage duration [25]

However, this technology is still under development stages and has some disadvantages which include higher capital and running cost [28]. The lead acid batteries are the most matured technology among the electro-chemical batteries. Some of the largest battery storage plants installed and operating include a 20MW, 14MWh (lead-acid) at Puerto Rico, a 27MW, 6.75MWh (nickel cadmium) at Alaska are typically used for spinning reserve, voltage and frequency control applications [28], [29]. Compared to these batteries, the lithium-ion batteries have higher storage efficiency close to 100% and a high storage capacity which are increasing further with the introduction of its new models. The superior characteristics of lithium-ion batteries have made it popular for large production of battery electric vehicles of higher driving range [28].

The increased use of electric vehicles is actively promoted in Denmark as part of the future energy policies and strategies to reduce green house gas emissions and energy sustainability in the transportation sector. A significant fleet of electric vehicles with the use of local intelligence can provide temporary distributed electricity storage in the electricity grid, when they are not used for driving. The electric vehicle batteries could charge as a load and store energy during high winds and low electricity prices and could also discharge when required. This emerging concept of power balancing using electric vehicles is collectively termed as the Vehicle-to-Grid systems [30].

There is a huge potential of distributed electricity storage available in the future grid from the electric vehicles whose primary purpose is for transportation, but can also complement the variability of the wind power. The installation of other stationary electricity storage technologies as dedicated units may be limited due to large investments, time and space constraints. The electric vehicles holds a significant potential not only to supply clean and cheap energy in the transportation sector but also could function as a generator, a load or a storage which is one of the most efficient and flexible solution for providing power system ancillary services to support more wind power in electricity grid.

1.2 Research objective and methodology

The objective of this research project is therefore defined based on the important role, the battery storage of electric vehicles can deliver as an ancillary service provider in future power systems. This project investigates the use of aggregated battery storage of electric vehicles (Vehicle-to-Grid systems) in providing active power balancing to support large amounts of variable wind power in Denmark.

Some worst case scenarios are identified in this project which represents the future power system operation in interconnected as well as islanded mode. The whole analysis is divided into five different case studies which are conducted as steady-state or dynamic simulation studies performed in the DIgSILENT PowerFactory software.

1. Short-term dynamic simulation study to investigate the role of electric vehicle battery storages as primary reserves in an islanded Danish distribution system with large penetration of wind power.
2. Long-term dynamic simulation study to examine the role of electric vehicle battery storages as secondary reserves in an interconnected wind power dominated Danish power system.

3. Long-term dynamic simulation study to analyse a worst case islanded power system operation involving reduced conventional reserves, battery storage constraints and coincident system demand and wind ramp periods.
4. Steady state analysis to study the integration levels of electric vehicles with different power ratings and charging type in a Danish distribution network.
5. Electro-technical analysis to improve the future renewable energy based planning scenarios and planning tools using dynamic power system simulations incorporating new power regulation tools like Vehicle-to-Grid systems.

1.3 Technical contribution of the thesis

The main technical contribution of the thesis is summarized as follows

1. A long-term dynamic simulation model of an aggregated battery storage representing the Vehicle-to-Grid systems is developed in this thesis. The battery storage model developed is generic and has the capability to represent the battery state of charge constraints and storage duration of the battery.
2. Modified conventional Load Frequency Control model to integrate and verify the performance of Vehicle-to-Grid systems in an interconnected power system operation.
3. Control strategies are formulated to incorporate the Vehicle-to-Grid systems in an islanded power system operation.
4. Analyses to quantify the reserve power requirements of electric vehicle battery storages which could minimise the conventional generation reserves.
5. A methodology to investigate the impact of increasing number of electric vehicle loads on the power distribution networks.
6. A technical evaluation is provided by using dynamic power system simulation models to verify and deduce the limitations of the energy planning scenarios which were devised by the planning software tools.

1.4 Project limitations

1. A deterministic model is used in this thesis to represent the fleet of electric vehicles as an aggregated battery storage model in the simulations. The number of electric vehicles that are

grid connected for ancillary services, the storage capacity and the charger ratings at a particular period of time may be variable. These factors are not accounted in the battery storage model as the real-time transportation demand and vehicle driving profile data were not available to model these uncertainties.

2. The regulation of wind power production is not modelled in this thesis, as it assumes that it is technically and economically more reliable to use battery storages for balancing the system than to spill the "clean" energy from wind turbines.
3. The long-term dynamic simulation models of aggregated battery storage and conventional generators are used in this thesis. The aggregated wind power is modelled as negative loads, as most of the case studies in this thesis examine the active power balancing of minute-to-minute wind power variations. Also the real time series data used in simulations which were available from the Danish Transmission System Operator, Energinet.dk has a time resolution of five minutes. The analyses are conducted on a system perspective rather than local levels to quantify the overall performance of Vehicle-to-Grid systems on a larger scale.
4. The rotor angle and voltage stability studies are not considered in this analysis as the project focuses on mostly on the minute reserves from Vehicle-to-Grid systems to balance out the wind power variability. The voltage control capability of the battery storages is not examined in this thesis which may be a future secondary application of the Vehicle-to-Grid systems. The promising and attractive application of the whole concept of Vehicle-to-Grid systems primarily focuses on the active power balancing services.

1.5 Outline of the thesis

The thesis is organized as eight different chapters.

Chapter 1 Introduction

The Chapter 1 gives the background and objective of this thesis. Also the technical contributions and the limitations in the project are discussed.

Chapter 2 Electric vehicles and Vehicle-to-Grid Systems

This chapter gives an overview of the history, present and future trends of the electric vehicles. A small section outlining the relevance, promotion policies and support mechanisms for electric vehicles in Denmark is discussed. The concept and application of Vehicle-to-Grid (V2G) systems is described and the prospects of V2G in power system ancillary services are presented.

Chapter 3 Vehicle-to-Grid Systems for Frequency Stability in Danish Distribution System

This chapter presents the role of aggregated battery storages represented by Vehicle-to-grid systems as primary reserves in maintaining frequency stability in a Danish distribution network with large amounts of wind power. The electricity network used in this study as test case is a simplified model of a part of the Lolland-Falster distribution system in East Denmark. The simulation scenarios in this analysis were defined to replace some of the conventional generation capacity by wind power. The investigation is carried out using short-term dynamic simulations emulating power system events like step load change and loss of generation.

Chapter 4 Vehicle-to-Grid Systems for Interconnected Power System Operation

The integration of Vehicle-to-Grid systems in a Load Frequency Control model is examined in this chapter. A long-term dynamic simulation model of the aggregated battery storage is modelled. The interconnected power system of West Denmark is used as the case study in this investigation. The simulation scenarios in this chapter are based on a weekday with high wind and a weekend day with low wind. The role of Vehicle-to-Grid systems participating as secondary reserves is analysed to minimise the deviations of planned power exchanges across the West Denmark-German border.

Chapter 5 Vehicle-to-Grid Systems for Islanded Power System Operation

In this chapter, the performance of the long-term dynamic simulation model of Vehicle-to-Grid systems for maintaining an active power balance in an islanded power system operation is studied. The Danish island of Bornholm is used as the test case. Two worst cases of morning up-ramp and peak demand periods which demands for large reserve power requirements in a power system is considered in this analyses. The isolated power system operation constrained with less conventional reserves and high variable wind power during the above periods forms the basis of this study.

Chapter 6 Impact Assessment of Electric Vehicle Loads on Distribution System Operation

This chapter investigates the impacts of increasing the electric vehicles in a primary distribution network of Bornholm. Steady state analysis of the test network is conducted by adding electric vehicle loads in the order of 0-50% of the vehicle fleet to verify the violations on the safe operating limits of the network parameters. The percentage loss of insulation life of a low voltage distribution transformer is also studied for an increasing number of electric vehicles. The intelligent strategies for controlling the household loads to prevent transformer overloading are also discussed.

Chapter 7 Dynamic Power System Simulations to Validate Energy Planning Scenarios from EnergyPLAN

This chapter is part of the electro-technical analysis of the CEESA project which intends to improve the EnergyPLAN model which is a planning tool used to verify energy planning scenarios. The results of the hourly energy system analysis performed by the EnergyPLAN model for 2030 CEESA project scenarios for the island of Bornholm is compared with the dynamic power system model (used in Chapter 5) simulations. The Vehicle-to-Grid system is used as a flexible power balancing tool in both cases.

Chapter 8 Conclusions

This chapter presents the summary and main conclusions of this thesis. The topics for future work are also discussed in the end.

List of publications

The scientific articles published during the course of this PhD. project are listed.

Appendix

The additional and detailed models of simulation components, parameters and additional results are listed in the appendix section

Chapter 2

Electric Vehicles and Vehicle-to-Grid Systems

2.1 Introduction

In the recent years, electric vehicles (EVs) have gained renewed interest in the global research and the industry sectors. The major factor attracting the promotion of electric vehicles is the pollution and emission free transportation it could offer, which is a much needed global necessity for a sustainable future. The advancement of high efficient and high density battery technologies has provided an encouraging trend of producing electric vehicles of higher driving range. However, one of the major issues preventing the fast acceptance of the electric vehicles is its battery cost, but it is expected that this will reduce significantly with time [31]. This could enable the electric vehicles to be competitive with the conventional gasoline vehicles in the market. Other significant factor that attracts the use of electric vehicles is its potential role in supporting renewable electricity [32]. The battery storages of electric vehicles could buffer variable electricity from renewable energy which will benefit the electricity sector in promoting clean electricity. Many countries like Denmark is prominent in promoting the electric vehicles at a rapid pace due to the unique feature of this social synergy that exists between the renewable energy and the electric vehicles to provide carbon dioxide free electricity and transportation [7].

This chapter presents a brief introduction about electric vehicles and its relevance in providing ancillary services in electrical power systems. Section 2.2 discusses about the history of electric vehicles and its re-emergence in the recent years. The strategies adopted to encourage electric vehicles in Denmark are presented in Section 2.3. The fourth section discusses about the application and prospects of aggregated battery storage of electric vehicles represented as Vehicle-to-Grid (V2G) systems in stabilizing the electricity grid. A brief discussion is presented in the Section 2.5 of this chapter, where the performance of conventional power plants and electric vehicle battery storages are compared when participating in grid power balancing services. The future trends, strategies and deployment issues of Vehicle-to-Grid systems are also briefed in this section.

2.2 The History of Electric Vehicles

The electric vehicles are a hundred plus year old technology. They were introduced during the mid-nineteenth century and became very popular towards the start of the 20th century. The electric cars even outnumbered the gasoline cars by a factor of two [33]. The driving range was not an issue during those days as they were used only for commuting in the local towns, where only a few good roads existed. The electric vehicles were free from noise, vibration and smell. The electric vehicles did not require the use of hand crank (as starter) and there was no need for changing gears when compared with gasoline cars which made the former superior than the latter. This supremacy of electric cars did not last long due to the introduction of electric starters, large volumes of crude oil discovery, better system of roads which resulted in mass production of cheaper and reliable gasoline cars. The electric cars virtually disappeared by 1930s. For another six decades they were available only in very small numbers and its development and use were limited.

By 1990s, the electric cars were resurrected in the United States and other parts of the world due to the legislative and regulatory reforms to introduce fuel efficient and less polluting vehicles. Primarily in United States of America, the zero-emission vehicle policy was enforced by the California Air Resources Board (CARB) [34]. In view of these regulations, many models were introduced by most of the reputed car companies. However, this was not enough for the electric vehicle markets to gain a sustained momentum and long-term presence in the market. Most of the electric car models were discontinued after a few years. The major issues for their withdrawal were the low battery performance and less driving range of the vehicles. With the high oil prices coupled with the environmental damages being caused by the conventional gasoline vehicles, an absolute need for electric transportation is getting socially and politically acceptable on a large scale. This is further encouraged by the technological advancement made in the lithium-ion batteries which have higher energy density and higher efficiency.

The plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) are the two major types of electric vehicles. Several models of these electric vehicles are now commercially available in the market. The PHEVs are equipped with a combination of battery storage system chargeable from the grid and conventional internal combustion engine (ICE). The hybrid electric vehicles utilise the batteries for shorter distances ranging from 20km to 80km, especially for "city drive" which could increase the vehicle efficiency [31]. The ICE of the vehicles could be employed for travelling longer distances, thus retaining the same levels of driving range of today's conventional vehicles. The hybrid electric vehicles are available in different configurations like the parallel, series and parallel-series models based on how the power is fed to the drive train [35], [36]. Some of the popular models of PHEVs are the Toyota Prius, Chevrolet Volt etc. It is the pure battery electric vehicles (BEVs) which could offer the prospects of zero vehicle emissions as it uses the onboard battery storage to supply all the motive and auxiliary power of the vehicle. The batteries are recharged mainly from the grid electricity and also by the regenerative power from braking. The pure battery electric vehicles with an average driving range of 150-200 kilometers are now commercially available in the market. The 2009 battery electric car "Tesla Roadster" has a driving range of 350 kilometers, a top speed of 210 km/h and uses lithium-ion battery units with a capacity of 53kWh [37].

The launch of many new EV models in the market has been announced by various car manufacturers for the next few years. These vehicles will have a higher driving range and superior performance than the current models available. The Tesla Model S set to launch in 2012 aims for a driving range of 480 kilometers and a lithium-ion battery capacity of 85kWh. The cost of this car is estimated to be 50% less than the 2009 model [37]. The wheel-to-wheel efficiency of the electric vehicles is three times higher than the gasoline vehicles and the fuel cost is only one-third for the former compared to the latter. The performance and reliability of the new electric vehicles are comparable to that of the conventional vehicles. This is expected to improve with more research and innovations being encouraged worldwide in the electric vehicle sector. These factors have vastly contributed to bring the electric cars back into the limelight with a very realistic proposition.

Several aggressive targets have been set worldwide by many countries for the wide spread use and adoption of the plug-in hybrids and battery electric vehicles. Fig. 2.1 depicts the national sales targets set by various countries for electric vehicles by 2020 [31]. Most of these announcements were made in the last one year which demonstrates the priority given to electric vehicle deployment in the international level. If these targets are achieved, 4 million electric vehicles would be sold by 2020. The global sale of electric vehicles projected by the International Energy Agency roadmap for the period 2010-2050 is shown in Fig. 2.2 [31]. The targets set on electric vehicles for 2050 is expected to meet a share of 50% of the total cars available worldwide.

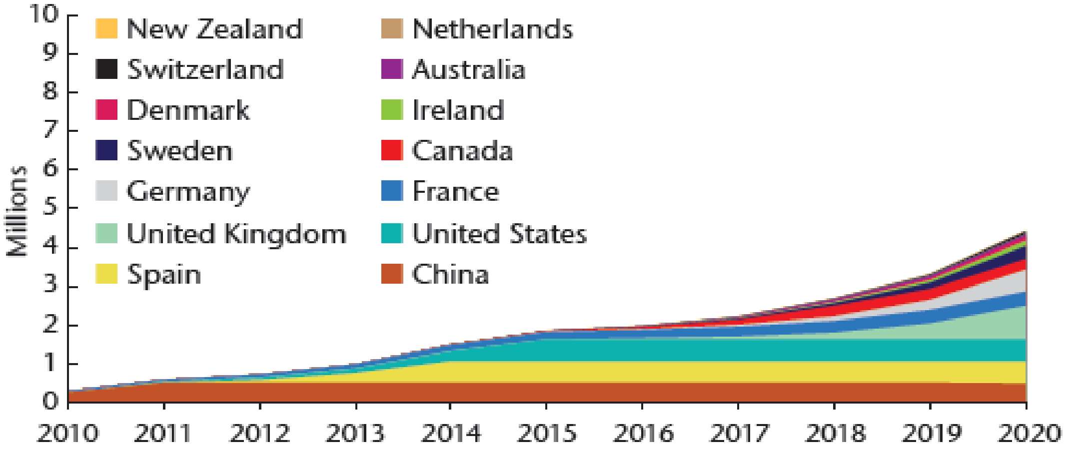

Fig. 2.1 National electric vehicle sales targets, 2010-20 [31]

However, for a full scale adoption of electric vehicles, there are several challenges to be addressed. The major issues like vehicle range, battery energy density and battery life are expected to improve further in the coming years with innovative technologies and technical breakthroughs. The present high purchase price of electric vehicles could be made affordable to the end user by implementing various government subsidies, rebates and incentive schemes. The batteries of electric vehicles are normally expected to plug-in and charge at home during the off-peak hours (night hours) and when the electricity prices are low. This corresponds to slow charging of batteries which may take 6-8 hours [38].

However, this may not be the case with every other electric vehicle user who may desire for faster re-fuelling of their cars like that of the gasoline vehicles. There exists the need for fast charging (5-10 minutes) of vehicles like that intended for longer trips, taxis, business cars and emergencies during the course of a day [39]. This factor of fast charging thus has a significant influence on the commercial deployment of electric cars. However, the fast charging demands for high currents which may coincide with peak-demand periods and it could also reduce the life of components and over loading of the electricity distribution network [40]. As the penetration of electric vehicles increase, dedicated electricity infrastructure and smart charging strategies have to be in place to avoid overloading of distribution networks and higher peak loads [40],[41].

An alternative method for fast battery recharging is the battery swapping process which is proposed by Better Place, an EV infrastructure company [42]. This could offset all the above charging issues by replacing the empty car batteries with full charged ones at battery swapping stations which will take only few minutes to complete. Some of the electric car manufacturers like Renault and Tesla motors have already adopted and incorporated this feature in their new EV models. For this method to be reliable and effective, there is a need for standardisation of the shape and chemistry of the batteries used in the electric vehicles.

The charging infrastructure, battery charging or swapping stations and smart grids for controlled charging have to be mobilized in conjuncture with the targets of EVs set by the utilities and the respective governments. International standards play a key role in reducing research and development costs and lay a strong foundation for innovation and rapid implementation and deployment of a product in the market. Some of the international standards which are relevant to EVs that deals with the important aspects like vehicular communications, EV charging/discharging, power transfer with grid and battery performance are the SAE standards [43] (SAE J1772, SAE J2847 etc.) and IEC standards (IEC 61851, IEC 62196).

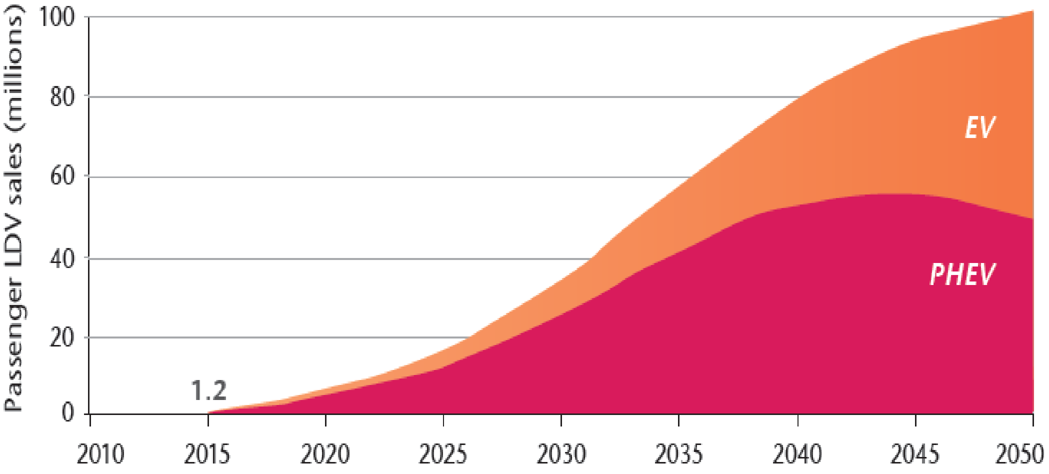

Fig. 2.2 Global electric vehicle sales projections, 2010-50 [31]

2.3 Electric Vehicles in Denmark

There are currently more than two million cars in Denmark [44]. In 2005, the total annual CO_2 emission in Denmark was 49 million tons. The road transport sector contributed to 13 million tonnes of CO_2 emission, out of which more than 55% came from cars [45]. The energy consumption and the CO_2 emissions in the transportation sector are increasing at a large proportion every year compared to other sectors like households, industry and power plants where energy conservation and less polluting technologies are being adopted. The introduction of hybrid plug-in cars and battery electric vehicles could reduce the emissions to a great extent in the transportation sector. The electric cars not only benefit the climate, but could also act as a large rechargeable battery which could store environmental friendly renewable electricity. This would lead to an increasing amount of electricity from renewable energy which would further reduce the CO_2 emissions from the electric vehicles.

It is estimated that 10% of the total vehicle-fleet in Denmark will be electric by 2020 [31]. As part of the future 2025 Danish Energy Policy, discussed in Section 1.1.2, the aggressive renewable targets set in the transportation and the electricity sector, provides a large impetus and encouragement to the promotion of electric vehicles. As part of the policies to support more electric vehicles in Denmark, many incentives and subsidies are offered by the Danish Government. The registration taxes of 180% are exempted for electric vehicles under two tons in Denmark until 2015 [46]. They are also exempted from the annual green owner taxes (ranges from 500DKK to 25000DKK) which are calculated based on the vehicle's fuel consumption. The Danish Energy Agency offers many grants and subsidy schemes to support experimental electric car projects [47].

The free parking provision is permitted for battery electric vehicles in Copenhagen and other cities like Odense. This exemption does not apply to hybrid vehicles. Since 2008, both large scale and demonstration projects on electric vehicle to utilise more wind power in the power system have been initiated in Denmark. One among the major electric vehicle projects, "EDISON" aims to validate the use of the electric vehicles as a balancing resource to support the long-term goals of integrating 50% wind power capacity [48], [49]. The project plans to demonstrate electric car based smart grids in the Danish island of Bornholm which is characterized by large proportions of wind. Also the leading wind power producer in Denmark, DONG Energy and Better Place plans to implement a full-scale electric vehicle infrastructure by 2011 [50].

2.4 Vehicle-to-Grid Systems

In any electricity grid, there is only a limited scope for storing electricity. In order to maintain the match between electricity production and fluctuating load demand, the generation has to be continuously increased or decreased, else, a power deviation occurs, disturbing the power equilibrium. The electricity produced from the renewable energy sources are unpredictable and variable and thus has a poor load following characteristics. This has resulted in more imbalances and flexible generation demand in electricity grids which limits the level of integration of renewable energy in any power system. The energy storages are complementary to the stochastic nature of renewable energy. They can charge whenever there is an excess of electricity in the connected system and discharge when required. This unique feature of the energy storages could allow large scale integration of renewable energy in the electricity grid.

The battery storages are one of the most efficient and compatible technologies available for various power system utility functions. Even though the battery storage is a matured technology, they are limited to a few MW or kW applications. The battery technology is still under research stages to develop more efficient, high power and energy capacity battery types. The most recent lithium-ion batteries are superior to other commercially available batteries in terms of energy density and efficiency. However, due to the high cost, the market applications of lithium-ion batteries are still limited to low power applications (kW range) in electronic products, electric vehicles etc.

The use of battery storage in the form of electric vehicles for power balancing is one of the emerging concepts, which could act as a load reacting to changes in the power supply. Electric vehicles when coupled to an electricity network can act as a controllable load or generator in power systems with high penetration of renewable energy sources. The reliability of the renewable electricity will be enhanced with the vast untapped storage of electric vehicle fleets when connected to the grid. This could be considered as a large aggregated MW battery storage which is termed as “Vehicle-to-Grid” (V2G) systems [30], [51], [52]. Vehicle-to-Grid systems could provide back up electricity storage as well as quick response generation to changes in the power balance of the electricity grid.

Vehicle-to-grid (V2G) systems uses the electric vehicle battery storages to transfer power with the grid when the cars are parked and plugged in to the charging stations at parking lots, at offices or at homes, where they will have bidirectional power transfer capability. The electricity supplied by the V2G will reach the consumers through the grid connection and in return, any surplus energy in the grid could be stored in the electric vehicles. Fig. 2.3 illustrates the power flow connections between the electric vehicles and the electricity grid to realize the Vehicle-to-Grid concept [52]. The Transmission System Operator (TSO) or grid operator could request for a power transfer through an aggregator (intermediate entity) who manages the individual vehicle or a fleet of vehicles through control signals in the form of a power line carrier, radio signal, internet connection or mobile phone network [30], [53], [54].

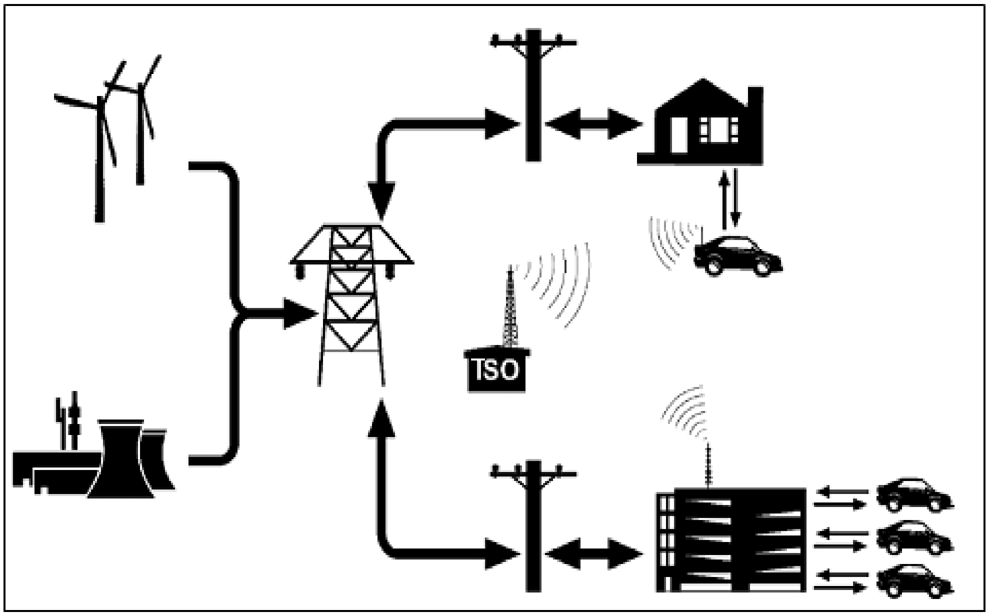

Fig. 2.3 Schematic illustration of Vehicle-to-Grid system [30]

The aggregator appears to the TSO as a large battery storage which could behave as a rapidly controllable generation or load with good regulation capabilities. This aggregation of the electric vehicles as a virtual power plant provides an opportunity for the individual vehicles to take part in the electricity markets and provides flexibility and value-added benefits to the power system like power balancing. The distribution network operators, automakers, power utility companies, electric car network service providers or a combination of any of these parties could act as aggregators. The aggregators are paid for the power system services by the TSO, where a portion of the amount is paid to the vehicle owners. To keep track of the vehicle location, availability status, metering and battery storage status, communication interfaces like Global Positioning System (GPS) or wireless are required to be established between the aggregator and vehicles. Fig. 2.4 shows the aggregator based Vehicle-to-Grid system [34]. The daily average vehicle kilometers travelled in Denmark is 40km/day [55]. The light motor vehicles are idle almost for a period of 20-22 hours a day [30], [56]. In general, the utilisation factor of the vehicles is less than 10%, compared to an average 40-50% utilisation of central power plants. This establishes the importance of introducing the Vehicle-to-Grid systems which could improve the capacity factor and added value to the use of electric cars.

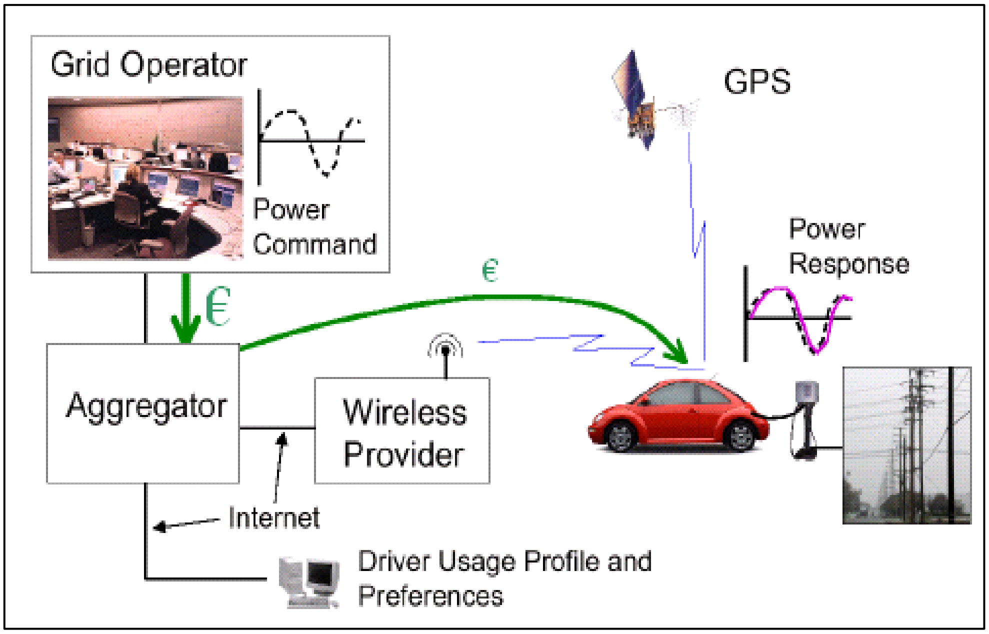

Fig. 2.4 System architecture of Vehicle-to-Grid [34]

Many electric car models commercially available in the market operate with the highly efficient lithium-ion batteries. From a calculation based on equation (2.1) [30], the net energy available in the battery for grid services, after a typical daily driving requirements, by a Tesla Roadster (vehicle efficiency is 9 km/kWh and energy storage capacity of 53kWh) in the Danish context could be approximated as 40kWh.

$$E_{veh} = (E_s - \frac{d_d + d_b}{\eta_{veh}}).\eta_{inv} \tag{2.1}$$

where E_s is the battery storage capacity in kWh,

d_d is the average daily driving kilometers,

d_b is the minimum reserved kilometers by the driver for emergencies (approx. 32 km),

η_{veh} is the vehicle efficiency,

and η_{inv} is the inverter efficiency (0.90)

The V2G connected vehicles are reported to be best suited for electricity balancing markets to provide grid services like "regulation" and manual reserves [32], [34], [57]. These are considered as mandatory ancillary services required in any power system for its reliable operation [58]. The use of electric vehicles as a provider of ancillary services will be more relevant with the increasing amount of renewable energy in the power systems. The grid regulation service is the Load Frequency Control which tunes the power system frequency to satisfy the power balance. The regulation may be up-regulation or down-regulation. The up-regulation is necessary when the demand exceeds the supply, causing the frequency to drop and if the supply exceeds the demand, a down-regulation is desired for a stable operation of the system. The regulation requirement is continuously needed throughout a day and requires fast response from the V2G connected vehicles. The generators supplying the manual reserves (spinning and standby reserves) must be able to provide balancing power to the system, especially during large power imbalances or contingencies like that of loss of generators or lines, where the regulation reserves may be insufficient.

It makes economic sense to utilise the vehicle batteries for power system ancillary services, whose primary purpose is meant for driving, rather than depending on dedicated stationary batteries where the capital cost must be amortized exclusively from grid services. The typical guaranteed calendar life of battery units by the car manufacturers would be either between 3 to 5 years or more than 160,000 kilometers. Considering the average annual distance travelled by the passenger cars in Denmark which is close to 16,000 kilometers, the battery units within its life cycle would be utilized less than 50%. The V2G systems for grid ancillary services by the battery could compensate for this under utilisation, with no marginal battery cost. Thus, it is worth to use the vehicle batteries for ancillary services which will in turn improve the service factor of the battery, gain extra revenue and provide support for promoting sustainable energy [59].

The V2G based electric vehicles participating in the ancillary services will be paid a capacity cost for availability and an energy cost based on the activation [52],[60]. Various studies had reported that sufficient revenues could be earned by the vehicle owner for participating in the balancing market. The revenue that could be earned from V2G systems for grid regulation depends on the value of ancillary services in the power system control area. The profits will increase with higher kWh capacity of the vehicle battery and with higher power connection capacity. The gross annual revenue that could be earned by an electric vehicle by providing grid regulation services in the CAISO market is estimated as \$1000 to \$5000 [59]. The net value that results will be an amount reduced from the aggregator services and battery degradation costs.

Other business models are also proposed where the battery units are owned by the aggregator, who will also take care of the battery replacements costs. The vehicle owner will be guaranteed a good battery pack all the time and will be paid for plugging in the car for the contracted period to provide grid regulation services. A significant profit potential of $1000 to $10000 per electric vehicle is also reported in studies for V2G ancillary services in four different US electricity markets analysed for different years and fleets of vehicles [52]. The Net Present Value result for the V2G ancillary services based on the studies in the German electricity market is in the range of €3000 to €9000 per vehicle, even after considering the costs for battery ageing [61].

In Denmark, the electricity grid is characterised by high wind power penetration and many new wind turbines are being installed. As wind energy is intermittent in nature and cannot be forecasted or scheduled accurately, additional power balancing reserves are required to fill in the variance between predicted and scheduled wind generation. This creates an ideal market situation for utilizing the ancillary services from electric vehicles based battery storages in the Danish power system. From a study conducted in the Danish regulation market, the annual earnings that could be gained by the electric vehicle owner from providing ancillary services are about 1000DKK to 15000DKK [60]. During hours of critical surplus power production from high wind, the magnitude and frequency of negative down-regulation prices in the electricity grid could be reduced by charging the battery storages of electric vehicles.

This provides an economic method of integrating more wind power into the electricity grid. The EV battery storages could also reduce the extra costs due to wind power forecast errors. During hours of high up-regulation prices due to low wind power production, the EV battery storages could provide power back to the grid. Studies conducted by Zpryme [62], highlights Denmark to be the seventh largest market for V2G vehicles in the next ten years. The renewable energy initiatives, smart grids and EV promotion in Denmark are the major driving forces which could make it a market leader in V2G technology. As per the studies, a market value of $0.38billion and sales of 13,300 units are expected to be achieved by V2G vehicles by 2020 in Denmark.

2.5 Electric Vehicles as provider of Grid Regulation Ancillary Services

The power plants providing grid regulation services will have nominal scheduled operating points, minimum and maximum power output limits. These values are contracted and fixed through the ancillary services market on hourly basis. The grid operator directly controls the generator output up or down in order to match the electricity generation, consumption and power exchanges with other areas and to maintain the power system frequency within nominal operating limits. Therefore, the actual power dispatched by the generators would not be the same as the scheduled output level. The generator output power varies around the reference operating point in response to regulation signals from the grid operator. The energy generated by the power plant on regulation is the area under the actual power dispatched curve.

The same process could be realized from plug-in electric vehicles under the Vehicle-to-Grid contract to be utilized by the grid operator, utilities, or aggregators, by remotely controlling the power charging levels of the batteries. The main difference lies in the scheduled power output levels. The operating points for electric vehicles could be zero or negative (power consumption as loads), whereas only positive values can be applied for power plants which can change only the levels of generation. The scheduled operating points for electric vehicles under the Vehicle-to-Grid systems for regulation services can be positive (generation) or negative (as load). The up-regulation and down-regulation services could be realized by the Vehicle-to-Grid systems with either bidirectional or unidirectional charge control. Using the bidirectional charger the vehicle can provide up-regulation by discharging and down-regulation by charging. Fig. 2.5 illustrates an example of a bidirectional power transfer from an electric vehicle with a scheduled operating point of 0kW, a down-regulation limit of 8kW and up-regulation limit of 8kW for a period of one hour.

A total regulation capacity of 16kW is available from the vehicle. The grey areas under the curve, above zero in the figure represent the total energy supplied by the Vehicle-to-Grid, and that below zero represent the energy stored in the vehicle battery from the grid. Fig. 2.6 illustrates a unidirectional charger of 8kW with an hourly scheduled power consumption level of 4kW. It is capable of providing a down-regulation (minimum operating limit) of 4kW from the nominal level and 4kW of up-regulation without discharging to the grid, which could be managed by controlled charging of the battery. It does not matter whether the electric vehicles are charging at a constant or variable rate. The vehicle could charge with a power profile based on the grid regulation signal which could also offset some of the electricity cost from charging.

The Vehicle-to-Grid systems can potentially give better performance in providing ancillary services than the large conventional power plants. The power plants have generation rate constraints which make them slower to change their power output levels [63], but the vehicles can respond almost instantaneously to any power regulation commands. Fig. 2.7 illustrates an example of V2G power response to the grid regulation signal. The V2G power tracks the regulation signal very closely as the battery storage responds faster to the power command. Fig. 2.8 illustrates the slower response from a steam power plant to the regulation signal. The typical ramp rates of steam turbines are 4% per minute, the fastest being the diesel power plants with 20% per minute [64]. The results shown in Fig. 2.7 and Fig. 2.8 are simulated using the dynamic models of aggregated Vehicle-to-Grid systems and steam turbine power plants respectively which are presented in Chapter 4 (Section 4.3 and Section 4.4.1).

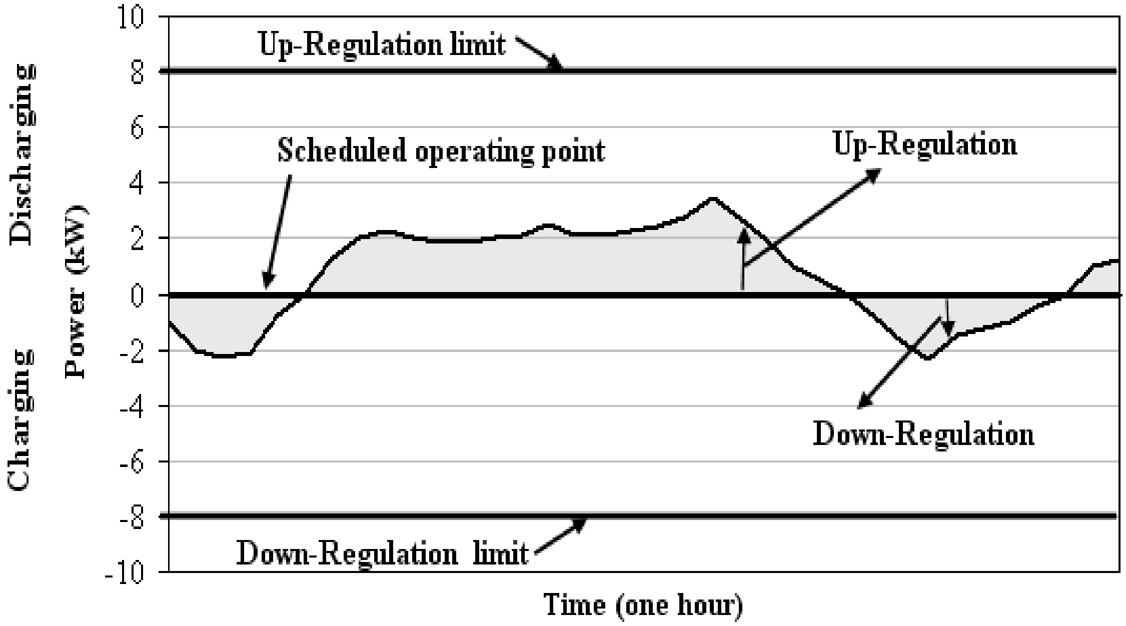

Fig. 2.5 Example of an electric vehicle in Vehicle-to-Grid mode using bi-directional charger providing both up-regulation and down-regulation grid ancillary services

The Vehicle-to-Grid systems are still in its earlier stage of deployment. Most of the research and development on V2G systems are carried out as demonstration projects. The V2G systems will start gaining acceptance once the electric vehicles gain sufficient market share. As EVs become more common or deployed in large numbers in the distribution grids, communication and control are inevitable for not overloading the grid. The integration of smart meters and standardised two-way Information and Communication Technology (ICT) interfaces are expected to be common in every household or at every service points, once the smart grids initiative which forms the basis of the emerging electricity grids with many distributed generation units are implemented. The electric vehicles will also be one among the important components in the smart grid puzzle.

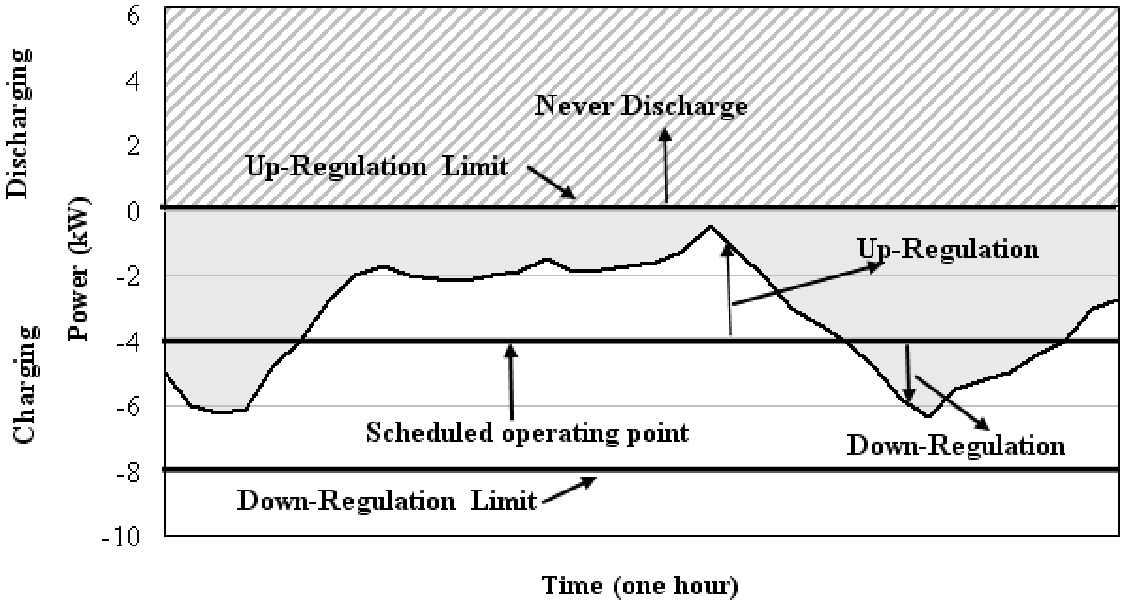

Fig. 2.6 Example of an electric vehicle in Vehicle-to-Grid mode using unidirectional charger providing both up-regulation and down-regulation grid ancillary services

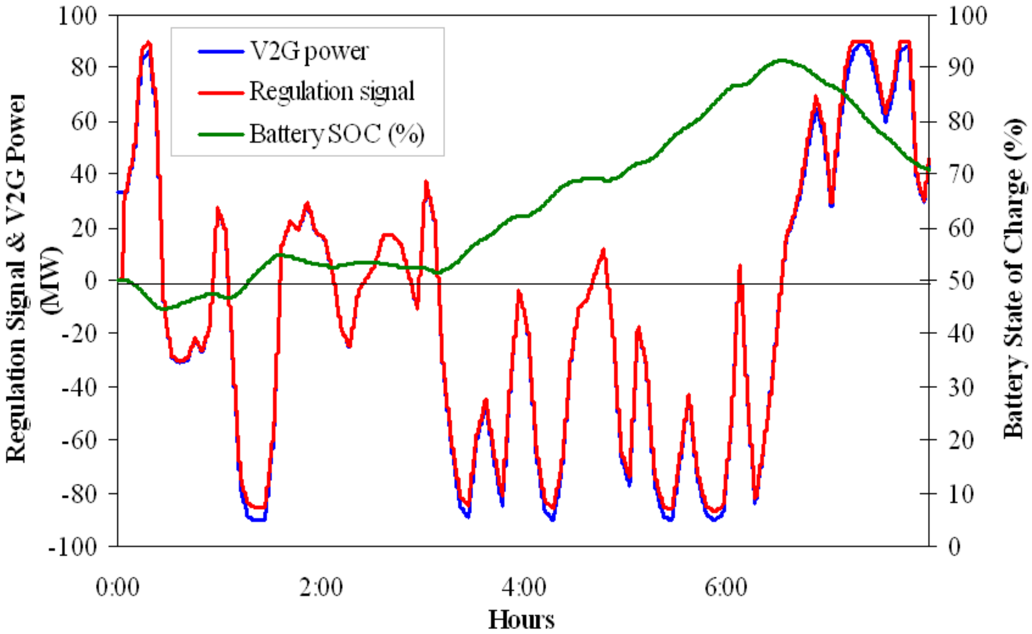

Fig. 2.7 Vehicle-to-Grid response to grid power regulation signal

The gradual progression for not overloading the grid by "using timer control" to "using price signal" to "controlled load using demand signal" to "distributed storage" could be seen as the most suitable trend in adopting more EVs. The electric vehicles operating as a grid-controlled load (unidirectional) could be the first phase (0-5 years) in deployment of the Vehicle-to-Grid technology. The battery wear and tear from bi-directional power cycling from regulation services is not well understood as of now. More research and attractive business models are needed to account for the battery degradation costs. This is one important factor that could prompt the bidirectional Vehicle-to-Grid concept to be adopted as the second generation (5-10 years) of grid-connected vehicles.

There is also a need for standardization on reverse power flow from electric vehicles and other grid interconnection issues to be addressed like anti-islanding, power quality, re-coordination of protection relays where more research are to be conducted. However, there exist standards like IEEE 1547.3-2007, IEC 61850-7-420 etc. which defines clear procedures for integrating distributed storages. IEEE Std 929-2000, IEEE SCC21 etc. proposes reliable technical solutions for incorporating small distributed generation systems like small solar and wind energy which could be equally or closely applied for distributed storages from plug-in vehicles. Once the Vehicle-to-Grid concept becomes commercially acceptable and technically matured, other diverse applications could also be utilised from EV battery storages for the reliable operation of local distribution system including voltage support, emergency power, microgrid support etc.

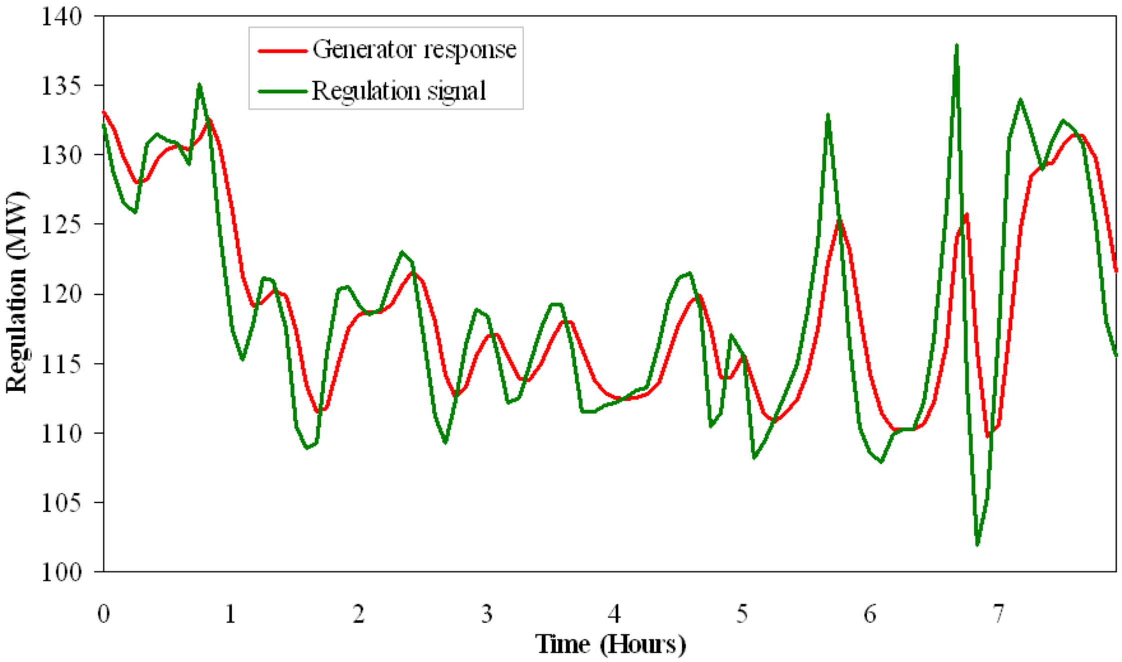

Fig. 2.8 A 250MW steam power plant response to grid power regulation signal

2.6 Summary

The electric vehicles have an important role to play in realizing global oil independence, environmental and energy security. They are one of the most attractive and promising strategies to reduce and replace the conventional fossil-fuel based energy systems in both the transportation and electricity sector. The electric cars are environmental friendly as they are free from any green house gas emission compared to gasoline vehicles. Using V2G systems, the electric cars could also play an important role in the electricity grid as a controllable load or energy storage. On a daily average, about 90% of the time the vehicles are not used for transportation, where the battery storages of electric cars could provide grid ancillary services earning revenue. Apart from this remuneration, the synergy between renewable energy and V2G-capable cars aggregated to form large battery storages in the electricity grid are very compelling.

Such abundantly dispersed electricity storages could be used as a large buffer for supporting high penetration of variable renewable energy like wind and solar power in the electricity grid. The electric vehicles would be beneficial to the electricity grid as a new source of ancillary services. The response of the battery storages to the grid operators request for ancillary services is faster and more accurate than the conventional power plants. This will increase the reliability and efficiency of these services, where the conventional power plant could go back to generation at constant output levels. This flexible power function of electric vehicles, in addition to providing clean transportation and potential to support fluctuating renewable energy leads to a sustainable and green economy.

Chapter 3

Vehicle-to-Grid Systems for Frequency Stability in Danish Distribution System

3.1 Introduction

The Danish power systems is characterised by a large number of dispersed generation units at the voltage levels 60kV and below. These units comprise mainly wind turbines and small to medium scale combined heat and power (CHP) units. In the Western part of Denmark, these units contribute to more than 50% of total installed production capacity [65]. These active distribution networks have become net power exporters where the generation exceeds the loads several times, especially during days of high winds. The operation of CHP units is primarily based on the heat demand and secondly on the market for the units above 5MW. The smaller CHP units operate on the basis of time-of-day tariff [66]. The wind turbines produce power, whenever the wind is available. These operation patterns of distributed units have resulted in difficulties for predicting and controlling the total electricity generation. Such large in-feeds of uncontrolled operation of wind turbines and heat constrained CHP units is challenging to a reliable and secure operation of the power system.

The large domestic power plant units and efficient power trading have negotiated these challenges successfully to maintain the power system stability. As the share of large power plants are reducing, their functions have to be supplemented by smaller units in the local grids. The role of the local grids has to be more proactive and self sustainable in utilizing local solutions like distributed storages, controllable loads and flexible generation units. To maintain the power balance and stability in the power system, distributed generators have to be grouped into controllable virtual power plants. The Vehicle-to-Grid systems utilising the car batteries has a unique feature of being able to act as an aggregated distributed storage which could be seen as one of the feasible solutions satisfying the above criteria. This chapter presents the role of Vehicle-to-Grid systems as a controllable load or generator to maintain the frequency quality of a distribution network subjected to different power system events like step load change, loss of

CHP and wind farms. The digital simulations are performed in a wind power dominated Danish distribution network. Simulation scenarios where more wind power is used to replace the conventional CHP generation are analysed in this chapter. The distribution network is considered as operating in an islanded mode to validate the effectiveness and flexibility of the domestic resources like Vehicle-to-Grid systems in stabilising the power system frequency in the local grids.

3.2 Simulation Case Study

A part of a medium voltage distribution network in the Lolland-Falster area of East Denmark is simplified and used here as the test case for simulations. Fig. 3.1 shows the test distribution network where the power system is disconnected or islanded from the 132kV external grid. The generation units are scattered over the 10kV and 0.4kV networks. The two combined heat and power (CHP) generators are based on gas turbine units. The installed capacities of the CHPs are 20MW and 4MW respectively. The three wind farms are all of fixed speed wind turbines units rated 6MW, 2MW and 3.5MW respectively. The wind turbine generators is operated close to unity power factor with the use of local shunt capacitor banks which facilitates the necessary reactive power compensation. The system loads are aggregated at the 10kV voltage levels.

The Vehicle-to-Grid systems are represented by aggregated EV based battery storages at each of the four 0.4kV feeders. The total load of the distribution network is 24MW which includes the electric vehicle battery charging demand of 1.6MW. This represents 6.6% of the total system load. The Vehicle-to-Grid systems are modelled here to operate as primary reserves responding to the frequency deviations in the distribution system. The total available capacity of the electric vehicles is considered here as 4MW equally distributed as aggregated 1MW battery storage per 0.4kV feeder. A power contract capacity of 1MW is a typical minimum generation reserve level that is required from units participating in the grid ancillary services [67].

3.3 Modelling of Components

The distribution network and the components are modelled in the DIgSILENT PowerFactory software (Version14) [68]. The data for the generators, loads, lines etc. and the parameters of the various control blocks of the components are given in different tables in Appendix A (Tables AI to AV).

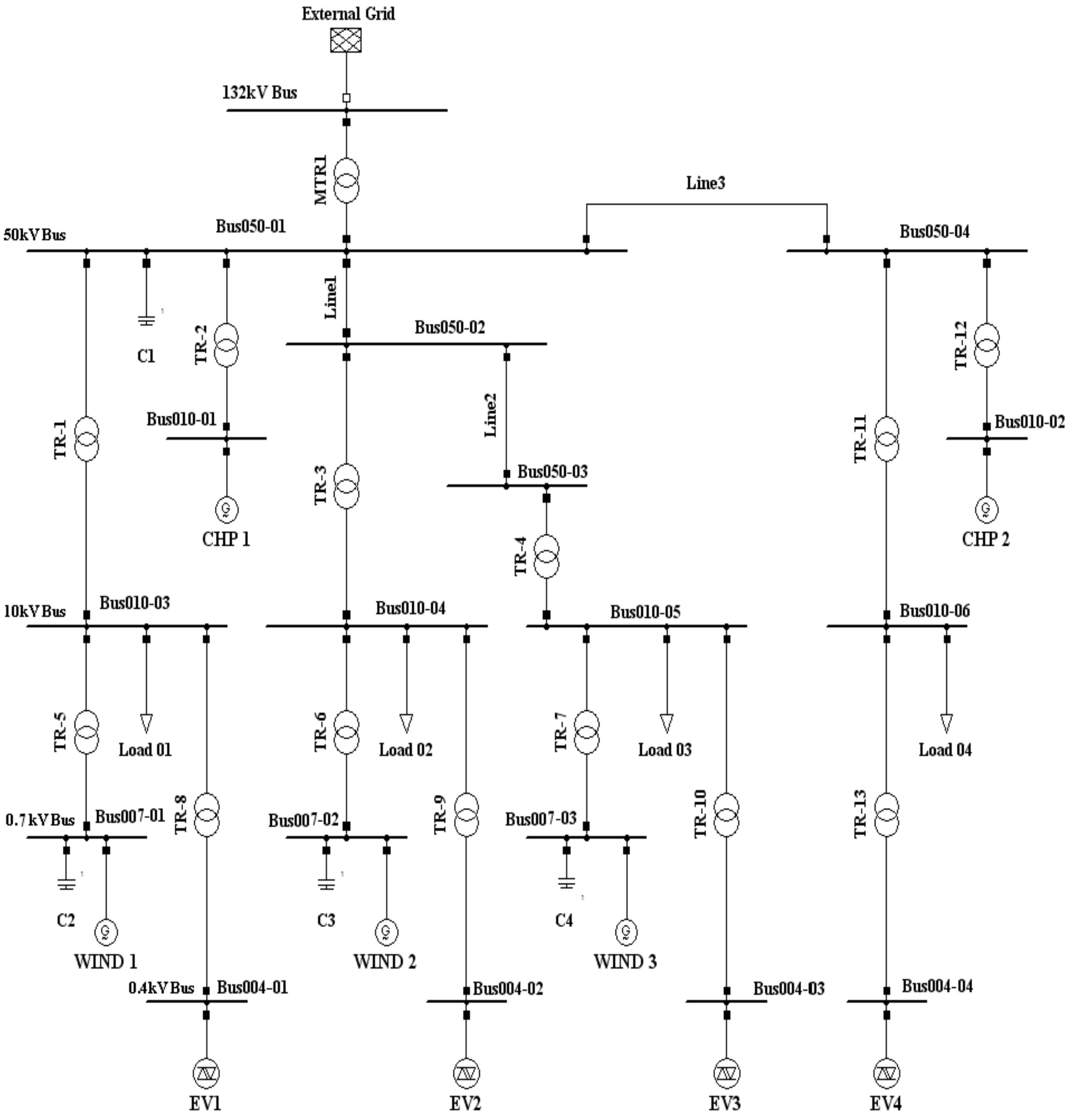

Fig. 3.1 Test Distribution Network

3.3.1 CHP units

The CHP units are modelled based on the GAST turbine-governor model, which is one of the most widely used model for dynamic simulations [69]. The GAST is a simple-cycle, single-shaft gas turbine model. The model is available in the global library of the PowerFactory software. For simplicity, only the frequency loop and temperature control loop are considered in the model

[70]. Fig. 3.2 illustrates the block diagram of the GAST model operating in droop mode or proportional control mode of frequency regulation [69], where P_{ref} is the reference power, R is the governor droop, T_1 is the first fuel system lag time constant, T_2 is the second fuel system lag time constant, T_3 is the load limiter time constant, K_t is the temperature control loop gain, V_{min} and V_{max} are the minimum and maximum valve positions respectively and D_{turb} is the turbine damping factor. In the GAST model, the loop which has a minimum value at the low value gate takes command of the fuel system and mechanical power production. It is also assumed here that the exhaust temperature limits are not violated, such that the temperature control remains constant during simulations.

The proportional or droop control is commonly used for parallel operation of generators, where the control gain is the inverse of the permanent droop. For an islanded power system, it is essential to run at least one machine (possibly the largest generator unit), CHP1 in isochronous mode so as to take care of the load variations and the other generators (in this case CHP2) in the droop mode [63], [71], [72]. In the isochronous mode, regardless of the load, the machine will control the governor to maintain the frequency. The speed governor or the droop control in Fig. 3.2 is therefore replaced by a conventional proportional-integral (PI) controller for the CHP isochronous mode operation.

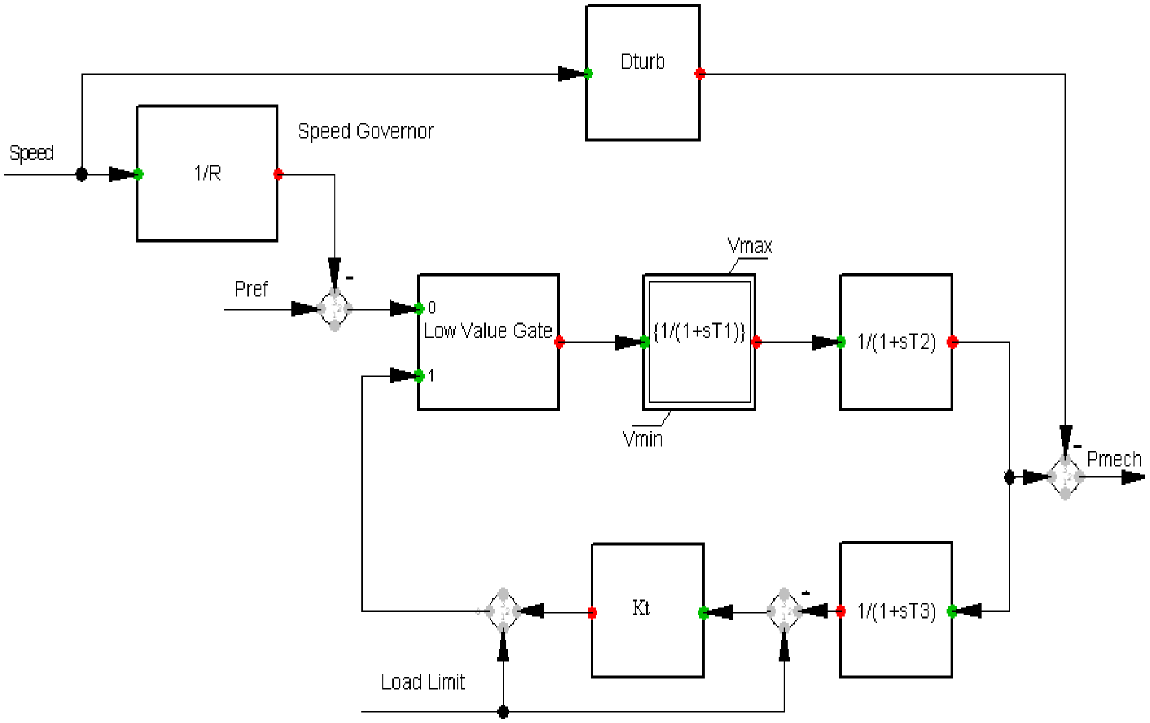

Fig. 3.2 GAST model with droop control [69]

3.3.2 Aggregated EV battery storages

The Vehicle-to-Grid systems representing the aggregated battery storages of electric vehicles are modelled here as static generators. The static generator is an element available in the library of the PowerFactory software which is used to represent any generator which is not rotating, but static like fuel cells, battery storages, photovoltaic generators etc [68]. For the electromechanical transient simulations, the static generator is equivalent for an ideal PWM converter. To control the active and reactive power independently using the static generator, the reference values in the dq reference frame have to be set. This can control the currents in the d-axis and q-axis, if the reference frame is synchronized with the voltage angle. This approach is normally used to control the power output of the PWM converters. Fig. 3.3 shows the simplified control block diagram of a static generator to represent the aggregated battery storage. The inverter output current id and iq are controlled by the reference current signals id_ref and iq_ref which are generated from the outer loop using the power controller block. The active power controller generates the current reference id_ref which is shown in Fig. 3.4.

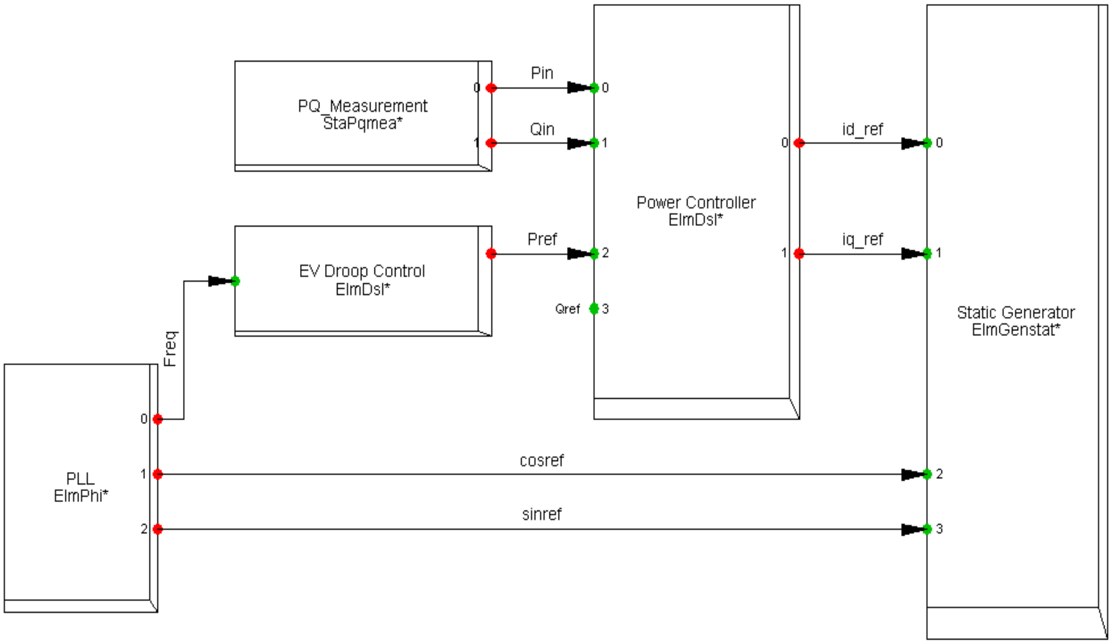

Fig. 3.3 Static generator control block diagram used to simulate aggregated EV storage

The static generator is assumed to be operating with unity power factor such that the reactive power reference, Qref is considered as zero. As part of the power controller block, the aggregated EV storages are operated in a droop mode responding to the system frequency deviations. A dead band is applied to the input signal which is added to prevent the storage from responding to very small frequency changes, thus preventing excessive charging and discharging of the battery. This is desirable for improving the life time of the battery storages participating in the frequency regulation. A dead band of ±10mHz is used in this study after several simulation tests. A limiter is used to limit the battery power within its maximum charging and discharging capabilities. The battery charges for positive frequency deviations and discharges (or reduce the charging levels) when the frequency drops. In this way the aggregated electric vehicle storage which are interfaced by smart grids are capable of responding to the local frequency deviations.

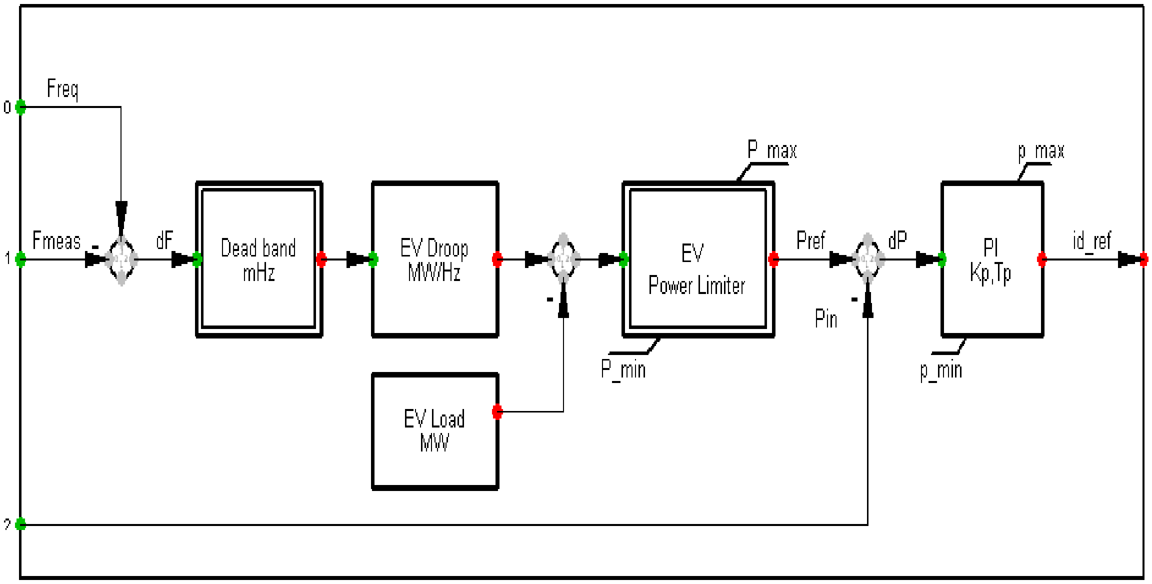

Fig. 3.4 V2G active power controller

3.3.3 Wind Turbine Generator (WTG) model

The wind farms are modelled in this chapter as land based aggregated fixed speed wind turbines (FSWT). The simplified fixed speed wind turbine model that is available for transient stability studies in PowerFactory is depicted in Fig. 3.5 [73], [74], [75]. The turbine block is the aerodynamic part of the model which generates the torque developed on the rotor blades. The aerodynamic torque produced by the wind turbine, T_{wind} is given by the following equation [74].

$$T_{wind} = \frac{C_p \rho \Pi R^2 V^3_{wind}}{2\omega_{rotor}} \tag{3.1}$$

where ρ is the air density,

R is the rotor radius of the wind turbine,

V_{wind} is the wind speed,

ω_{rotor} is the turbine rotor speed,

and C_p is the power coefficient.

The shaft block is the mechanical part of wind turbine-generator represented by a two mass model. The mechanical torque produced by the wind turbine, T_{mech} is given by the following equation [74].

$$T_{mech} = K.\theta - D.(\omega_{gen} - \omega_{rotor}) \tag{3.2}$$

where K is the shaft stiffness,

θ is the rotor angular displacement,

D is the torsional damping,

ω_{rotor} is the rotor speed,

and ω_{gen} is the generator speed.

The turbine power, P_{turb} which drives the generator, is given by the following equation [74].

$$P_{turb} = T_{mech}.\omega_{gen} \tag{3.3}$$

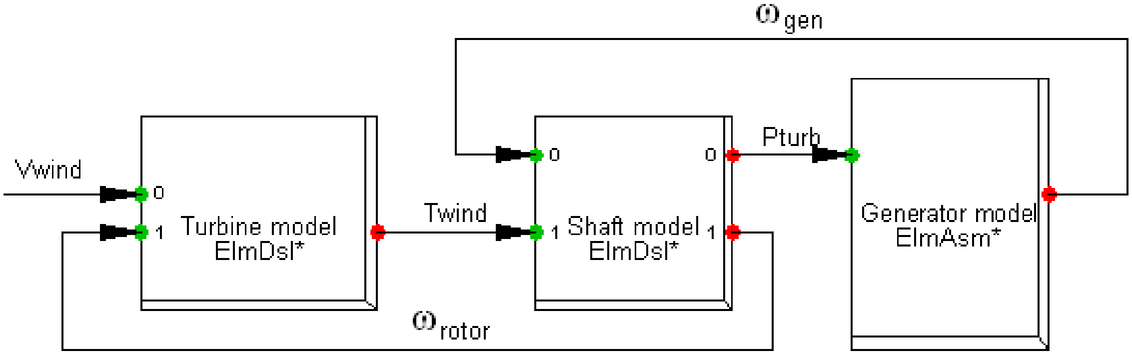

Fig. 3.5 Simplified PowerFactory Wind Turbine Generator model

The generator block is represented by a squirrel cage induction machine. A full converter based wind turbine generator (FCWT) model is also used in this analysis using the static generator model available in PowerFactory [4]. This model is sufficient enough to represent a WTG, as the wind farm behaviour from the view of the grid side is determined by the converter in a power system.

3.3.4 Load model

To account for the voltage and frequency dependence of a load in a power system, a simplified dynamic model of the load [68] is represented as

$$P = P_0(1 + k_{pf}\Delta f + k_{pu}\Delta V) \tag{3.4}$$

where, P and P_0 are the resultant and initial active power respectively,

k_{pf} and k_{pu} are the frequency and voltage dependent coefficients of active load respectively (assumed unity here),

and Δf and ΔV are the frequency and voltage deviations respectively.

3.4 Simulation Scenarios

Three different simulations scenarios defining different component configuration or capacities are defined in this Section. The first case is the base case with sufficient conventional regulation reserves available in the test distribution system with large penetration of wind power. In the second case, some of the CHP power capacity is replaced by wind power and in the last case all the wind turbines are considered to be based on full-converter interfaced generators.

Case 1- This scenario is the reference case where the wind power supplies 48% of the total load. The CHP1 operates in the isochronous mode, while CHP2 and the Vehicle-to-Grid operate in the droop mode. As initial operating conditions of the network, the CHP1 which is 37% loaded supplies 9MW and the CHP2 which is 72% loaded, generates 3.5 MW power. This ensures that sufficient system up-regulation and down-regulation capability is available from the conventional CHP generation units.

Case 2 – The installed capacity of CHP1 is reduced by 50%, which is now reduced to 10MW. The total demand and the EV storage capacity are the same as in the previous case. The wind capacity of the first wind farm (WIND 1) is increased to 10MW and the wind power now supplies 65% of the total demand in the network. The distribution network becomes a wind power dominated power system constrained with reduced balancing power from the CHP units. This scenario represents the future power system configuration where more wind power is integrated displacing the conventional synchronous generators.

Case 3 – This is a case where the fixed-speed wind turbines in case 2 are replaced with full converter wind turbines. The wind farms are assumed here to produce maximum possible power. The droop frequency control from a possible active power reserve of a converter interfaced aggregated wind farm is not considered here in this work [75], [76]. This scenario considers only the case where the EV battery storage is sufficient enough to supply the frequency regulation power and thereby utilizing the maximum available renewable wind power. This case is studied to examine the relevance of power regulation from the flexible V2G systems in a power system dominated with converter interfaced generation units. This scenario of replacing the older wind turbines with efficient converter interfaced wind turbines can be considered as the repowering scheme of wind power which is already being implemented in Denmark [19].

3.5 Simulation Results

Various power system events are simulated in the test distribution network using the PowerFactory software for the scenarios described in the above section.

3.5.1 Step load change

To analyse the power system frequency response of the test distribution network, a step increase of active power of a system load is simulated here. When the demand is increased, the system frequency will reduce. The extra demand has to be met by the generators and the EVs participating in the frequency regulation process to normalize the system frequency. A step load increase of 100% (2MW) is applied at time, t=5 sec on the system load 04. The frequency response of the distribution network with and without V2G regulation for case 1 (reference case) is given in Fig. 3.6. The rate of change of frequency (ROCOF) and the minimum frequency drop (frequency nadir) in the network with the support of V2G regulation is less when compared to the case without EVs participating in power balancing. The V2G regulation provides a more stable, better damped and fast recovery of the system frequency. The EVs battery storage units have only very small delays when compared to the dynamics of the conventional generation unit which gives the former a more active role in the frequency control. For the simulation case without V2G regulation as shown in Fig. 3.7, the aggregated battery storage of EV1 acts only as a load (charging mode).

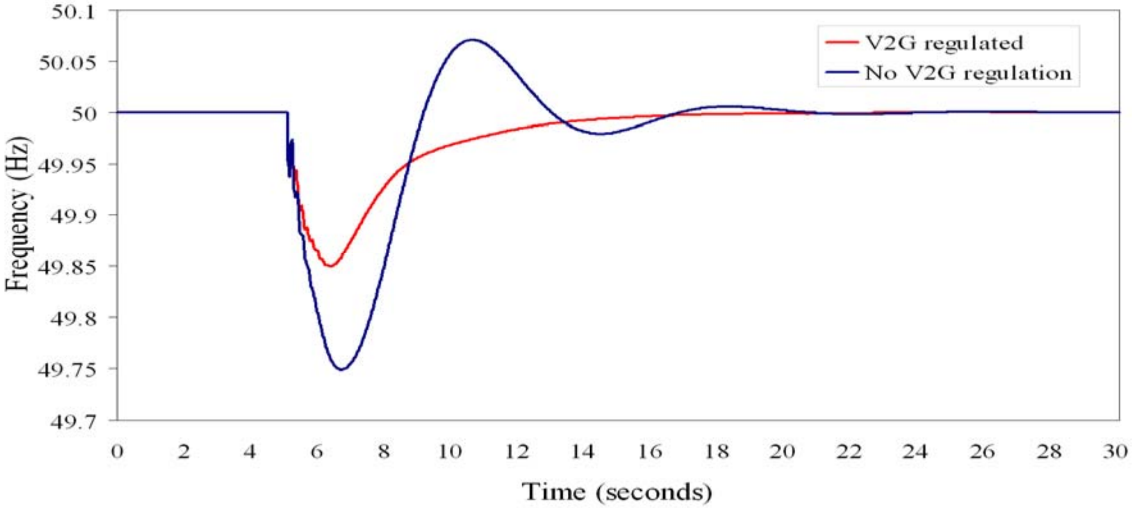

Fig. 3.6 Frequency profile for step increase of load– Case 1

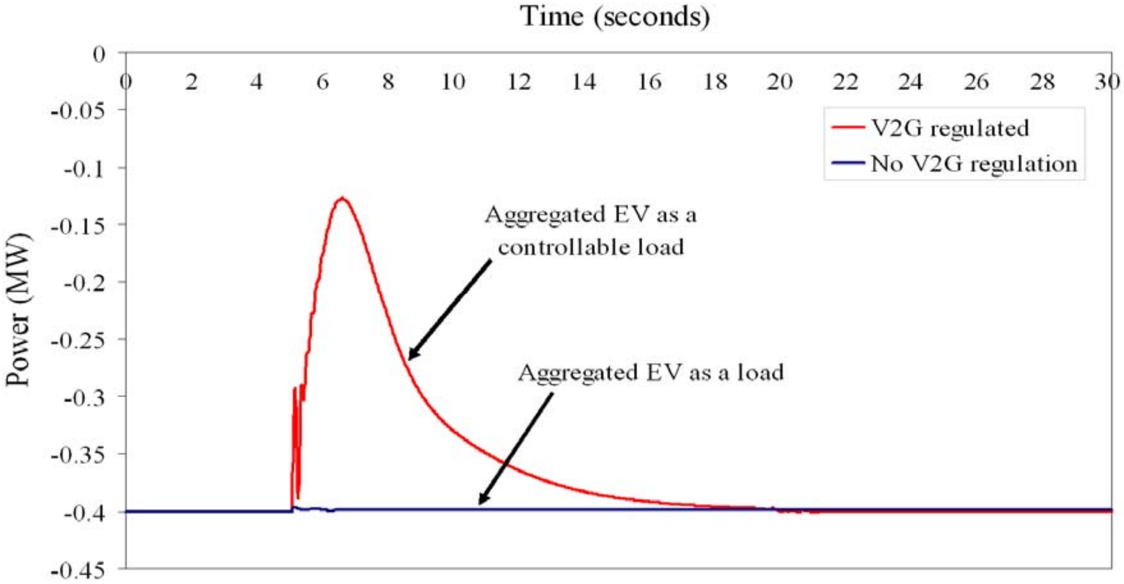

Fig. 3.7 Aggregated EV1 active power for step increase of load– Case 1

The simulation result using V2G regulation shows that the EV storage acts as a controllable load by reducing the charging to 0.13MW from the initial load of 0.4MW.The active power produced by CHP1 for the case with V2G support offers a smooth generation and less “up-regulation” power requirement compared to the simulation results without V2G as shown in Fig. 3.8. Fig. 3.9 also shows that less balancing power is required from CHP2 when the aggregated EV storage functions as system frequency regulation component. Fig. 3.10 depicts the turbine power supplied by a wind farm (WIND1) in response to the frequency deviation caused by the step load change event. The demand for inertial reserves from wind turbines are reduced for the simulation case with the V2G participating in frequency control. The frequency responses of the three simulation scenarios with V2G support for a step load increase are shown in Fig. 3.11. The frequency drop for case 2 is higher than the reference case but less than case 3.

From the results, it can be inferred that for case 2 and case 3, the conventional generators being replaced with more wind power reduces the system inertial response and regulation capabilities in the power system. This necessitates the need for more power balancing reserves in the power system. The situation is more demanding for case 3 as the asynchronously connected power electronic interfaced wind turbines cannot contribute to the system inertia. However, with the support of the V2G systems, the system frequency is able to retain to the nominal value of 50Hz for all the three cases.

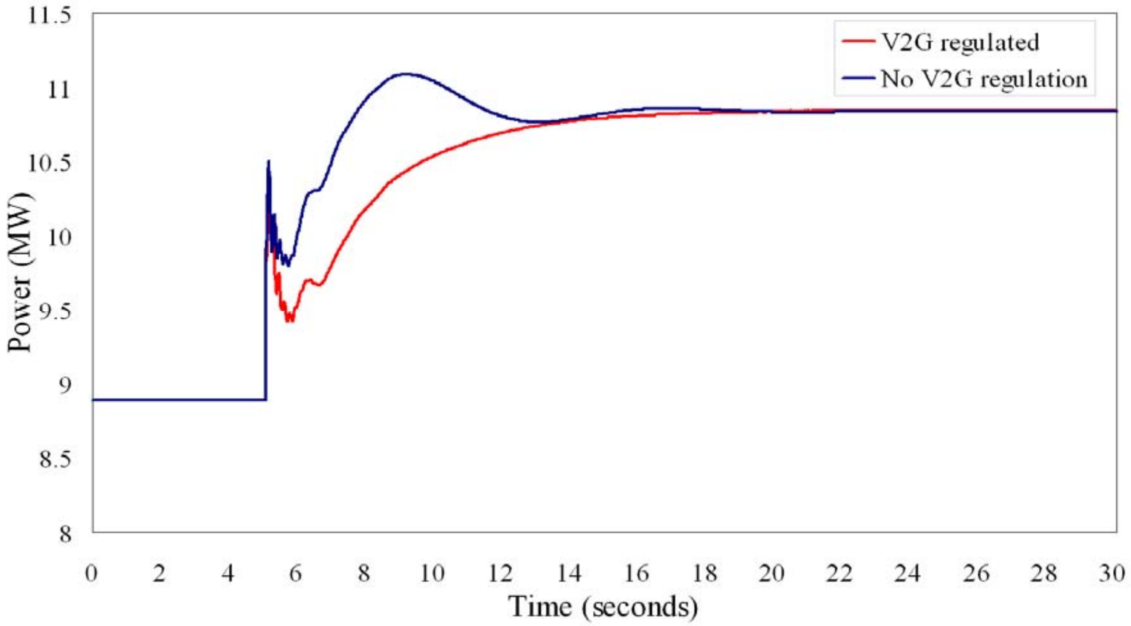

Fig. 3.8 CHP1 active power for step increase of load – Case 1

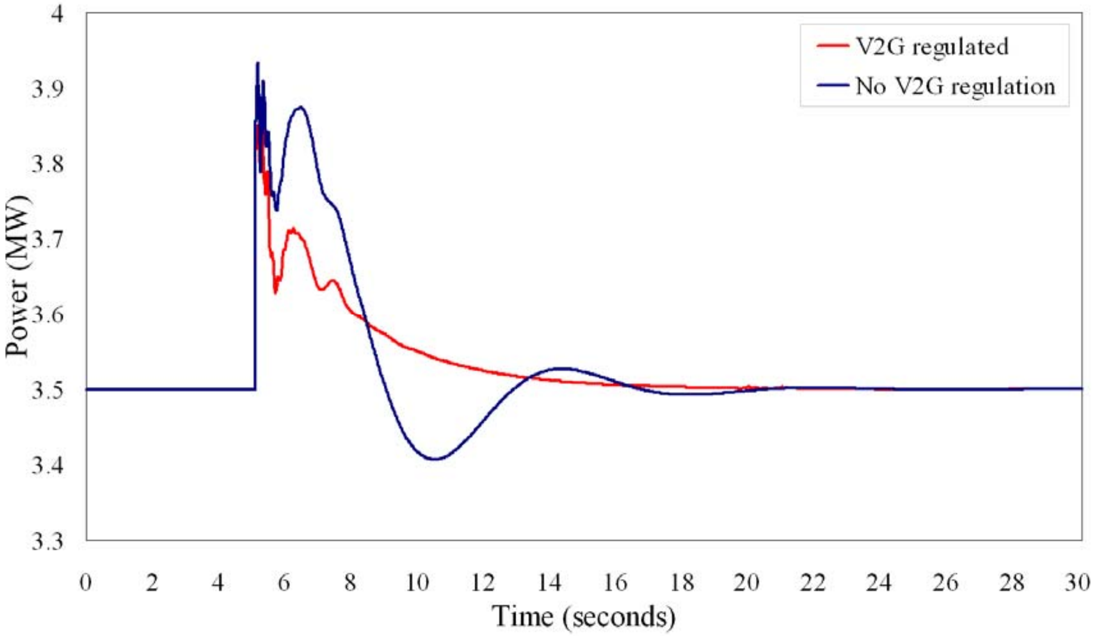

Fig. 3.9 CHP2 active power for step increase of load– Case 1

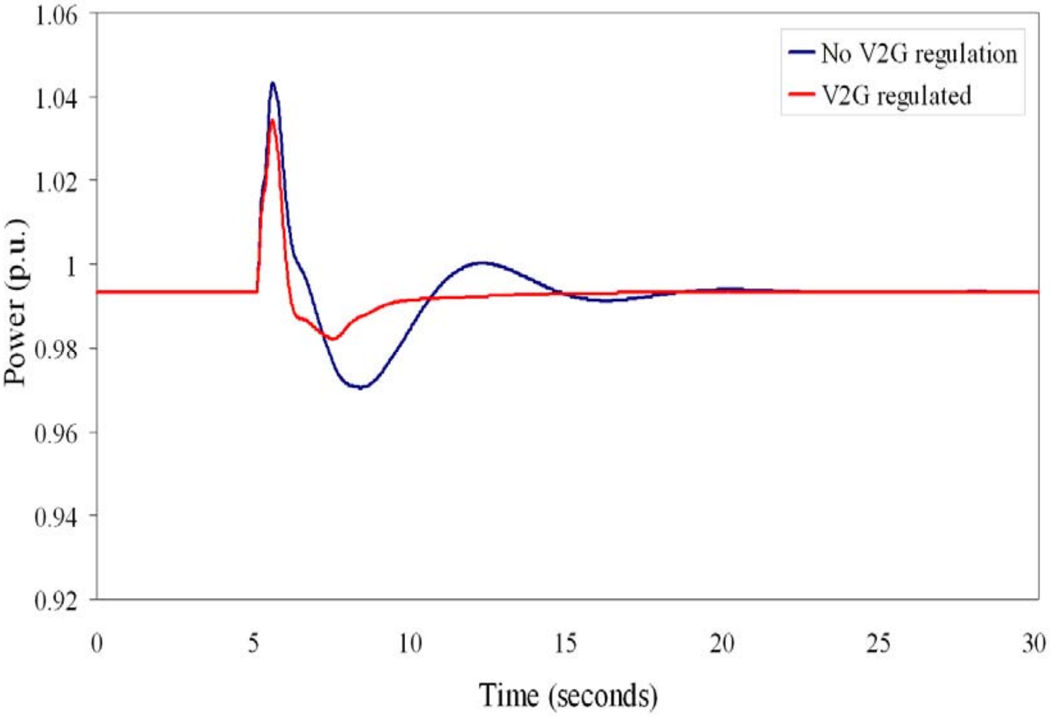

Fig. 3.10 Wind farm (WIND1) turbine power for step increase of load – Case 1

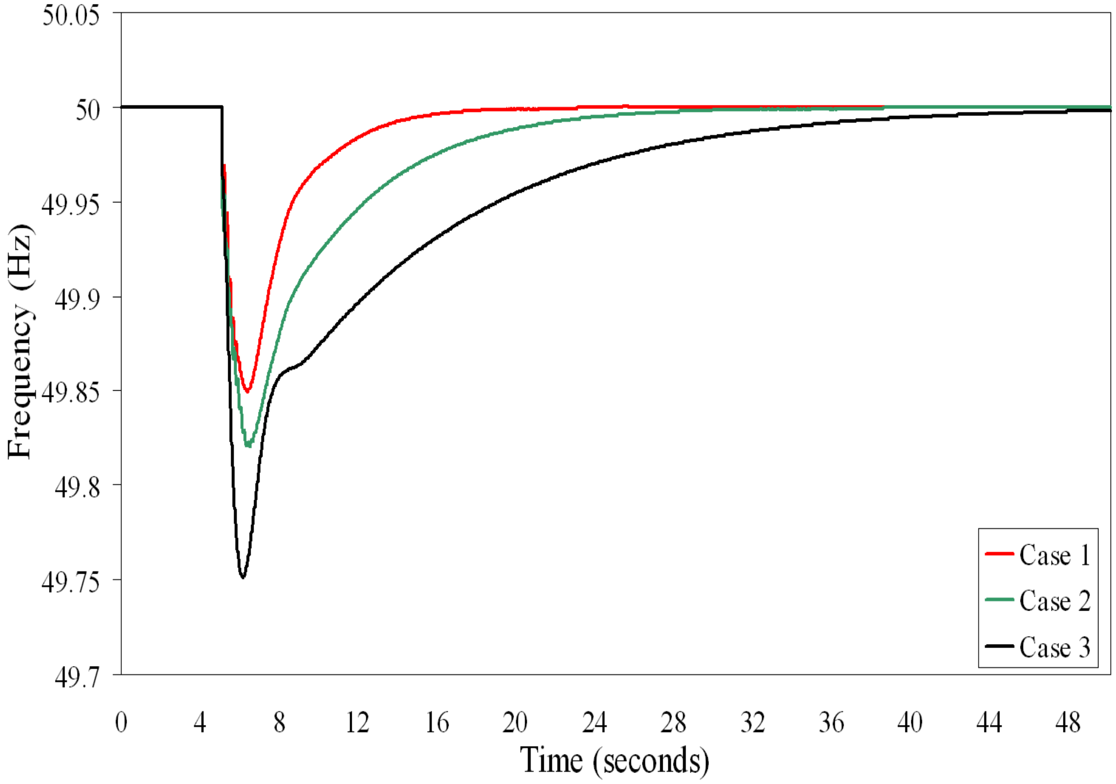

Fig. 3.11 Frequency profile for step load increase

Thus, the use of quick start and fast regulation alternative systems like V2G are essential to provide frequency stability for large wind power penetration in the future electric power system. Fig. 3.12 depicts the active power from the aggregated EV, connected to one of the distribution feeders for all the three scenarios.

The EV battery storages acts as controllable load (controlled charging mode) for case 1 and case 2 where the EV load consumption is reduced by 68% and 83% respectively during the frequency regulation process. For case 3, the aggregated EV storage operates for a period as a power generation source where the battery operates in the discharging mode injecting power into the network. This demonstrates the regulation capabilities of V2G by injecting or absorbing active power to ensure the desired frequency quality in an islanded distribution system operation with higher proportions of wind power.

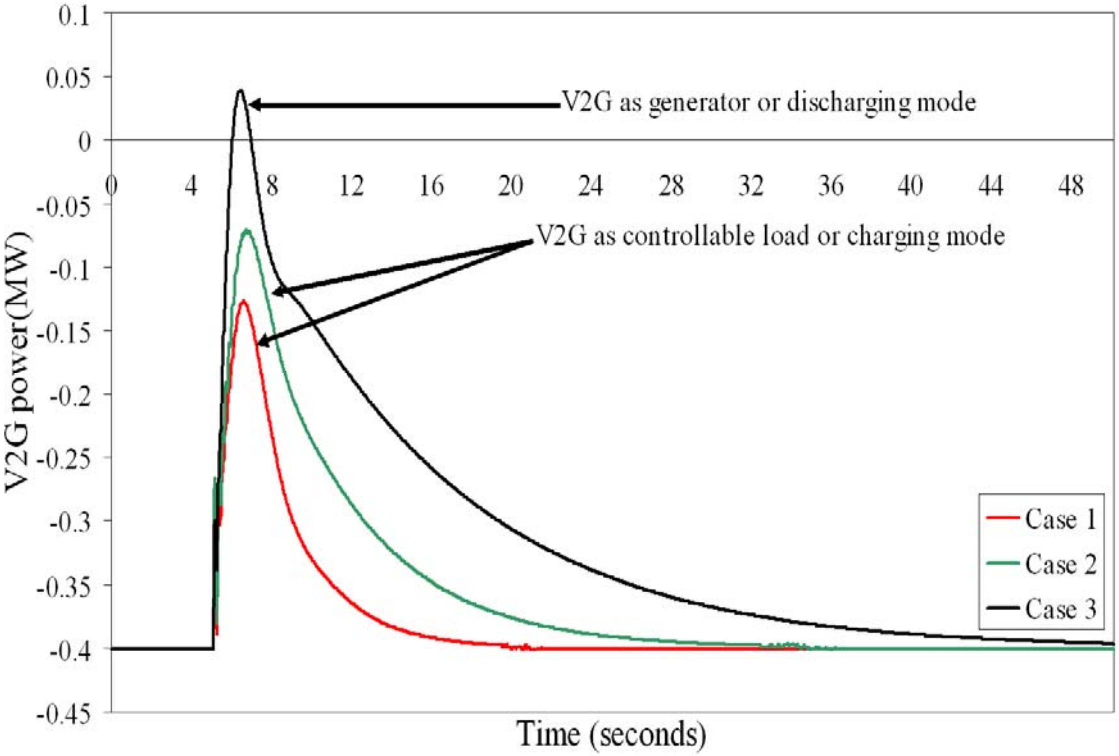

Fig. 3.12 Aggregated EV1 power for step load increase

3.5.2 Loss of CHP and Wind farm

To investigate the use of V2G regulation for recovering the system frequency due to a loss of generation, the 4MW CHP2 unit which generates 3.5MW is tripped at time t=5sec. Similarly, the wind farm (WIND 3) is also disconnected as another simulation event where the power generated is the same as that by the CHP2 generator. Fig. 3.13 and Fig. 3.14 show the frequency response of the distribution system following the loss of CHP2 and the loss of a wind farm respectively. All the three simulation cases are plotted where the frequency regulation is supported by the V2G. Comparing the results, the frequency dips are larger for the CHP2 outage than for the wind farm loss, especially for case 3 with the full converter based wind turbines. The case 3 simulation results for the loss of wind farm gives a frequency nadir of 49.62Hz compared to 49.53Hz for the CHP outage. This observation reiterates the fact that the rotational inertia and reserves are more demanding in a future wind dominated network, especially for the power electronic converter interfaced wind turbines.

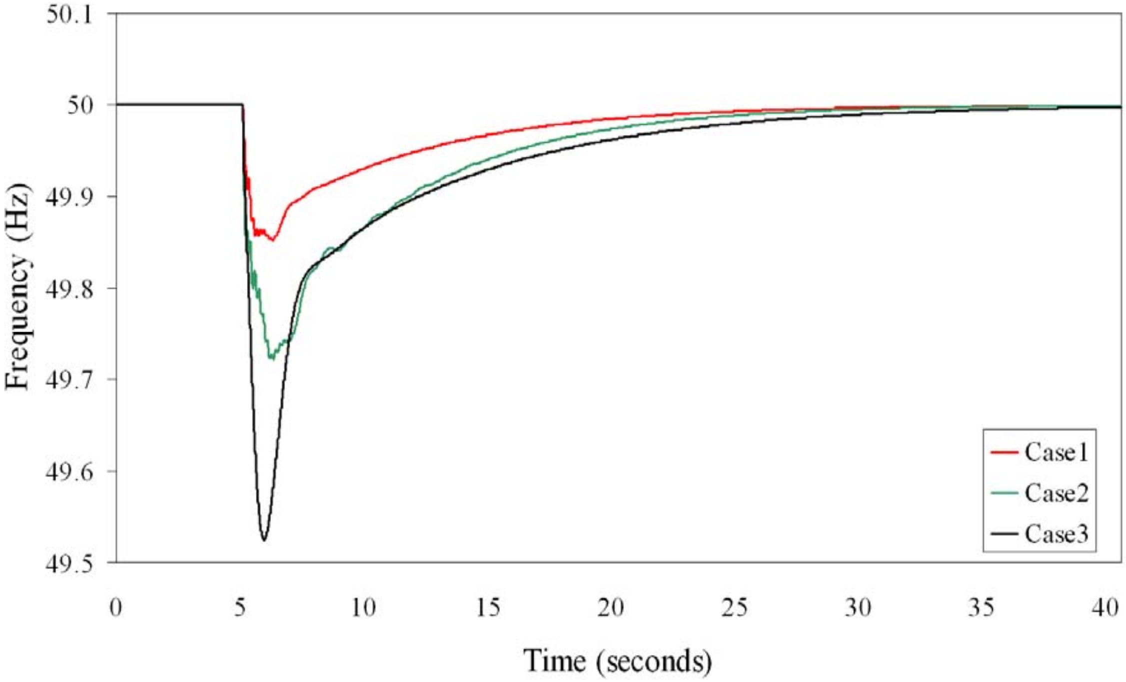

Fig. 3.13 V2G regulated frequency profile for loss of 3.5MW CHP

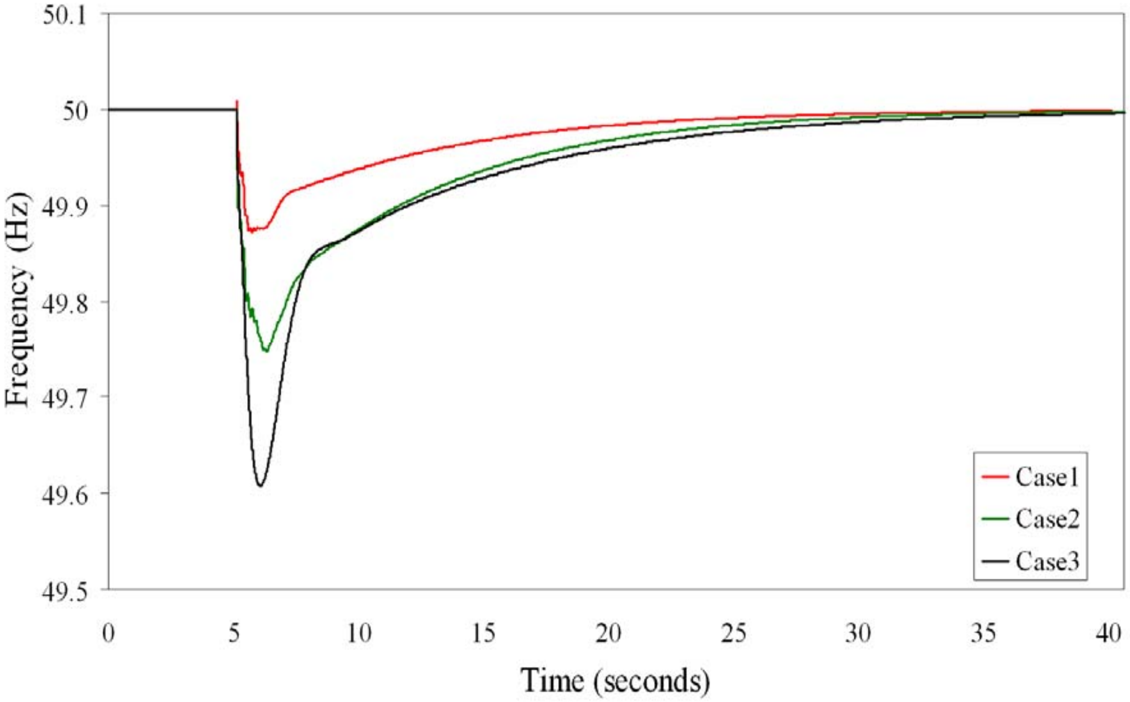

Fig. 3.14 V2G regulated frequency profile for loss of 3.5MW Wind farm

But with the support of V2G regulation, the distribution network is able to retain the frequency quality for all the simulation scenarios to ensure a stable power system operation. For an increasing penetration of both fixed-speed and full converter based wind turbines, the effect on the frequency nadir caused by the loss of CHP2 unit, with and without EV regulation is given in Fig. 3.15. The frequency nadir is significantly reduced for the simulation results with V2G regulation for both wind configurations.

Fig. 3.16 depicts the maximum aggregated EV power required to retain the frequency stability of the distribution network for an increasing wind power penetration. More regulation reserves are desired from the EV battery storages for the simulation case with full converter interfaced wind turbines. This may necessitate the need to consider methods of primary frequency regulation from modern wind turbines [75], [76]. However, this strategy is not always dependable due to the variable nature of wind power. Also it could spill the 'clean' wind power and could also increase the production cost. To decide whether to utilise the grid frequency regulation from the wind turbines or not, there must be a trade-off between reliability, energy efficiency of the wind power and the availability of local and fast regulation reserves like Vehicle-to-Grid systems.

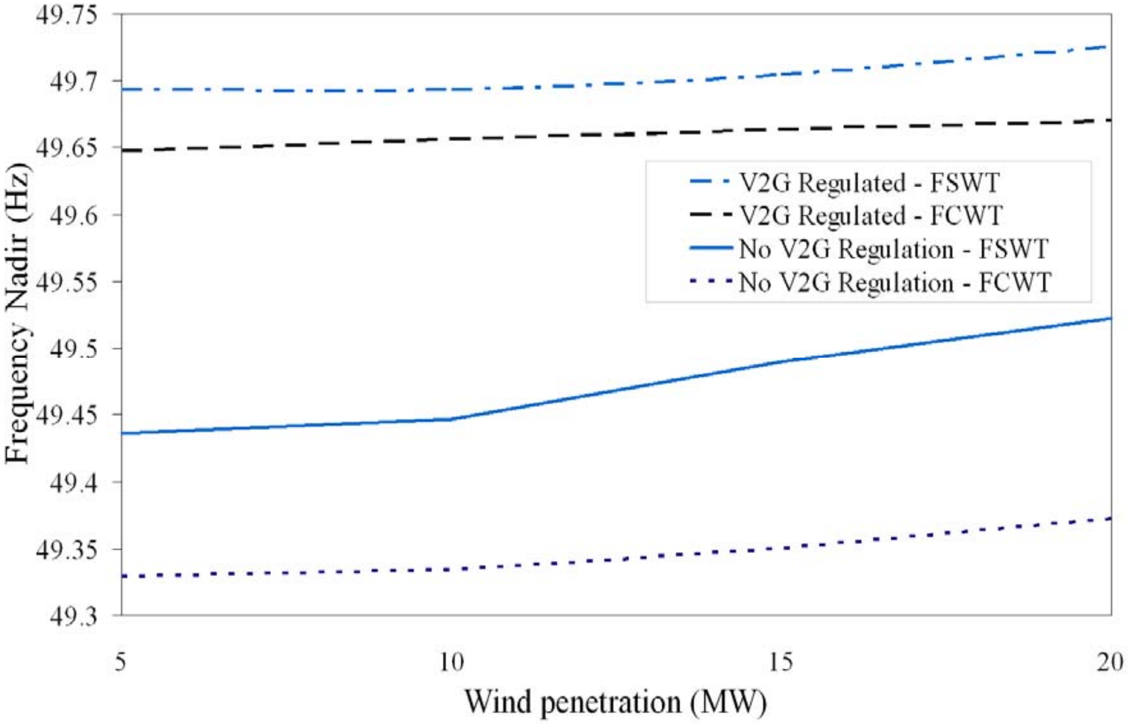

Fig. 3.15 Frequency nadir following the loss of CHP2 event for increasing wind penetration (FCWT and FSWT generators)

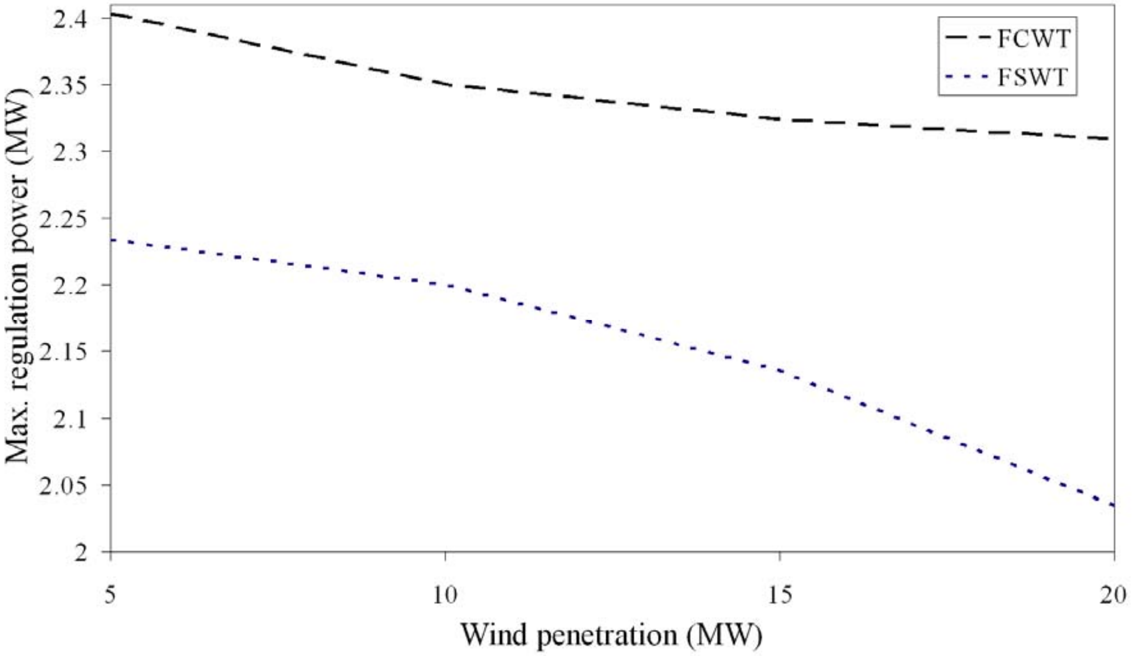

Fig. 3.16 Maximum power from EVs following the loss of CHP2 unit for increasing wind penetration (FCWT and FSWT generators)

3.6 Summary

The use of Vehicle-to-Grid systems to support frequency stability in an islanded Danish distribution system is investigated here in this chapter. The different components are modelled using the standard models available in the Power Factory software library. Three different scenarios with high wind penetration are analysed for simulations. The simulation results for various power system events like the step load change, loss of generation etc. in the network shows that the Vehicle-to-Grid systems ensures a faster and a more stable frequency regulation than the conventional generators. The model of Vehicle-to-Grid systems uses a droop frequency control loop to adjust the active power levels of the aggregated battery storage. This primary frequency control from the Vehicle-to-Grid systems are realised by the controlled load or generation mode by suitably charging or discharging the battery storages of electric vehicles.

The rate of change of frequency (ROCOF) and frequency nadir are reduced with Vehicle-to-Grid regulation compared to frequency regulation from the CHP generators. The Vehicle-to-Grid systems are able to suppress the frequency deviations for the simulation scenarios with large wind penetration of 48% and 65% which are characterised by the reduced system inertia and conventional generation reserves. The Vehicle-to-Grid systems are thus an attractive alternative to the conventional generators for the future power system regulation services. The large availability of such battery storages in the distribution grids could allow integration of higher levels of renewable energy feasible without compromising the power system stability and security.

Chapter 4

Vehicle-to-Grid Systems for Interconnected Power System Operation

4.1 Introduction

The average annual wind power supplies more than 25% of the electricity consumption in the Western part of Denmark [77]. There are many days in a year where the wind power production exceeds the load demand. The total wind power capacity installed is higher than the minimum load demand in West Denmark. Thus, the Western part of Denmark could be considered as a case of large wind power system. Denmark has strong electrical interconnections with its neighbouring countries which are one of the major factors for its high wind power penetration. The power imbalance caused by the difference between the forecasted wind power and actual wind power production in the Danish power system are essentially allocated to the central power plants and the decentralised combined heat and power units participating in the secondary control. As more wind power is being deployed, there is a huge perception that the volatility may increase which demands for higher capacities of secondary control based minute reserves.

The Vehicle-to-Grid concept using the fast-acting battery storages of electric vehicles for grid regulation services show promising prospects as a solution to the above problem. This chapter investigates the application of V2G systems as a provider of regulation power in an interconnected power system. This is realised by utilizing an aggregated battery storage model in the Load Frequency Control (LFC) simulations. These simulations are performed in the context of Western Danish power system which is characterized by a large proportion of variable wind power production. The LFC simulations are analysed for two typical days with high and low wind profiles in West Denmark. The first three sections of this chapter discusses the key features of the Western Danish power system, modeling of an aggregated generic battery storage and LFC integrated with V2G respectively. The objective of the Load Frequency Control simulations is to analyse the performance of the V2G systems in minimising the power exchange deviations between West Denmark and UCTE (Union for the Coordination of Electricity Transmission) control areas. The scheduled power exchanges are necessary for a reliable power system operation for reducing the transmission congestions, grid reinforcement costs and deviations of electricity balancing and market prices against the system price.

4.2 The Western Danish Power System

The Danish power system has two synchronous areas, the Western part of Denmark is connected to the UCTE (European Transmission Network) system and the Eastern part is connected to the Nordic power system. The Great Belt HVDC link which was commissioned recently in August 2010 connects the two parts of Denmark. The generation capacity in the Eastern part of Denmark is primarily from the coal-fired power plants, whereas the wind power constitutes 15% of the total installed generation capacity. In the Western part, the larger power plants are either coal or gas based thermal units. Most of the wind turbines are onshore wind farms and the decentralised units are gas-turbine based CHP units. The transmission voltages in the Western part are operated at 400kV and 150kV. The capacity of the offshore wind farm, Horns Rev A is 160MW and is connected to the 150kV HV transmission system. The Horns Rev B was commissioned in September 2009. Currently, it is the second largest offshore wind farm in the world with a total installed capacity of 209MW. Table 4.1 depicts the capacity figures in the Western Danish power system (WDK) for the year 2007 [78].

Table 4.1West Denmark power system capacity figures in MW [78]

Centralized power plant units	3400
Decentralized CHP units	1750
Wind turbines	2400
Offshore Wind - Horns Rev A	160
Maximum demand	3767
Minimum demand	1384
Transmission capacity from Germany to West Denmark	950
Transmission capacity from West Denmark to Germany	1500
Transmission capacity with Norway	1040
Transmission capacity with Sweden	740
[1]Great Belt Link (West Denmark and East Denmark)	600
[2]Offshore Wind - Horns Rev B	209

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[1] Commissioned in Aug. 2010

[2] Commissioned in Sept. 2009

The West Denmark transmission system is interconnected to the UCTE synchronous area in the south through Germany via two 400-kV and two 220-kV ac lines. The German power system is dominated by thermal and nuclear power plants and fast growing wind power. To the north, West Denmark is connected to Nordic synchronous area through HVDC links to Norway and Sweden dominated by hydro power plants. Fig. 4.1 shows the year 2007 map of the transmission system network of West Denmark including the central power stations [79].

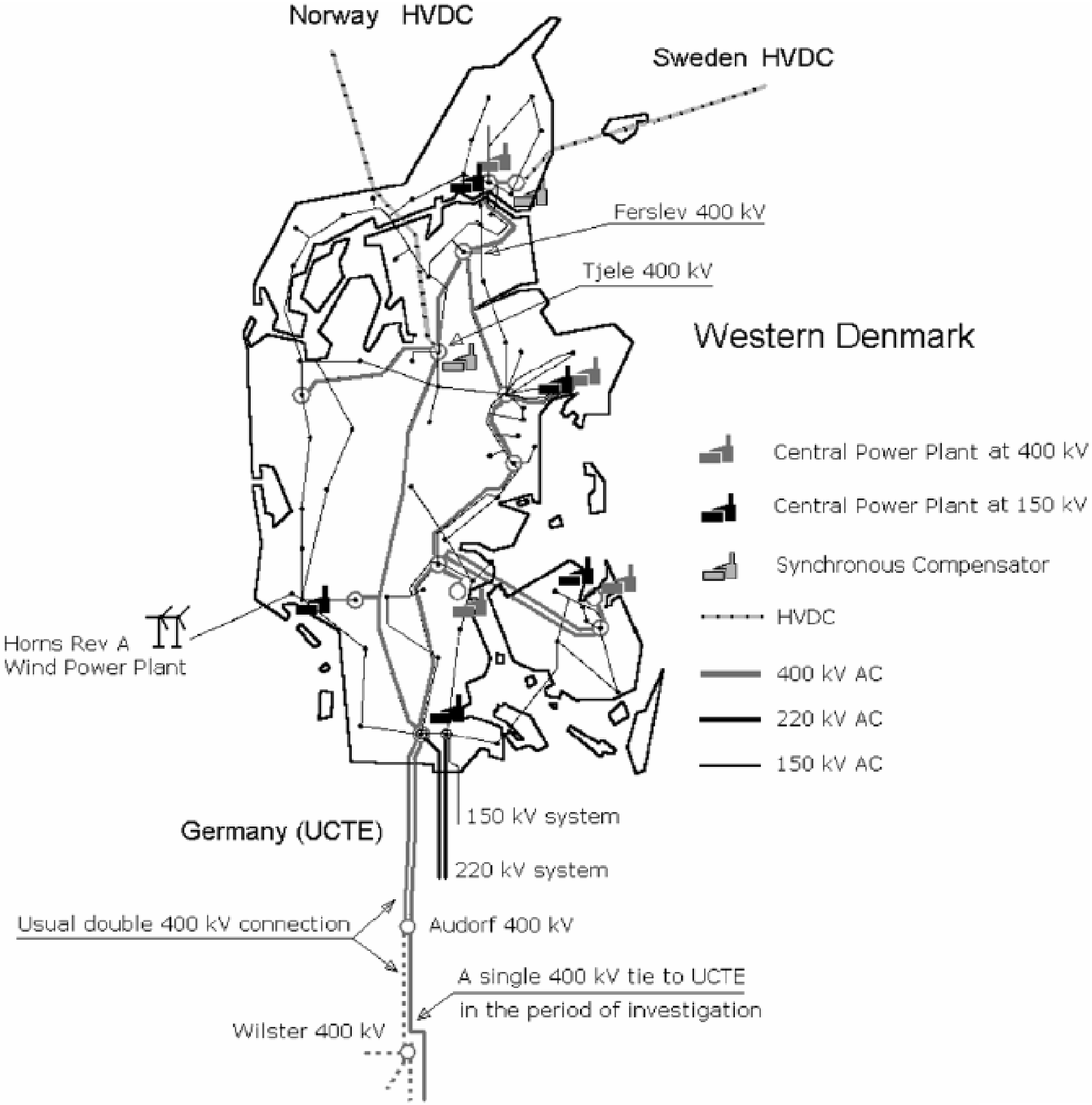

Fig. 4.1 Map of West Denmark Transmission System [79]

4.2.1 Reserve Power Allocation

Table 4.2 gives the reserve power types and typical capacities used in the Western Danish power system. The primary control is used as an instantaneous reserve to deal with sudden power imbalances. The droop characteristics of the generators are adjusted to a new operating point by which the frequency deviations are minimised. They are completely activated within 30 seconds for frequency deviations of ±200mHz [80]. The secondary control is a slow process which will replace the primary reserves to restore the nominal frequency and minimise the power exchange deviations.

The secondary control makes use of a centralised automatic Load Frequency Control in the Western Danish power system which will be fully activated within fifteen minutes. It operates as a single control area which is interconnected to the larger UCTE synchronous area. The total power deviations between West Denmark and the UCTE control areas are the resultant of any deviations from the planned electricity production, demand and the power exchanges to the Nordic area. The controller generates the regulation power demand so as to minimise the power exchange deviations between the two control areas. The acceptable deviation is approximately ±50MW from the planned power exchange [81], [82].

The manual or tertiary reserves are slowest of all the control reserves and are used to restore the secondary reserves by rescheduling the generation. Fig. 4.2 shows the general frequency control schemes and actions implemented under the UCTE synchronous area. As the geographic location of the Western Danish power system is between two large and different AC power systems, there are large power exchanges across its borders. To the south, the schedule of active power exchange with Germany has a resolution of five minutes. The active power exchange schedule with the Nordel synchronous area has a quarter-hourly resolution and follows an hour-by-hour settlement model [81].

Table 4.2 Details of Reserve Power in West Denmark [77]

Reserve Types	Primary	Secondary	Tertiary
Capacity (MW)	± 25	± 90	~ 450
Activation period	0 - 30sec	30sec - 15min	15min
Activation mode	Automatic - droop control	Automatic - Load Frequency Control	Manual

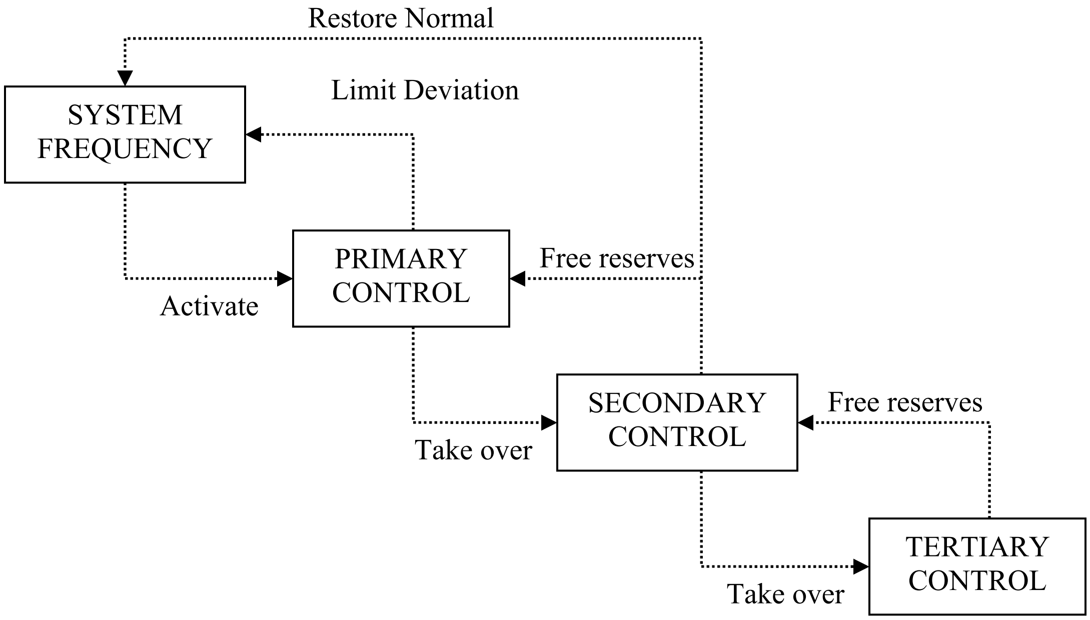

Fig. 4.2 UCTE frequency control scheme [80]

4.2.2 Short-term Wind Power Balancing

Today in Denmark, the reserve power to balance the planned generation and unpredictable load are provided by the large central power plants, large local CHP units and connections from abroad. The variable and unpredictable nature of the wind power also contributes to the power system imbalance. The wind farms are not often equipped to provide these regulation reserves, as their power outputs are not predictable. Studies from the Horns Rev A offshore wind farm reports that the wind power output may fluctuate between zero and rated power in less than quarter of an hour [83], [84]. Fig. 4.3 shows the expected wind power and the actual measured wind power generated on a typical day from Horns Rev A offshore wind farm [5]. There exist large deviations between the power forecasted and the actual power generated from the wind farm. The latest wind power forecasts are available closer to the operating hour and are applied for rescheduling the regulation power available from the conventional power plants. The power gradients observed at the wind farm are of the order of 15MW/min [84], [85].

These power fluctuations are even faster than the characteristic time steps of quarter-hourly and hourly based balancing in the Nordic power system. The faster response which is desired from the regulation reserves of the conventional generators to counter such imbalances is also limited by their generation ramp rates [63]. The rapidly varying offshore wind power output, power deviation limits and different resolution of power exchange schedules in the Western Danish power system are always challenging to achieve reliable power exchanges on the interconnectors and real power balance. These power balancing issues will become more critical when more wind farms are commissioned as part of the 2025 target of 50% wind power capacity in Denmark. Most of the new wind farms are expected to be commissioned in the Western part of Denmark and are offshore-based.

The central power stations, currently the major source of power balancing, being phased-out by the increasing wind power installations is also a major factor of concern for a reliable future power system operation. This creates the need for fast-acting, flexible, and domestic power balancing solutions like the Vehicle-to-Grid systems. The role of electric vehicles in providing regulating or secondary reserves (Load Frequency Control) in the future electricity grid is thus invaluable and inevitable. Also, it is encouraging for the vehicle owners from the fact the cars participating in the Danish regulating market could earn more revenue in rendering the Load Frequency Control than the manual reserves, as the availability payment offered to the former service is higher than the latter [59].

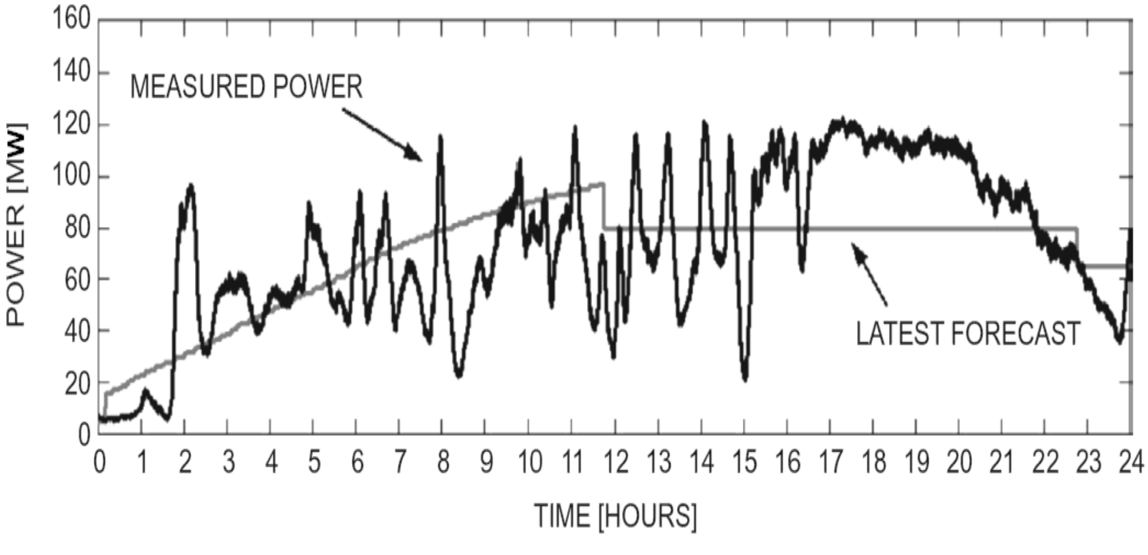

Fig. 4.3 Forecasted and measured power from Horns Rev A wind farm [81]

4.3 Aggregated Battery Storage Model

The battery storage is one of the most complex components to model for simulation studies. Most of the methods used for battery modeling are difficult, time consuming and unclear. The need for an accurate and complete battery model is dependant on the field of its application. In this study, aggregated battery storage for long-term dynamic power system simulation is modelled. Such a model can be made simple enough to illustrate the general behavior of the battery which does not require high levels of precision with large number of parameters and non-linear dependencies. However, it is important to include the feature of voltage dependence on the battery state of charge. For simulation studies, various methods are used to represent the batteries like the mathematical, electrical or electrochemical models [86].

Electrochemical models are ideally used for optimisation of battery design which is complex and time-consuming [87]. The mathematical model uses empirical equations or probabilistic models which can predict runtime, efficiency, and capacity of batteries. However, they are inaccurate and do not give a direct relationship between the battery parameters and the voltage-current characteristics [88], [89]. The most commonly used method for representing batteries in circuit simulations are the electrical models. The Thevenin-based model is the most generally used electric-circuit based representation of a battery in published research works [90], [91]. This model consists of an ideal voltage source in series with an internal resistance and a parallel RC network. The inaccurate estimation of the battery state of charge is the drawback in using this model. The model in [92] discusses a combination of a typical Thevenin model with a run-time model which accurately can provide the state of charge of the battery. Fig. 4.4 shows a modified Thevenin equivalent representation of a battery.

For power system stability and frequency regulation studies, simple transfer functions blocks are used to represent battery energy storages [93], [94], [95]. The combination of the Thevenin equivalent circuit and converter models are also suggested for dynamic power system stability studies [96]. The aggregated electrical vehicle based battery storage is modelled here for V2G regulation services responding to Load Frequency Control signals. The block diagram of a generic aggregated battery storage model representing a V2G system which can provide the state of charge (Soc) capabilities and the resultant battery power (P_b) is shown in Fig. 4.5. The input signal is delayed considering the V2G activation and communication delays. From the experimental field tests conducted on a V2G system, it is reported that the average wireless communication delay between a vehicle and the aggregator is less than 2 seconds and that between an aggregator and TSO is less than one second [34]. As a worst case, a delay of 4 seconds is assumed in this work for simulations.

The state of charge of the battery is calculated based on "coulomb counting". The current in or out of the battery is integrated to give a relative charge which when added or subtracted (based on charging or discharging mode) to the initial charge ($CR_{(t)}$) in ampere-hours, gives the current battery charge removed or received ($CR_{(t+1)}$) as shown in (4.1).

$$CR(t+1) = CR(t) + \int i(t).dt \tag{4.1}$$

This quantity is further normalized to the battery capacity so that the state of charge lies between 0 and 100%. The battery state of charge is limited within 20-95% in view of the strategy normally followed to avoid damage of the battery and to preserve battery life [97]. For battery storages which are part of the V2G systems, the battery management protection system should take over the priority from the V2G regulation services on reaching the above limits. By adopting a typical non-linear relationship between the battery voltage and charge status of a generic battery as shown in Fig. 4.6, the voltage equivalent of the state of charge is determined. This mapping of the battery state of charge to open circuit voltage is done in the "voltage translation" block using a look-up table. The series resistance voltage drop and equivalent voltage transient response are combined with the open circuit voltage to deduce the resultant battery terminal voltage (V_{batt}) as represented in (4.4).

$$V_{series} = R_{series} I_{batt} \tag{4.2}$$

$$V_{transient} = \frac{R_t}{1 + sR_t C_t} I_{batt} \tag{4.3}$$

$$V_{batt} = V_{oc}(Soc) + V_{transient} + V_{series} \tag{4.4}$$

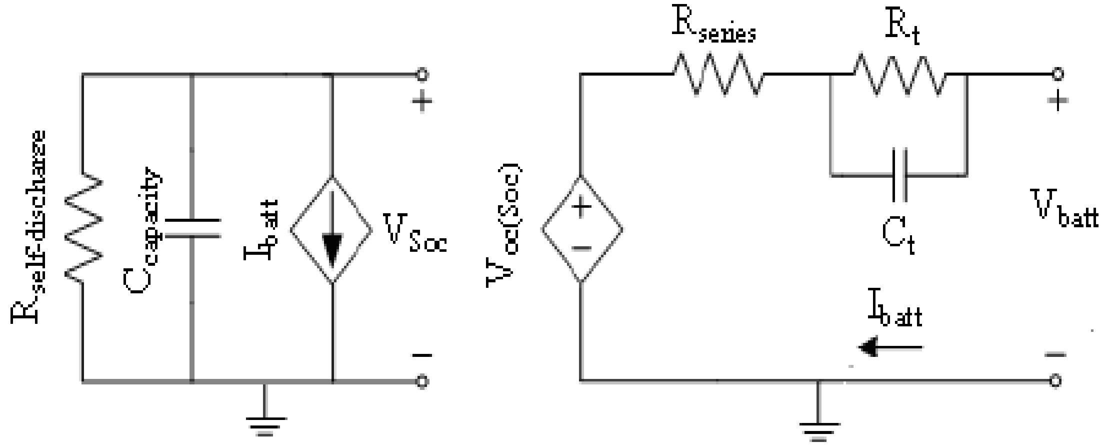

Fig. 4.4 Electrical battery model

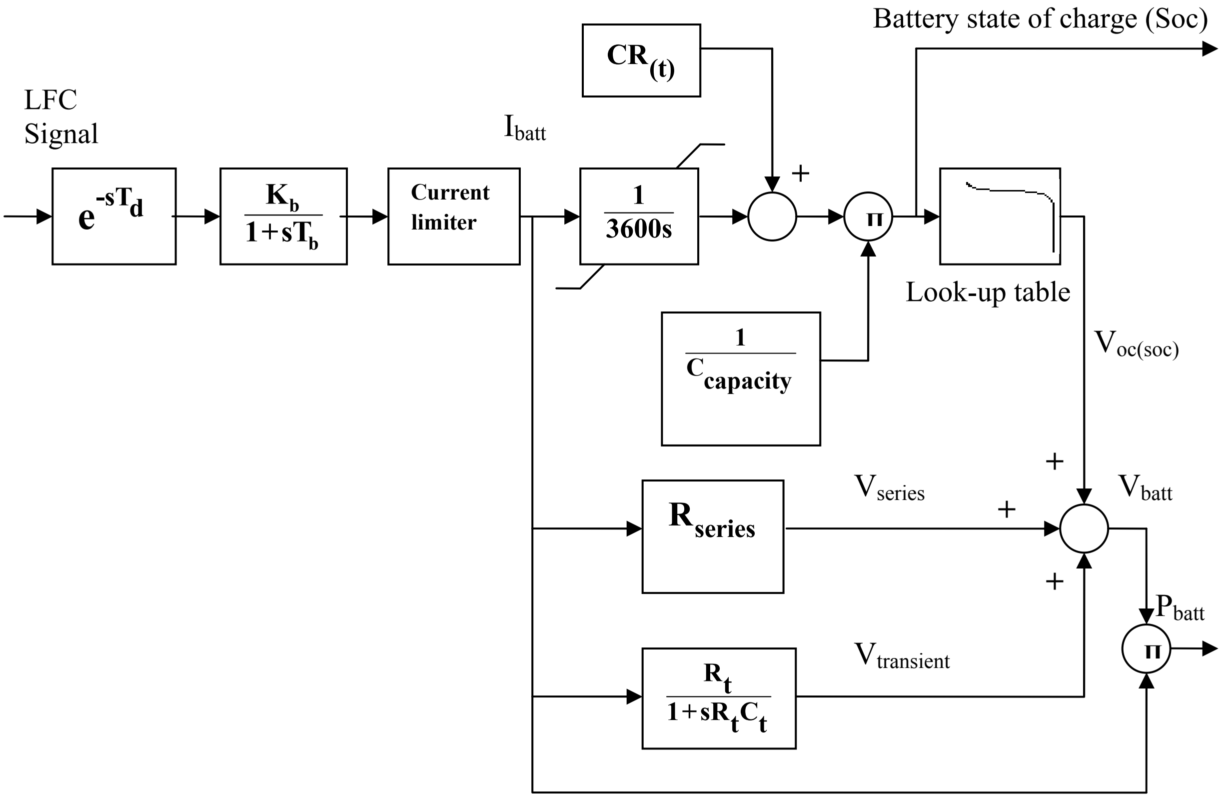

Fig. 4.5 Block diagram of a generic aggregated battery storage model

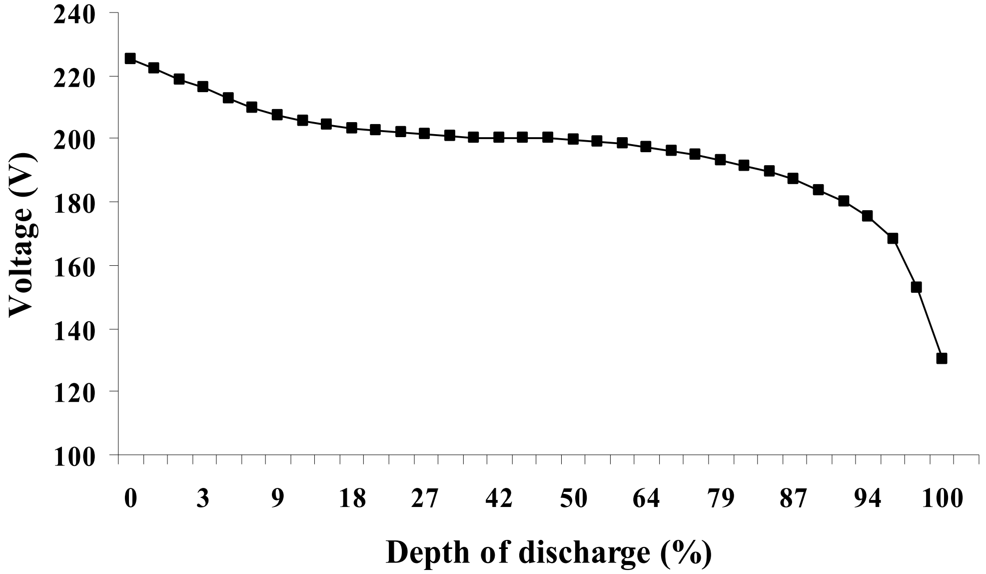

Fig. 4.6 Typical discharge characteristics of generic battery storage

The electrical circuit parameters for the MW range aggregated battery are adopted from an article based on a 10MW, 40MWh battery power plant unit, which is one of the largest of its kind in the world [95]. The parameters of the battery model used for simulations in this study are based on the discharging characteristics and are assumed to be the same for the charging conditions. The model does not include the self-discharge resistance as shown in Fig. 4.4, as longer periods of battery operation are not taken into account. Also the temperature effects are not accounted as it is assumed that the battery operates at the nominal operating conditions. In this analysis, as a V2G base case, the aggregated battery capacity is considered to be that of the current secondary reserve power requirement of West Denmark which is 90MW as given in Table 4.2. A battery storage capacity for four hours (360MWh) is considered here. This storage capacity of V2G system could be based on the "Tesla Roadster" electric car with a V2G power line connection capacity of 10kW [30], [51].

The net energy available in this battery electric vehicle after daily driving requirements may be approximately quantified as 40kWh as calculated in Section 2.4. For a V2G storage rating of 90MW, 360MWh, a total of around 9000 electrical vehicles is required, if the average power connection rating is 10kW. A minimum of 90% of the vehicles are idle even during the peak hours of transport demand [30], [56]. Therefore, it is reasonable to assume 50% availability of V2G vehicles all hours in a day which will need a total of around 18,000 electric vehicles. This is equivalent to less than 2% of the total fleet of 1 million cars in West Denmark. The uncertainties of the electric vehicle management system, the market conditions, and the power regulation effects on the battery life are not considered in this work. Instead, the effects of an aggregated EV based battery storage in providing power system regulation with charging and discharging limits is analysed here.

4.4 Load Frequency Control

The Load Frequency Control or a closed-loop secondary control is an essential ancillary service for maintaining the power system security and reliability. To match the load and generation and to maintain the scheduled power exchanges on interconnectors, the Load Frequency Control performs centralized automatic control. This is realised by the generation changes in the system by sending real time control signals directly to the participating units for providing "regulation", which is one of the main grid ancillary services. The control action is slower ranging from few tens of seconds to minutes. The Load Frequency Control is a commonly used term for grid regulation in the European interconnected system whereas in the American context it is popularly known as Automatic Generation Control (AGC) [98]. A generalized high level representation of the LFC model is depicted in Fig. 4.7. The generation and storage units are modelled as single large resources available for ancillary services at the system level.

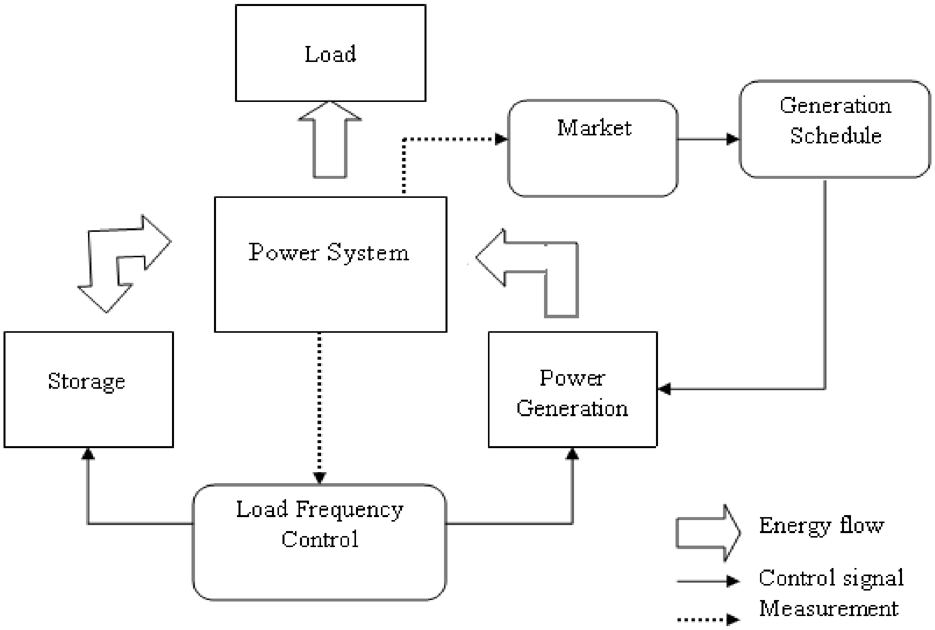

Fig. 4.7 High level representation of LFC model

4.4.1 Simulation model

To investigate the use of Vehicle-to-Grid systems providing grid power regulation in the Western Danish power system, a Load Frequency Control (LFC) model as illustrated in Fig. 4.8 is used in this work. The power capacities of thermal generation units use the year 2007 figures from Table 4.1. The models of large thermal power plants used in the simulations are standard IEEE models and are available in the global library of the Power factory. The centralized power plants are modelled based on the steam turbine units (IEEEG1) [99], [100] and the decentralised CHP plants are modelled based on the gas turbine units (GAST) [69]. The IEEEG1 model represents a generic steam turbine-governor unit. It is characterised by a speed-governing system and a four-stage steam turbine with different pressure stages. The speed governor consists of a dead band, a proportional regulator and a servomotor controlling the gate opening. The steam turbine has four different stages, the first being the steam chest and the remaining three represents the re-heaters or crossover piping. A first-order transfer function is used to model these stages. The boiler dynamics is not included where its pressure is considered to be a constant at 1.0 p.u. The coefficients K1 to K8 determine the distribution of turbine power to various stages [99], [100]. The intercept valve control action is not used in this model. The GAST model which is used to represent the decentralised CHP unit is described in Section 3.3.1

The power supplied by the wind and external interconnections is modelled as negative loads. The HVDC Nordic connections are considered to be operated according to the planned power exchange. The DSL models of the power plants and aggregated battery storage are given in Appendix B (Fig. B.1 to Fig. B.9). The ramp rates for steam turbine and gas turbines power plant units in their respective turbine control blocks are considered here as 4% and 10% per minute respectively [64]. Fig. B.5 and Fig. B.7 validates the response of steam turbine and gas turbine power plant models to a step change in Load Frequency Control signal with the above ramp limits respectively. Also a comparison between the response of aggregated battery storage and conventional power plant models to the regulation (LFC) signals are already discussed in Section 2.5 (Fig. 2.7 and Fig. 2.8) of the thesis. The aggregated battery and steam turbine models given in Appendix B are used to generate those simulation results.

A single bus bar model of the Western Danish power system is used in this simulation study as shown in Fig B.10. The model has multiple in-feed from aggregated models of generation units, battery storage, load demand, Nordic interconnections and the UCTE connection which is set up as the slack bus. The lumped representation of the generator units implies that the location specific parameters like the voltage at point of common coupling during a fault cannot be included directly in the model. The transient oscillations between synchronous generators at different locations in the system are not represented here in the model as all rotating masses connected to the system rotate in synchronism with each other permanently. Also the single bus bar approach cannot reflect power flow congestions or voltage instabilities. All the factors affecting the transmission system operation is neglected in this approach as this analysis primarily focuses on the collective performance and regulation capabilities of the aggregated battery storage and generators in the system.

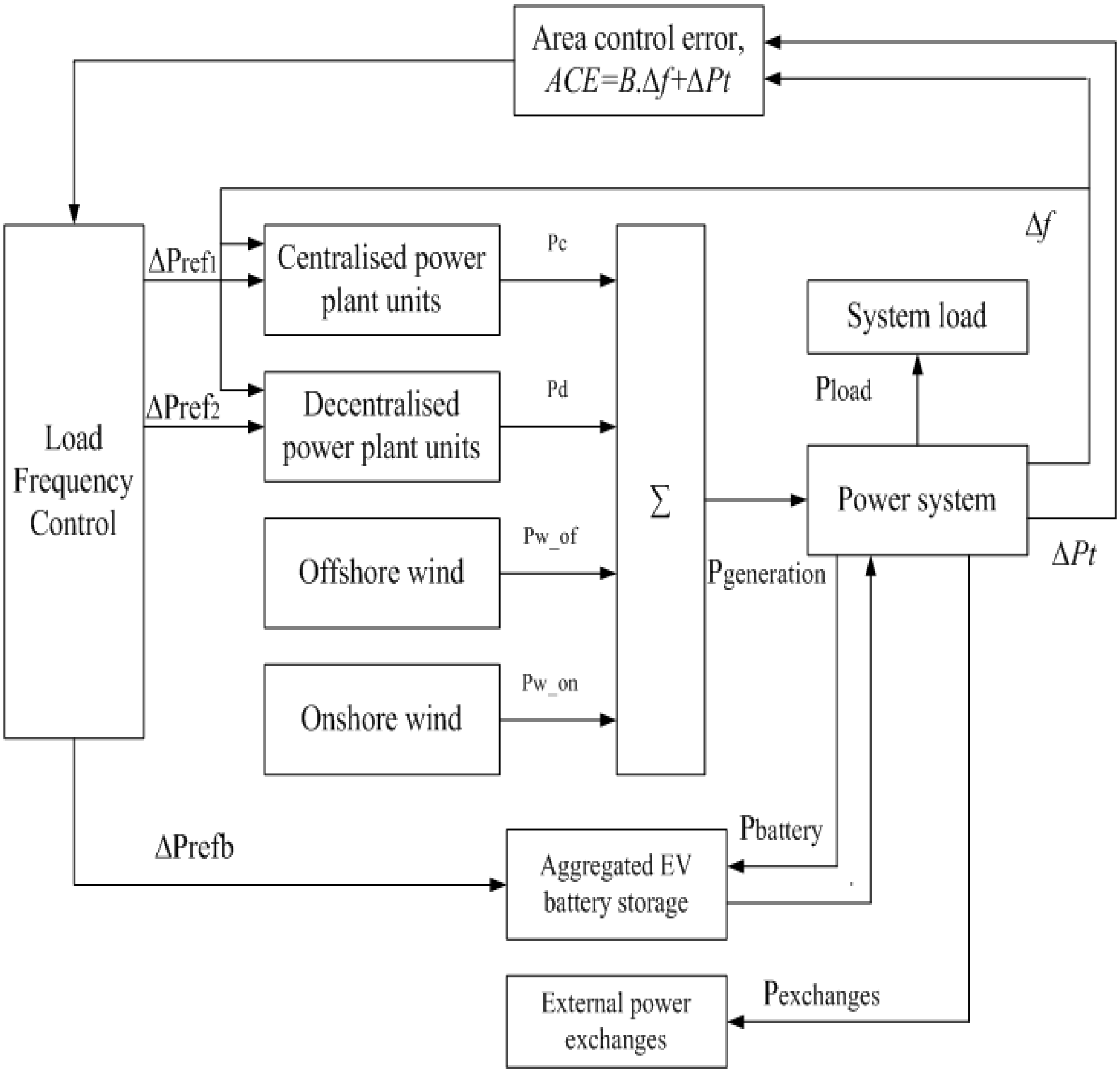

Fig. 4.8 LFC block diagram including aggregated EV battery storage

The LFC model used in this analysis is developed using the DIgSILENT Power factory software. The DIgSILENT Simulation Language (DSL) models of the LFC and the controller blocks are illustrated in Fig. B.11 and Fig. B.12 respectively. It shows the detailed block diagram of a LFC model integrating aggregated models of power plant units and the aggregated EV battery storage. The instantaneous measure of the balance between generation, load, interchanges, and frequency regulation contribution in a control area is called by the term Area Control Error (ACE). The Area Control Error of an interconnected system due to power imbalance is derived as follows,

$$ACE = (P_{meas} - P_{sch}) + B.(f_{meas} - f_0) \tag{4.5}$$

$$\therefore ACE = \Delta P_t + B.\Delta f \tag{4.6}$$

where B is the frequency bias factor (depend on the load sensitivities and governor response characteristics of the control area),

Δf is the frequency deviation,

P_{meas} is the measured power exchange,

P_{sch} is the scheduled power exchange,

and ΔP_t is the total power deviation between the interconnected systems.

The ACE signal is passed through a LFC control block where it is first fed through a first order filter to eliminate noise. The resultant LFC signal when large enough to overcome a LFC dead band and delay produces a smooth area control error (SACE) which is then passed through a conventional proportional-integral (PI) controller. The signal is integrated to generate the regulation power (ΔP_{ref}) which is the average power to be distributed among units participating in regulation.

$$\Delta P_{ref} = -ACE.\beta - \frac{1}{T}\int ACE.dt \tag{4.7}$$

where β is the proportional gain of the controller and T is the controller time constant.

A proportional gain of 0.4 and integration time constant of 180sec are used as parameters for the PI controller in the simulations [101]. As per UCTE guidelines, the typical values of the controller gain and the time constant recommended for the control areas are 0.1-0.5 and 50-200 seconds respectively [80]. The higher time constant is considered to ensure a smooth LFC operation and to avoid any interference with the normal primary regulation [102].

As the Western Danish power system is interconnected to a larger synchronous UCTE control area which can be considered as an infinite bus, the frequency deviations are assumed to be negligible in this study. The LFC operation is accomplished through a tie-line control where the inter-tie line power must be maintained at the scheduled values. The difference between the scheduled (P_{sch_ucte}) and actual power (P_{meas_ucte}) exchanges gives the power deviations (ΔP_{ucte}) between the two areas.

$$\Delta P_{ucte} = P_{meas\_ucte} - P_{sch\_ucte} \tag{4.8}$$

$$\Delta P_{ucte} = P_{generation} - P_{load} - P_{nord\_exchanges} - P_{sch\_ucte} \tag{4.9}$$

where $P_{generation}$ is the total generation, P_{load} is the system load and $P_{nord\_exchanges}$ is the total power exchanged with the Nordic power system.

The power deviations has to be minimised by the regulation power (ΔP_{ref}) which are to be supplied by the generating units involved in Load Frequency Control.

$$\Delta P_{ucte} = P_{meas\_ucte} - P_{sch\_ucte} - \Delta P_{ref} \tag{4.10}$$

The generator units are allocated their regulation shares (ΔP_{ref1}, ΔP_{ref2}) through economic dispatch functions, like the simple participation factor method [103], pf_1…..pf_n, where the $\sum pf = 1$. The general method of allocating participation factors is based on both the dynamic response and cost characteristics of the generation units. In the ideal case, the cheapest generators will be assigned the largest participation factor as long as they have sufficient generation capacity to provide regulation. However, the major criterion for system regulation should be a trade-off between the cheapest and the flexible units which can provide faster dynamic response in a deregulated and wind power supplied power systems to reduce the power deviations in the LFC. To respond to the LFC regulation demand, the turbine control block of each generation unit participating in LFC develops a new load reference (new active power set-points) which is applied to the governor-turbine control. The V2G systems in the LFC model are constrained by the state of charge limits as explained in Section 4.3. Apart from the activation and communication delay of 4 seconds, the V2G regulation (ΔP_{refb}) is free from any ramp rate limitations compared to that of conventional generators. The faster up-regulation and down-regulation characteristics of the V2G systems can reduce the reserve power requirements of the conventional generation units. This possibility is analysed here where the LFC order of the thermal generator units are found from the insufficiency of the aggregated EV battery storage in meeting the regulation power. The control parameters of the power plant, aggregated battery and LFC models used in the simulations are given in tables in Appendix B (Tables BI to BIV).

4.5 Simulation Scenarios

The LFC digital simulations are performed using the DIgSILENT Power Factory software. The LFC model integrating the V2G systems, attempts to minimise the LFC order of the conventional generators participating in regulation and the power deviations between the Western Danish - UCTE interconnected area. The time series data for simulations from the Western Danish SCADA system are obtained from Energinet.dk, the Transmission System Operator in Denmark. The data available is of five minutes resolution. The Horns Rev B wind farm and the Great Belt Link are not considered in this investigation as they were not commissioned during the course of this study and hence the data was not available. The LFC simulations are performed for two different scenarios. The scenarios are selected to represent two different cases of wind power production levels in the Western Danish power system.

4.5.1 Winter weekday

The electricity profile of the Western Danish power system obtained from the SCADA system for a typical “windy” winter weekday in January 2009 is shown in Fig. 4.9. The wind power meets an average of 40% of the total daily electricity consumption, and the total production exceeds the demand in West Denmark. Apart from the large wind power production, many decentralised CHP units are operated to balance the heat demand, resulting in a surplus electricity production. In Fig. 4.10, a positive power exchange deviation indicates less planned power being transferred and the negative value gives the surplus power exchanged with UCTE. Similarly, a positive LFC signal indicates up-regulation and the negative signal gives down-regulation values. This case represents a scenario where there are more periods of continuous down-regulation requirements and where the power deviations exceeds the acceptable levels of ±50MW at many instants due to the power imbalance caused by the errors in the estimated wind power and load demand.

4.5.2 Summer weekend

The summer weekend day is characterised by a low wind power production, where even the share of offshore wind power is almost negligible as shown in Fig. 4.11. The share of electricity consumption covered by the wind power production during a typical summer weekend day in July 2008 is less than 8%. The electricity production is much lower than the load demand, where the power deficit is compensated from imports from the neighbouring countries. This case also provides a scenario where there are periods of deviations exceeding the desired levels of ±50MW and continuous up-regulation requirement as seen from the LFC signal in Fig. 4.12.

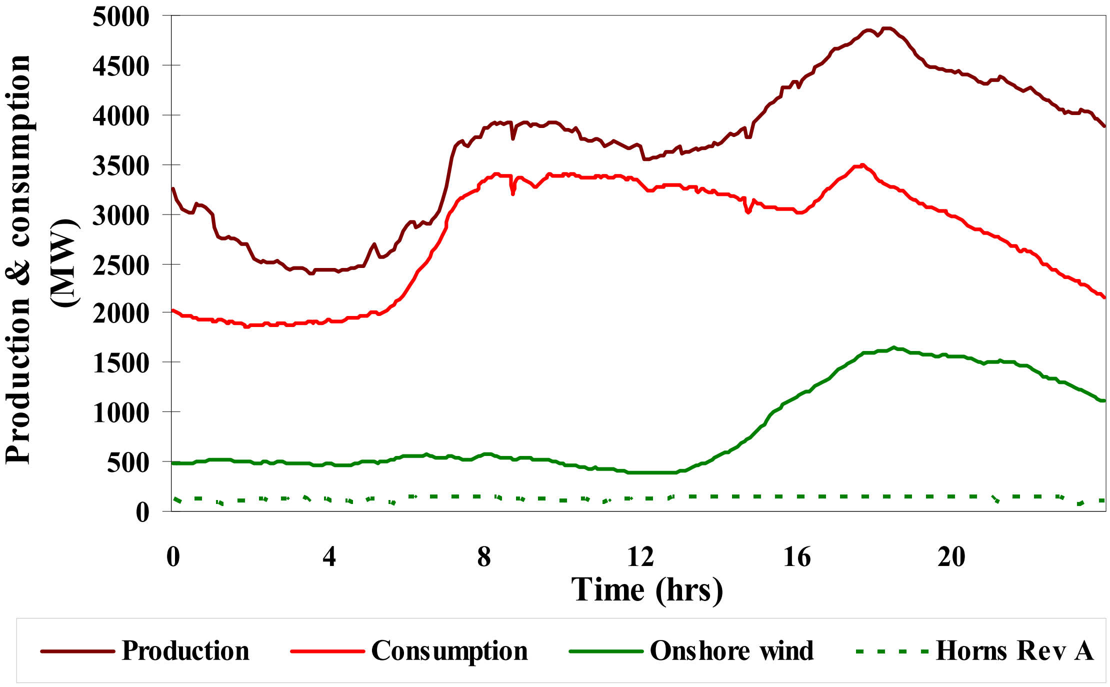

Fig. 4.9 Electricity profile data from West Denmark SCADA system for a typical winter weekday in January 2009

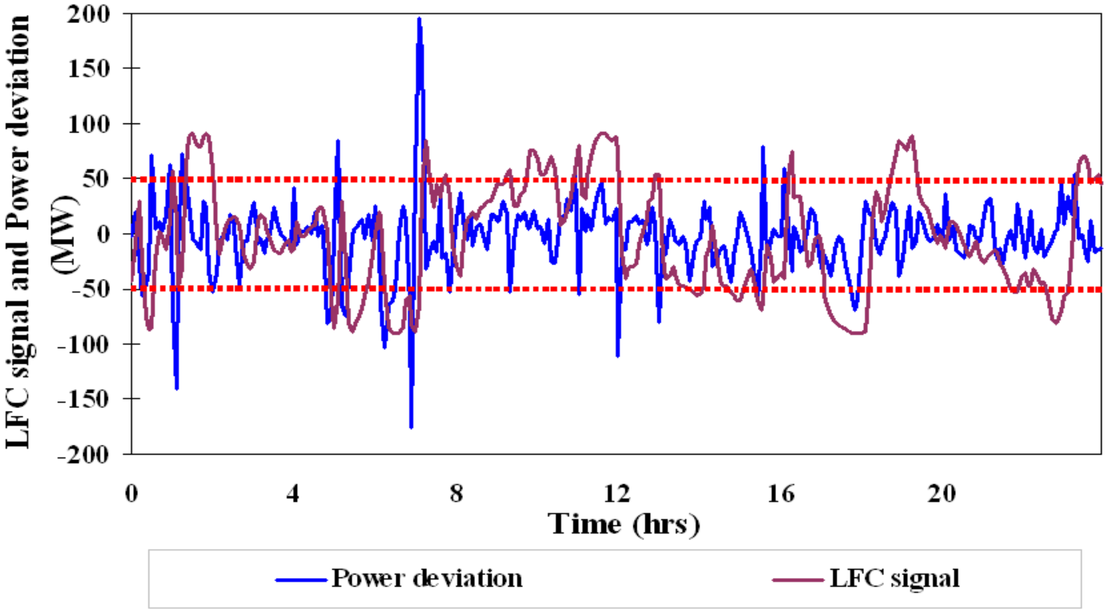

Fig. 4.10 Power deviations across WDK-UCTE and LFC signal data from the West Denmark SCADA system for a typical winter weekday in January 2009

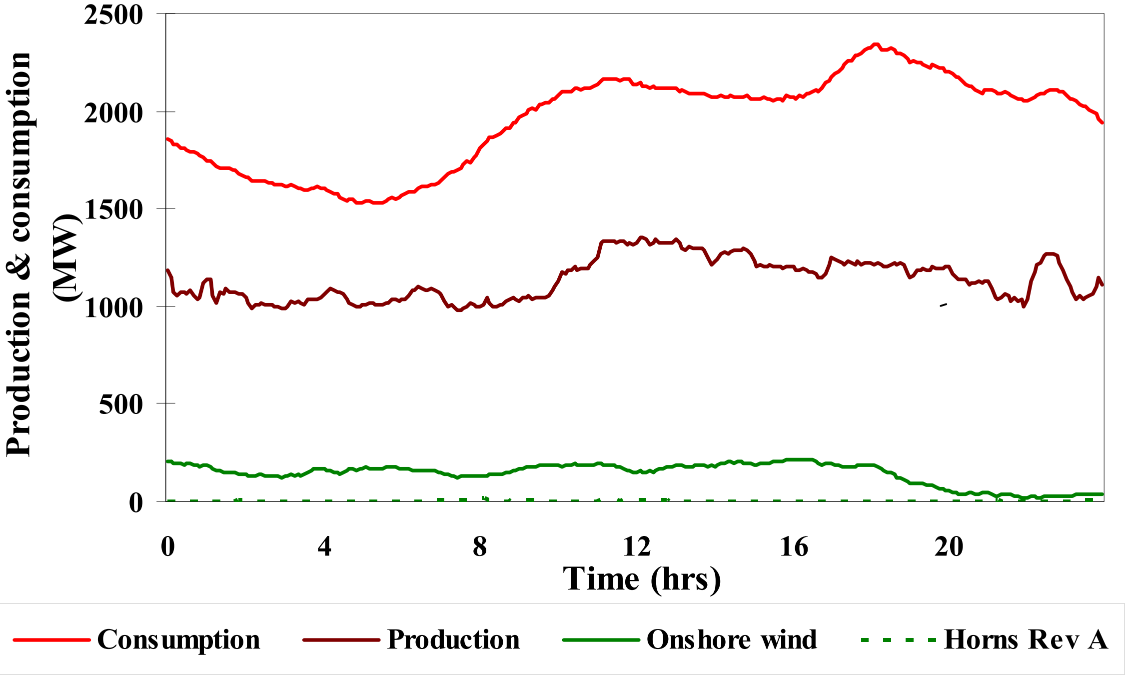

Fig. 4.11 Electricity profile data from West Denmark SCADA system for a typical summer weekend day in July 2008

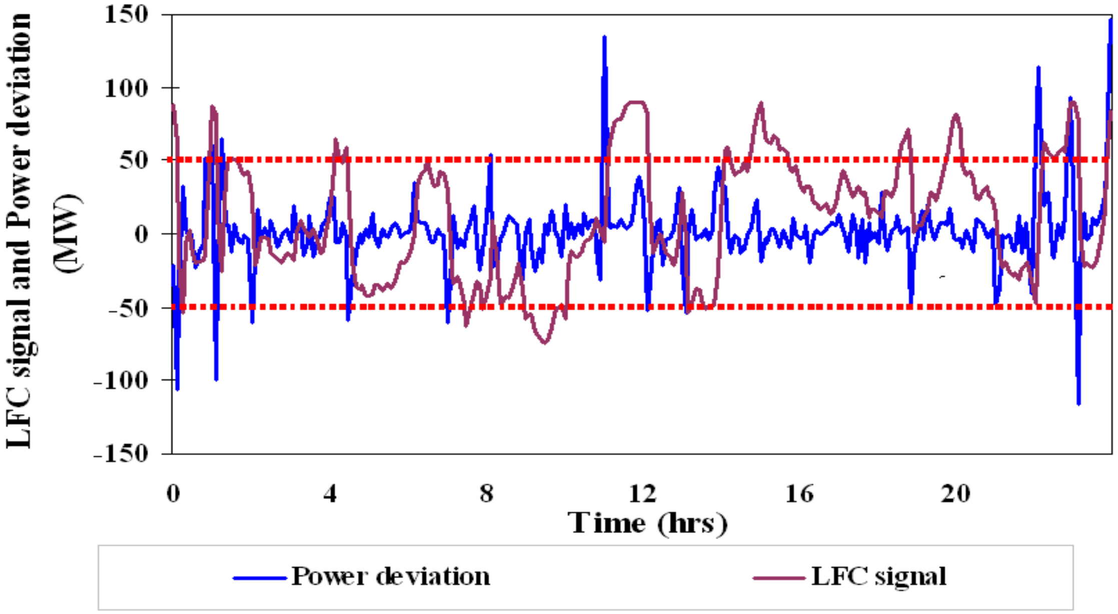

Fig. 4.12 Power deviations across WDK-UCTE and LFC signal data from the West Denmark SCADA system for a typical summer weekend day in July 2008.

4.5.3 Significance of the scenarios

The two typical days discussed above represents two worst case situations with large power exchange deviations and sustained up-regulation or down-regulation requirements in the West Danish power system. Typically, the power system regulation signal fluctuates more frequently between positive and negative values, so that a large deviation from zero is avoided. Under such conditions, the net energy balance of any battery storage participating in regulation tends to be zero over time and it could provide the regulation services indefinitely. However, there will be cases similar to the above scenarios, where the V2G regulation power requires extended periods in one direction (either charging or discharging). These scenarios could fairly represent the typical case of the future Danish power system operation with higher uncertainties and variability resulting from wind power generation.

4.6 Simulation Results

Three simulation cases were performed and compared to validate the use of V2G regulation in the West Denmark power system through Load Frequency Control simulations. The LFC simulation without the aggregated battery storage, where only the thermal generators participate in the LFC is considered as the first or reference case. For the remaining simulation cases, two different configurations of aggregated battery storages are analysed in the LFC model. As the second case, a V2G base case of 90MW, 360MWh equivalent to the automatic reserve capacity in West Denmark is used. The third case considers a five times larger battery storage (450MW, 1.8GWh) which is termed here as V2G+. The three different simulation cases are performed using the data available from the two scenarios explained in Section 4.5.

4.6.1 Scenario I: Large wind power production: winter weekday

The LFC simulation results of the first scenario are presented here, where the time series data of a typical “windy” winter weekday as in Fig. 4.9 are used. Fig. 4.13 shows the results of exchanged power deviation between the UCTE and the West Denmark (WDK) interconnection, obtained from the LFC simulations for the cases with and without V2G regulation. It is observed that the power deviations from the SCADA data available in Fig. 4.10 and the simulated case without V2G (reference case) are comparable. The responses are similar except for the sharp and peak values in actual data. This is because, the simplified LFC model used here may not replicate many shorter events that could happen within a highly dynamic power system operation and also due to the difference between the simulation system parameters used and the real power system data. Nevertheless, the simulated deviation provides a reasonable agreement with the real time data available.

This is sufficient enough to analyse the LFC model with V2G system for regulation services in the Western Danish power system. When comparing the cases with and without V2G, Fig. 4.13 shows that the deviations are largely reduced for the case with V2G, except for few periods, where the deviations in the form of sharp peaks are caused by the hourly scheduled power changes. But the deviations are within the acceptable range of ±50MW. Also towards the end hours of the day, it is observed that the regulation capability of the V2G is lost, resulting in similar power deviations as that of the reference case. These shortcomings are resolved with the V2G+ case as depicted in Fig. 4.14 where the battery storage has sufficient power and energy capacity to significantly reduce the power exchange deviations throughout the day.

Fig. 4.15 shows the simulation results of the battery state of charge for the two configurations of the V2G system participating in the LFC regulation. The initial battery state of charge is considered here as 50%. The V2G base case is fully charged towards the end hours, which accounts for the lost regulation capability. The V2G+ provides a better regulation and maintains an acceptable operating state of charge limits. The battery size of V2G+ case is indeed realistic, if less than 10% of the cars in West Denmark are V2G contracted electric cars.

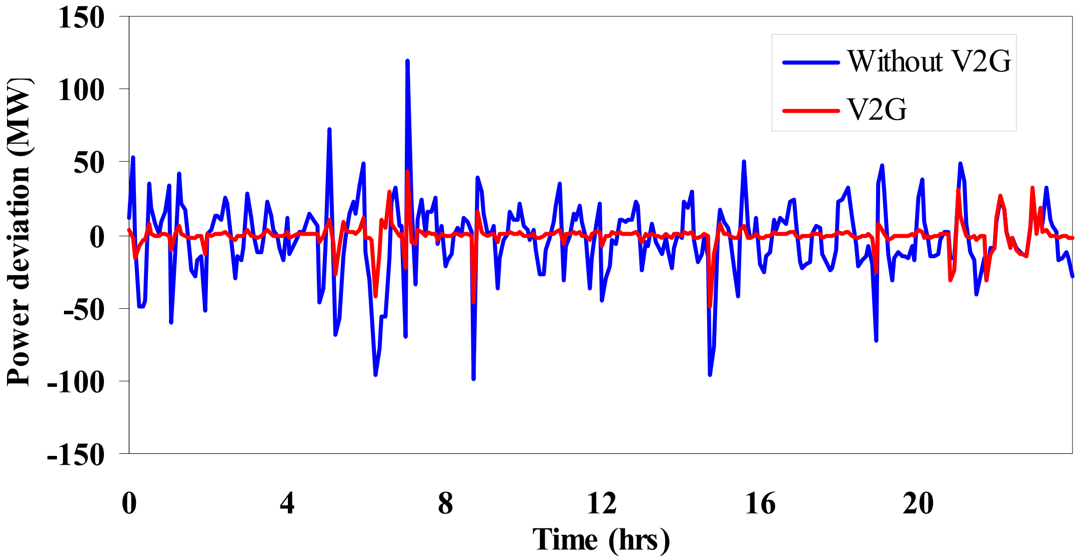

Fig. 4.13 Power exchange deviations between WDK and UCTE from LFC simulations without V2G (reference case) and with V2G case for winter weekday scenario

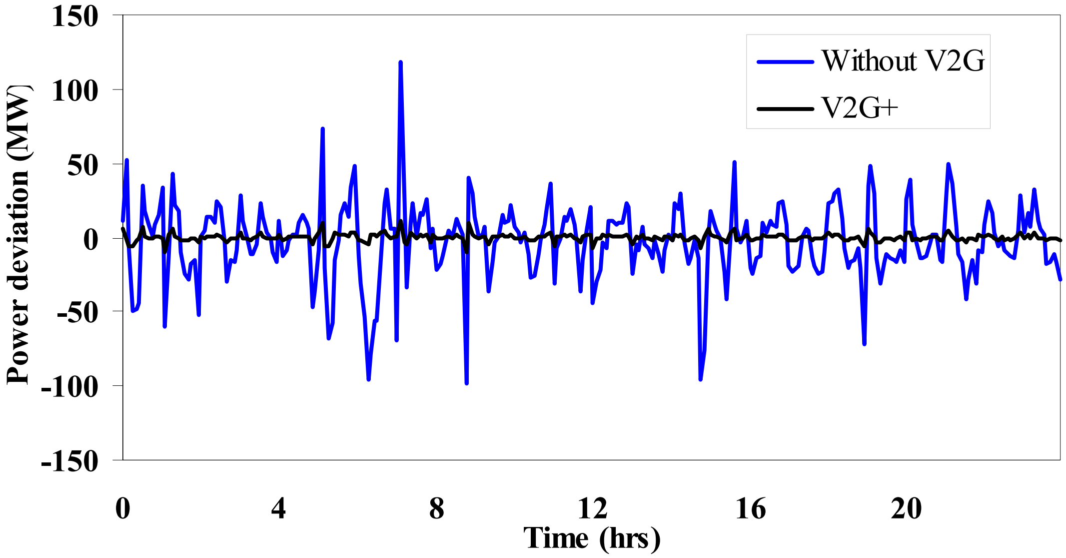

Fig. 4.14 Power exchange deviations between WDK and UCTE from LFC simulations without V2G (reference case) and with V2G+ case for winter weekday scenario

Fig. 4.16 depicts the LFC order of the generators for the case without V2G (reference), V2G base and V2G+ cases. The scenario for a windy winter day demands for more down-regulation requirement which is caused by the surplus electricity production, especially from the wind power. For the V2G base case, the regulation needs are similar to the reference case only towards the end hours of the day, where sufficient storage capacity is not available as is evident from Fig. 4.15, where the battery state of charge limit is reached. In the V2G+ case, less regulation power is demanded from the thermal generators, even during the sharp peaks and periods of hourly power shifts.

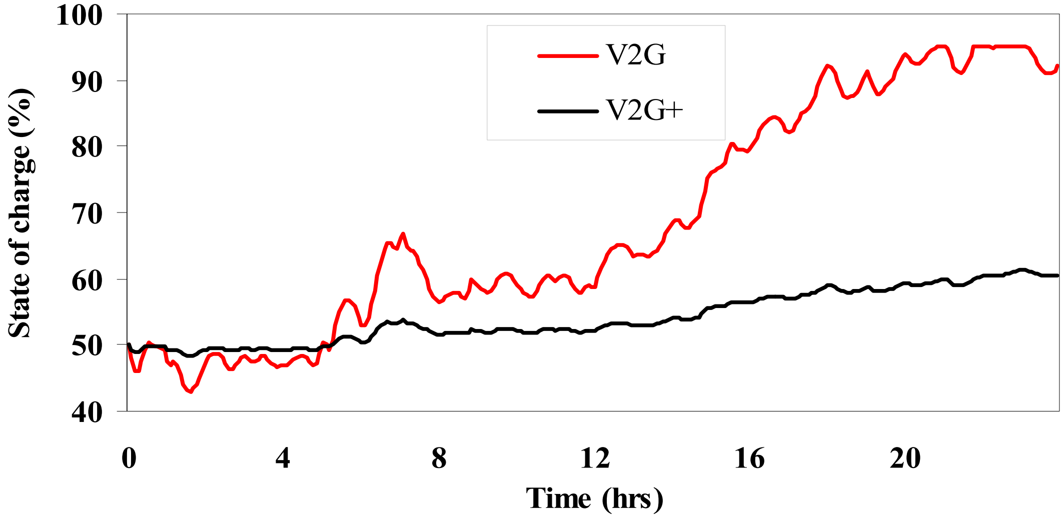

Fig. 4.15 Battery state of charge from V2G base and V2G + simulation cases for winter weekday scenario

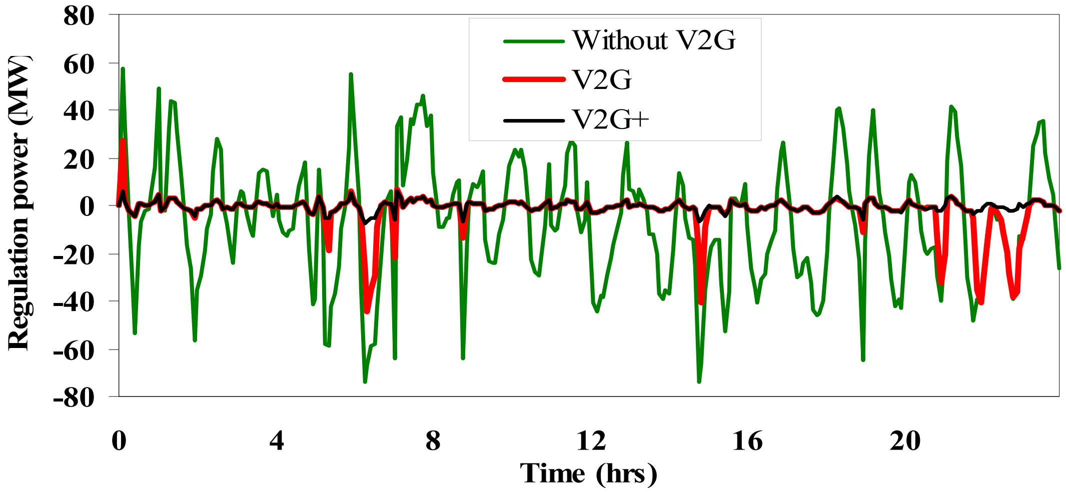

Fig. 4.16 LFC order of generators for the reference case without V2G, V2G base case and V2G+ case for winter weekday scenario

4.6.2 Scenario II: Low wind power production: summer weekend

The time series data from Fig. 4.11 is now used for LFC simulations of the scenario with less wind power production for a typical summer weekend day in West Denmark (WDK). The three different simulation cases as used in the previous section are also analysed here. The power exchange deviations between West Denmark and UCTE for the V2G base case is minimised only during the initial few hours of the day as shown in Fig. 4.17. The regulation capability of the battery storage is exhausted for the remaining period of the day, except for a few occasions where the battery storage operates within its state of charge limits.

Fig. 4.18 shows that the V2G+ case has sufficient power and energy capacity to significantly reduce the power deviations when compared with the LFC simulation results without V2G. For the V2G base case, the battery storage reaches its lower state of charge limits, beyond which it loses its up-regulation (discharging) capabilities. It further operates only during those instants where down-regulation (charging) is desired as depicted in Fig. 4.19. The V2G+ case is able to provide the regulation power for the whole day. However, the battery state of charge has almost approached its lower limits towards the end hours. This may not be an acceptable situation as the battery storage could lose its regulation capacity, if further regulation down is demanded in the following hours.

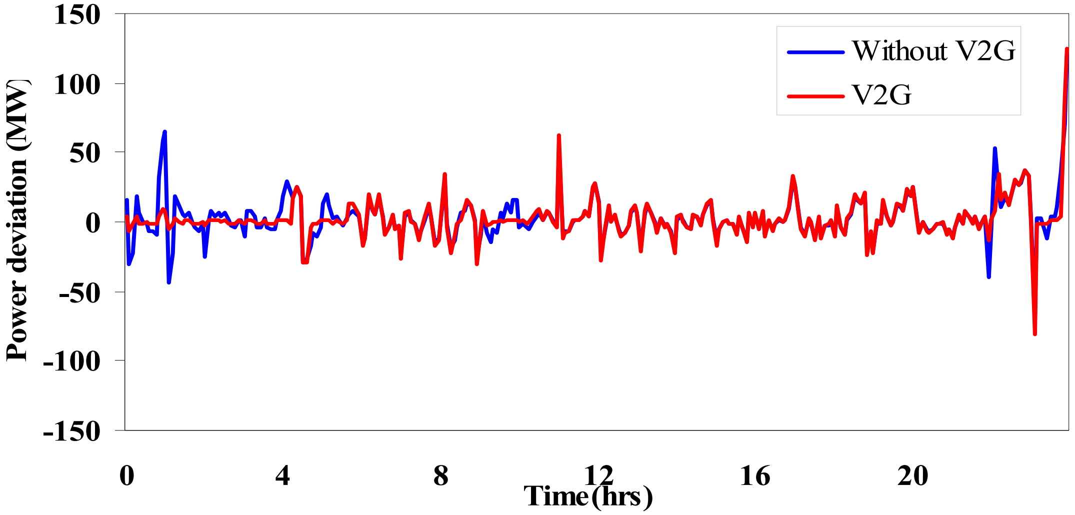

Fig. 4.17 Power exchange deviations between WDK and UCTE from the LFC simulations without V2G (reference case) and with V2G case for summer weekend scenario

Fig. 4.20 shows the regulation power demanded from the thermal generators for all the three simulation cases for the summer weekend day scenario. It is observed that the day is dominated by the up-regulation requirement, with more electricity production desired. The V2G base case was able to offer the regulation only during the few hours in the morning and at instants where regulation down was desired. As the V2G+ case had sufficient regulation capability throughout the day, the regulation requirement of generators was greatly reduced when compared with the V2G base and reference case without V2G. Thus, it can be inferred that the generator units could be relieved to a greater extent from the regulation services, if sufficient V2G system storage capacity is available.

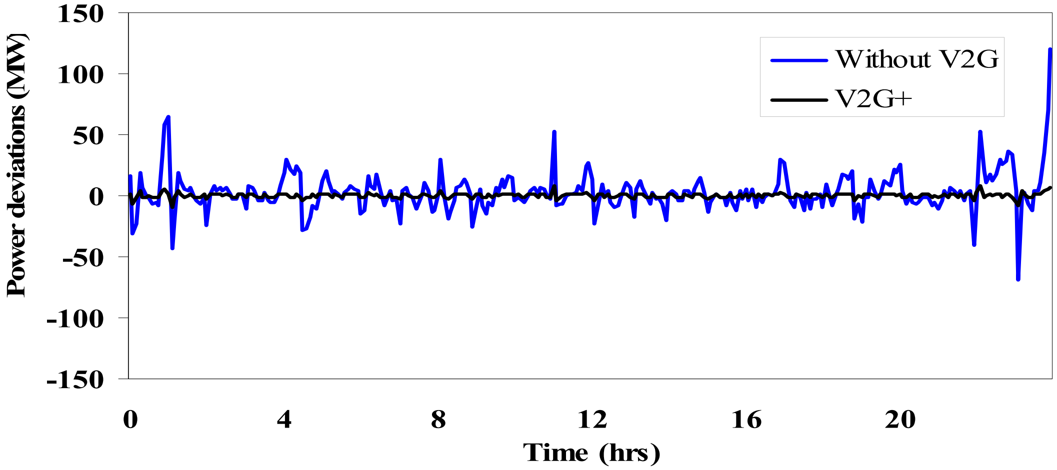

Fig. 4.18 Power exchange deviations between WDK and UCTE from the LFC simulations without V2G (reference case) and with V2G+ case for summer weekend scenario

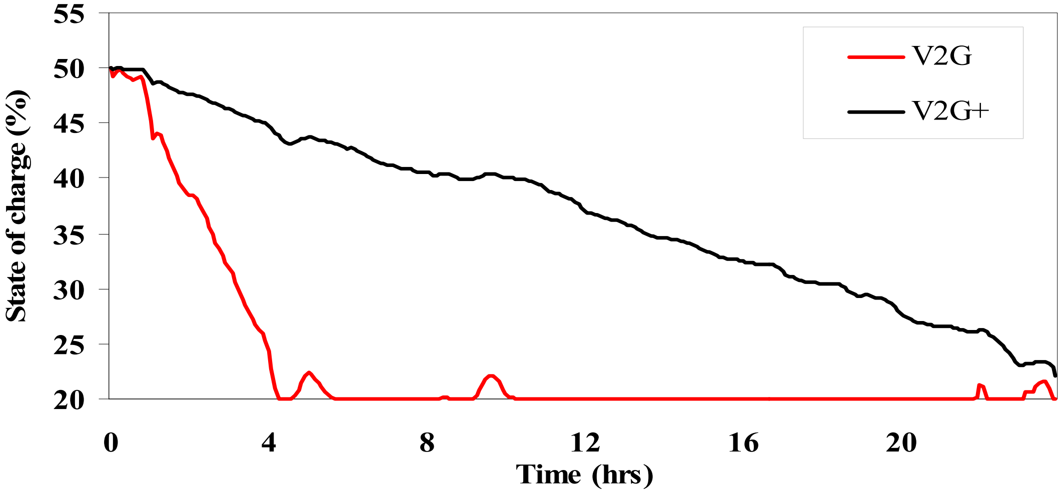

Fig. 4.19 Battery state of charge from V2G base and V2G + simulation cases for summer weekend scenario

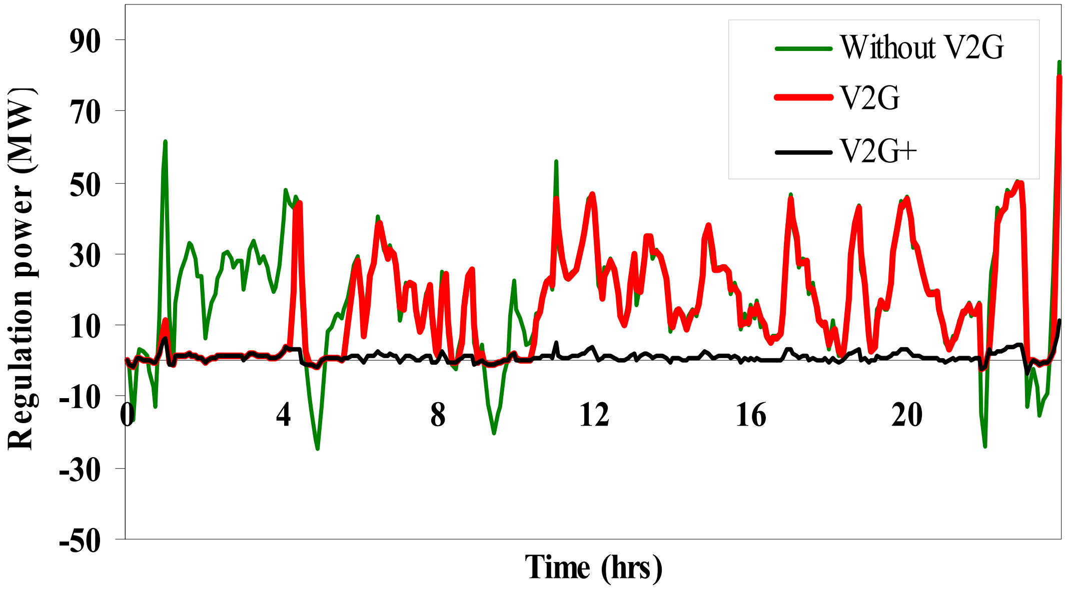

Fig. 4.20 LFC order of generators for the reference case without V2G, V2G base case and V2G+ case for summer weekend scenario

To assess the storage performance of the Vehicle-to-Grid based aggregated battery, a metrics is computed based on the availability of storage for regulation services. This is examined for different initial state of charge of the battery storage ranging from 20-95%. For the two simulation scenarios, the storage availability for the two configurations, V2G and V2G+ participating in the Load Frequency Control is calculated based on varying their energy-to-power ratio or the storage duration time in hours. These storage duration times could represent different storage capacities available from the electric vehicles.

This analysis can be considered as the V2G system performance with different aggregated vehicle storage capacities corresponding to varying battery state of charge. The results are summarized in Table 4.3 as storage availability for regulation services assessed over a 24-hour period. The storage is available all the time (100%) for regulation services, if the value is 1. Values less than 1, indicates that the storage is unable to respond to the load frequency signal for the whole period to provide regulation up or down services. The Vehicle-to-Grid based storage configuration with higher energy to power ratio are capable of providing better regulation services for the period considered in the scenarios.

Table 4.3 Storage availability for regulation services

V2G case	energy-to-power ratio	State of charge (%)								
		20	30	40	50	60	70	80	90	95
Scenario I – Winter weekday										
V2G	1	0.75	0.76	0.77	0.78	0.8	0.78	0.76	0.75	0.74
	2	0.88	0.97	0.91	0.87	0.85	0.82	0.78	0.76	0.74
	3	0.95	1	0.98	0.96	0.88	0.84	0.80	0.77	0.74
	4	0.95	1	1	0.97	0.93	0.88	0.84	0.79	0.74
V2G+	1	0.96	1	1	1	1	0.93	0.84	0.82	0.74
	2	0.96	1	1	1	1	1	0.97	0.80	0.74
	3	0.96	1	1	1	1	1	1	0.84	0.74
	4	0.96	1	1	1	1	1	1	0.88	0.74
Scenario II – Summer weekend										
V2G	1	0.09	0.10	0.13	0.14	0.16	0.17	0.18	0.19	0.20
	2	0.09	0.13	0.15	0.18	0.21	0.23	0.26	0.38	0.28
	3	0.09	0.14	0.19	0.22	0.26	0.28	0.35	0.39	0.44
	4	0.09	0.15	0.2	0.26	0.31	0.37	0.50	0.57	0.58
V2G+	1	0.09	0.29	0.36	0.41	0.48	0.57	0.63	0.69	0.74
	2	0.09	0.36	0.38	0.63	0.79	0.91	1	1	1
	3	0.09	0.41	0.63	0.79	1	1	1	1	1
	4	0.09	0.47	0.71	1	1	1	1	1	1

4.7 Summary

The Western Danish power system can be regarded as a wind dominated power system. The power mismatch caused by the variability and unpredictability of the high wind power are currently managed by the power plants, both domestic and from abroad. The increasing capacity of wind power installations in Denmark is replacing the central power plant units which demands for additional balancing power for a stable power system operation and control. The Vehicle-to-Grid systems are one of the alternate solutions for power balancing services which could substitute the reduced reserve power available from the central power plants in the future large wind dominated power systems. The regulation reserves in the form of V2G systems can charge and discharge the stored energy with quick start, fast ramp up and down features. These characteristics are well suited and essential for the integration of large amounts of fluctuating wind power in the future Danish power system.

This chapter has investigated the V2G regulation capabilities in the West Denmark power system using a simplified Load Frequency Control model. Aggregated long term dynamic simulation models of battery storage and generators are used. The transmission effects and constraints are neglected in this study. From the simulation results for two typical days with high and low wind power production, the power exchange deviations are significantly reduced between the West Denmark - UCTE interconnections with the use of faster V2G regulation power. In the simulations, two different Vehicle-to-Grid storage configurations, V2G and V2G+ are used. Considering an average power connection capacity of 10kW and battery storage capacity of four hours per vehicle, less than 10% of the passenger cars in West Denmark need to be electric vehicles under V2G regulation contract to realize the latter configuration. The regulation power requirements from conventional generators are also greatly reduced with the integration of a V2G system participating in Load Frequency Control. This could enable the power plants to generate power at constant levels, reducing the wear and tear, less maintenance and possibly reduced emissions effects.

Chapter 5

Vehicle-to-Grid Systems for Islanded Power System Operation

5.1 Introduction

The local distribution networks in the future are expected to be capable of operating under a planned islanded mode with sufficient balancing resources, efficient system control and black start capabilities. Many international research and development projects are giving considerable attention to such planned islanded operation of distribution networks. One of the main pilot projects in Denmark is the cell controller project investigated by Energinet.dk, the Transmission System Operator (TSO) [104]. As part of the cell concept, the transmission system is split in to several cells or sub-grid networks which must be capable of operating in autonomous island mode. The efficient and flexible domestic units like the distributed energy storages could play a major role for a robust and reliable control of such islanded power systems. The short-term dynamic simulations results presented in Chapter 3 shows that the Vehicle-to-Grid systems have superior performance as flexible consumption or generation units in ensuring fast, smooth and stable frequency regulation over the conventional generator reserves in an islanded power system mode. However in Chapter 4, from the long-term dynamic simulation results, it is evident that the regulation from these flexible Vehicle-to-Grid systems is dependent on their storage capacity, which is indicated by the battery state of charge.

In this chapter, the quantitative and qualitative performance of Vehicle-to-Grid Systems is investigated considering the battery storage capacity constraints in an islanded power system operation using long-term dynamic simulations. The simulation cases analysed in this chapter considers worst case islanded power system operation scenarios of few hours where the wind ramps coincides with the morning up-ramps and evening peak demand period. The capacity of battery storages that is required to support high levels of wind power in the islanded power system is determined in this study. The amount of conventional generation reserves that could be replaced by the aggregated battery storages to stabilise the power system frequency is also quantified. The Danish island of Bornholm is considered here as the test case for simulations.

5.2 Case Study - Bornholm

Bornholm is a small Danish island situated in the Baltic Sea. Bornholm is located to the south of Sweden, the east of Denmark and the north of Poland. The total area of Bornholm is 588 km^2 and it has a population of more than 42,000. Fig. 5.1 shows the location of the Danish island of Bornholm. The wind power production supplying the load demand in 2007 was estimated as 32%, which is approximately 10% higher than on the Danish mainland [105]. The total annual electricity demand and generation capacity in Bornholm is less than 1% of the total Danish demand and generation. The Bornholm power system is connected to the 132kV Swedish power system through a 60kV submarine cable. This interconnection makes Bornholm a part of the Nordic synchronous area that includes Sweden, Norway, Finland and East Denmark. The distribution network operator in Bornholm, ØSTKRAFT supplies electricity to more than 27,000 customers. The different voltage levels of the distribution network available are 60kV, 10kV and 0.4kV. Fig. 5.2 shows a map of Bornholm with the key power system installations.

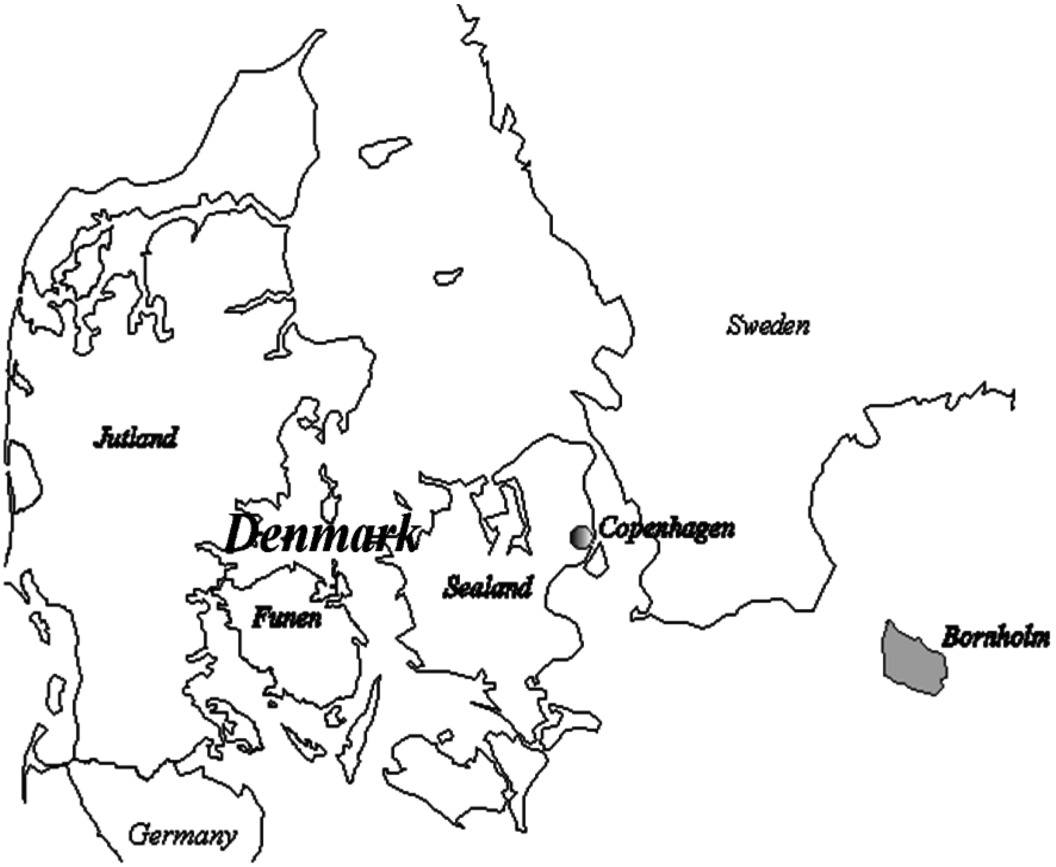

Fig. 5.1 Map showing the Danish island of Bornholm

The Bornholm power system structure is similar to that of mainland Denmark with the electricity production from both CHP and wind turbine units. The key power system figures of Bornholm for 2007 are given in the Table 5.1 [106], [107]. During normal grid connected mode, the electricity demand is mainly supplied by power generated from the 37MW large CHP unit, land based wind turbines and power imports from Sweden. Bornholm is primarily a net importer of electricity from Sweden. The electricity is exported mainly during the winter period, where the large CHP unit is obliged to supply the heat demand. Apart from the large CHP, wind and condensing power plant units, the island Bornholm has other generating units like diesel and biogas CHP plants. The information about the mode of operation of these generators is not available or reported. The diesel generators may be typically used for peak load or emergency modes and the biogas CHP units operated on the basis of heat demand.

Table 5.1 Bornholm electricity data – 2007 [106]

Electricity	
Customers	27,895
Annual electricity consumption	239GWh
Peak load	55 MW
Minimum Load	13 MW
External connection	Sweden, 60kV, 60 MW
Power Plants	
1 Steam Turbine (Coal/Oil) - Combined Heat and Power (CHP) unit	37MW
35 Fixed speed, Onshore Wind turbines	30 MW
1 Steam Turbine (Oil) - Condensing Power Plant (CPP)	27 MW
14 Diesel generators	39MW
1 Gas turbine (Biogas) unit	2 MW

Since Bornholm has a higher wind power share in electricity production, it could be representative of the future power systems and a test case to understand the challenges of variable generation in the operation and control of power systems. The island of Bornholm is regarded as a model region for testing new power system regulation strategies. It is capable of undergoing a planned islanded operation of the power system as reported in [105], [108], which are in focus of many research and demonstration studies for integrating more wind power.

In the islanded mode, there is sufficient power generation capacity available in Bornholm to satisfy the load demand. However, it is not possible to integrate the full installed wind power capacity in Bornholm as there are not enough reserves and system inertia to maintain the frequency stability [108]. Alternate solutions like demand as frequency control reserve (mainly electrical heating) and frequency control of wind turbines are currently under investigation in Bornholm [108], [109]. The efficient battery storage of electric vehicles can be an excellent solution for a flexible islanded operation for integrating more wind power in Bornholm. The V2G system integration study to support more wind power in Bornholm which is analysed here, could be applied as a model to other similar islanded or sub-grid power system networks.

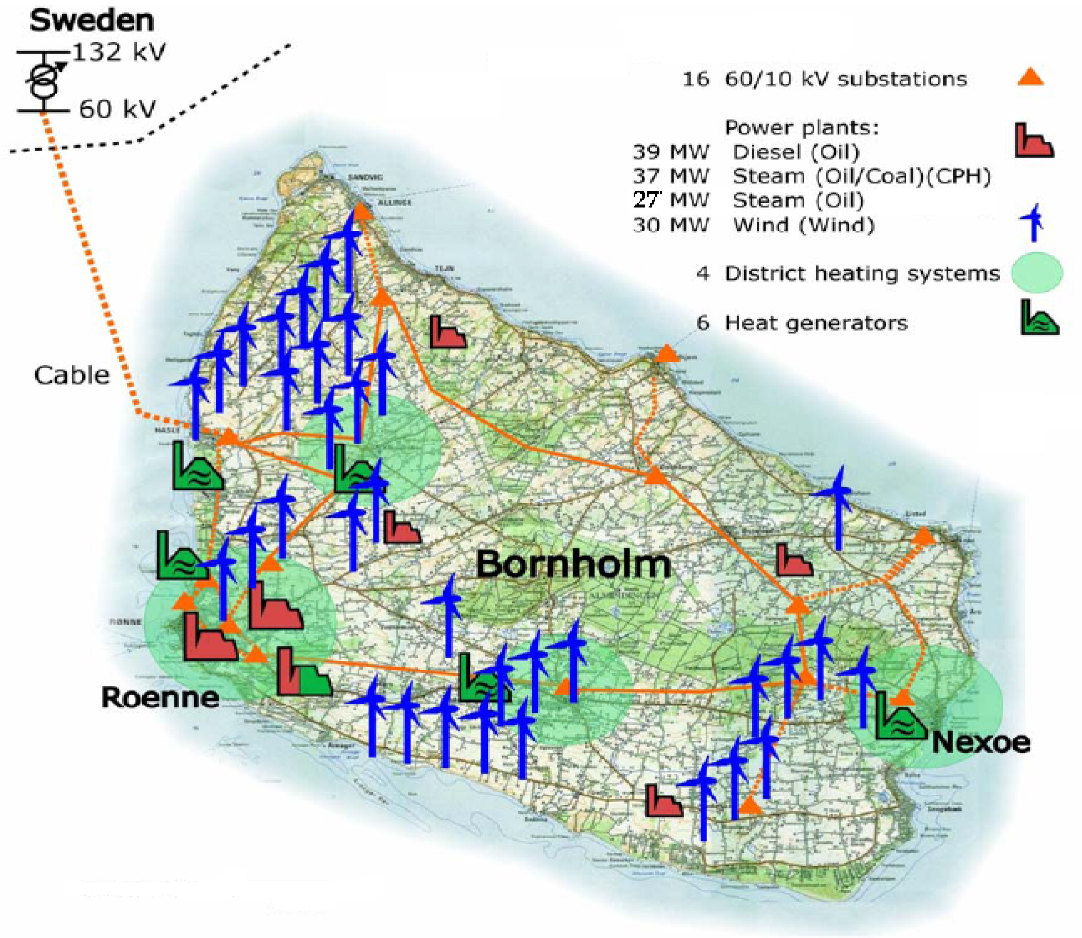

Fig. 5.2 The Danish island of Bornholm [106]

5.3 Simulation Data and Scenarios

Fig. 5.3 to Fig. 5.6 illustrates the plots of the time series data available for digital simulations. The real time data from the Bornholm power system were not available during the analysis. But data available from the Danish mainland was suitably scaled to match the electricity consumption in Bornholm on a typical winter weekday as shown in Fig. 5.3. The time series data for the load demand has a resolution of five seconds.

Two sets of system demand data for a period of three hours are analysed here in this study. Fig. 5.4 shows a morning up-ramp demand data (07:00 – 10:00 hrs) taken from the daily load curve in Fig. 5.3. Fig. 5.5 shows the peak demand data for the period 17:00 - 20:00 hrs which is characterised by both up-ramps and down-ramps. The wind power time series data used in the simulation during the above two periods is depicted in the Fig. 5.6 which is characterised by up/down ramps or a series of gust and lull wind events [110]. The wind turbines located in a geographically smaller area responds to such wind events in a uniform manner and could result in ramps larger than the system demand.

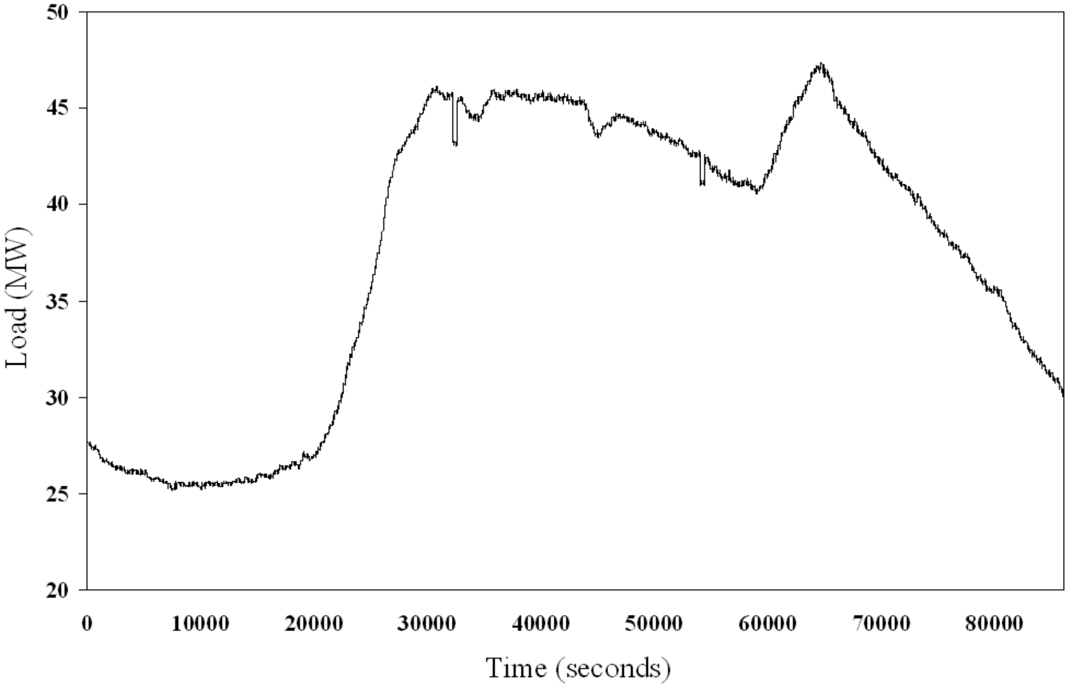

Fig. 5.3 Typical load curve

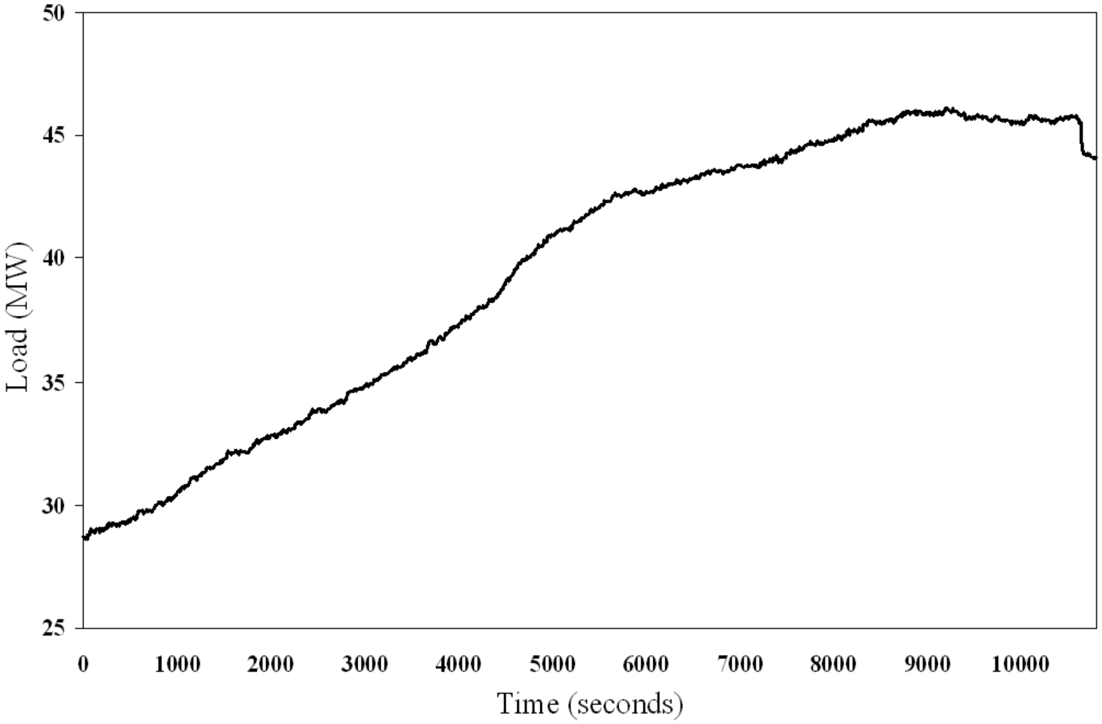

Fig. 5.4 System demand during the morning ramp-up hours

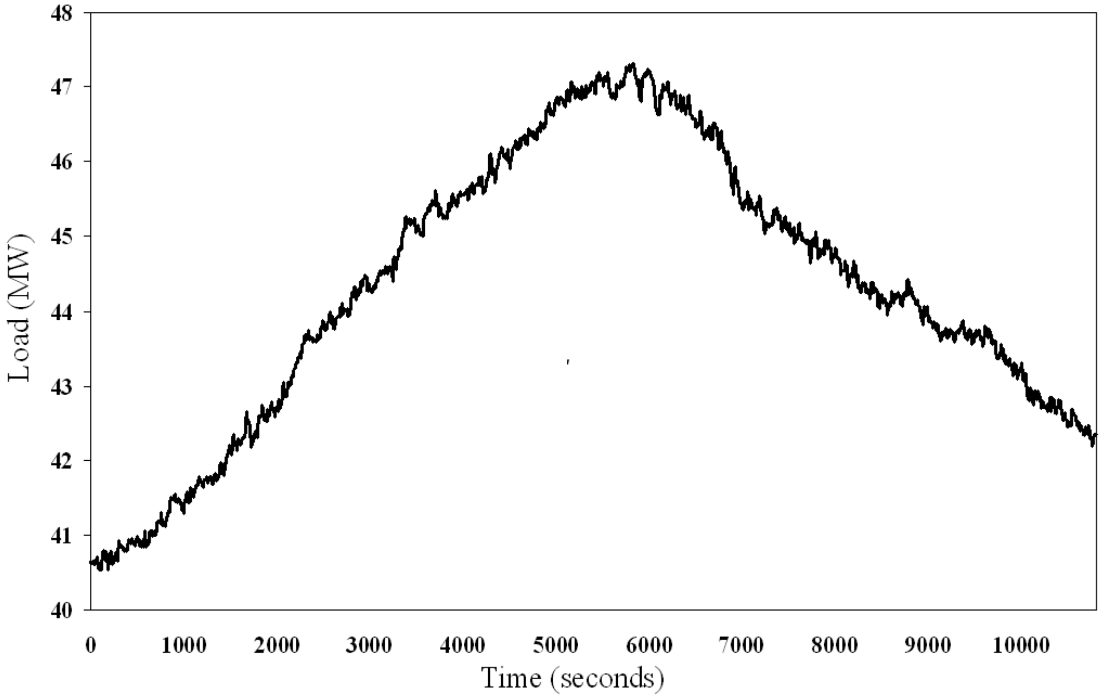

Fig. 5.5 System demand during the evening peak hours

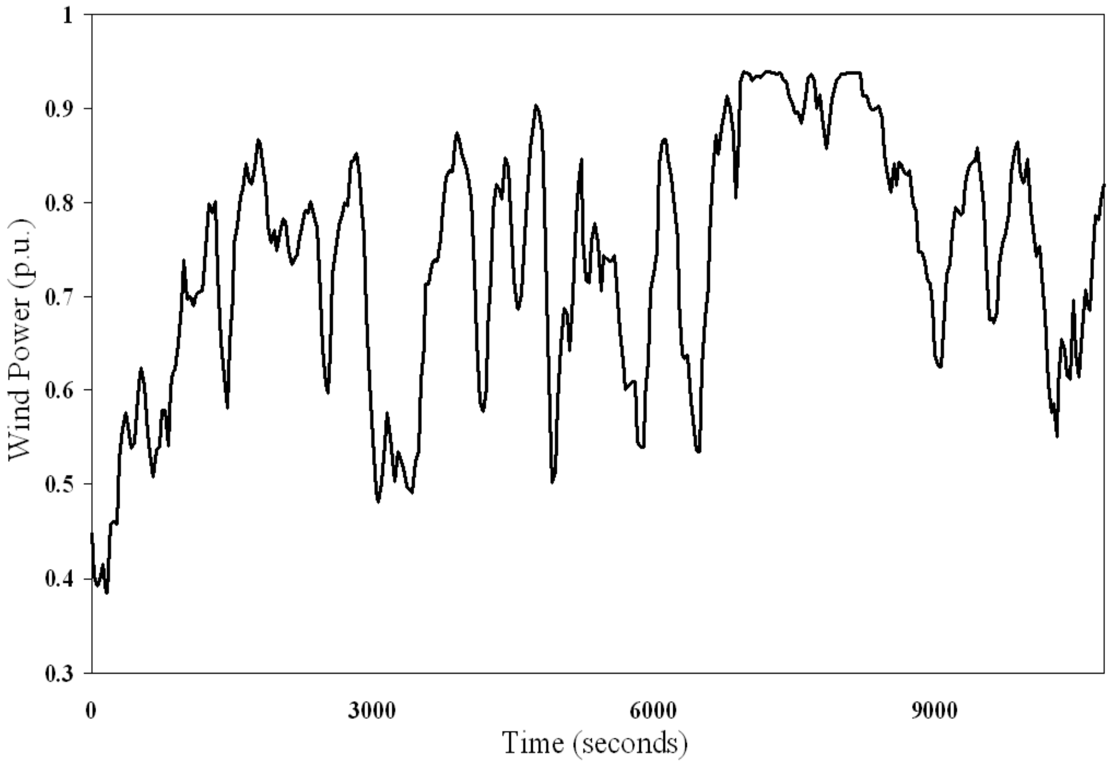

Fig. 5.6 Wind power profile

Typically, an interconnected power system may be able to handle these system demand and wind events smoothly if sufficient generation and reserves are available. But, the situation will be critical for a smaller isolated power system, which is more sensitive to changes in the load and generation. The scenario could be worse, when the reserve power is limited and the wind and system demand ramp periods coincides each other in a wind dominated island power system like Bornholm.

Table 5.2 gives the various test cases simulated in this work for an islanded Bornholm power system to test the frequency regulation capabilities of the Vehicle-to-Grid systems. The CHP and CPP units are the only conventional generators considered in the simulation cases as they are the largest and regularly operated units in the island. The generation capacity available at any time is considered to be more than the system demand. The aggregated battery storage power in MW is added in steps to the simulation cases. This is to observe the impact on the system frequency profile by increasing the V2G regulation power.

Table 5.2 Simulation Cases

Morning up-ramp hours			
	Case A	Case B	Case C
CHP			
P_{max} (MW)	37	37	27
$P_{initial}$ (MW)	13	15.29	10.82
P_{min} (MW)	7.4	7.4	5.4
CPP			
P_{max} (MW)	27	-	-
$P_{initial}$ (MW)	9	-	-
P_{min} (MW)	5.4	-	-
Wind capacity (MW)	15	30	40
Wind power supplied as % of load	28%	56%	75%
Maximum demand – 46.1MW Minimum demand – 28.6MW			
Evening peak hours			
	Case A	Case B	Case C
CHP			
P_{max} (MW)	37	37	27
$P_{initial}$ (MW)	20.9	27.2	22.7
P_{min} (MW)	7.4	7.4	5.4
CPP			
P_{max} (MW)	27	-	-
$P_{initial}$ (MW)	13	-	-
P_{min} (MW)	7.4	-	-
Wind capacity (MW)	15	30	40
Wind power supplied as % of load	25%	50%	67%
Maximum demand – 47.2MW Minimum demand – 40.3MW			

Case A: This can be considered as a reference case where sufficient generation and regulation reserves are available from the conventional generators. The present installed capacities of CHP and CPP generators are considered for the power balance. Half of the present installed wind power capacity is considered and it is observed that the wind power supplying the load is 28% and 25% for morning ramp and evening peak respectively. On an average, this percentage contribution of wind power supplying the demand could be considered as the current operating case in Denmark.

Case B: The condensing power plant (CPP) is not considered in this case. This scenario could be treated as a future operating case in Denmark where the operation of less thermodynamically efficient condensing power plants is reduced to accommodate more renewable electricity from wind [111]. The installed capacity of the more efficient generating CHP unit is taken into account since this also has to meet the heat demand obligation. An n-1 contingency situation is not taken in to account as the study is primarily focused on the viability of the V2G systems to provide frequency regulation for such an operating condition. The total installed capacity of 30MW wind power is considered for this simulation case. The percentage contribution of average wind power supplying the load demand is 56% and 50% for the two system demand periods considered.

Case C: The installed capacity of the CHP unit is reduced by 10MW and the wind power is increased by the same margin. This scenario could be treated as the future operating case in Denmark, where the large power plant units are replaced by more wind power. It is assumed that the reduced heat generation capacity of the CHP could be compensated by optimal scheduling of heat storages or utilisation of other sources like heat pumps. The average electricity supplied by the wind is 75% and 67% of the load demand for the morning up-ramp and system peak period respectively. This case represents a high wind power scenario where there is a large insufficiency of power balancing reserve from conventional generation units.

5.4 Modelling of Components and Operation Strategies

The modeling of the components and the simulations are performed using DIgSILENT Power Factory software [68]. The capacities of the wind turbines, steam turbine based CHP and CPP units are adopted from the Table 5.1. The generation from the aggregated wind turbines is represented as a negative load where the time series data of the wind power which is given in Fig. 5.6 is used. The system demand is represented by the Power Factory dynamic load model as discussed in Section 3.3.4 which accounts for the frequency and voltage sensitivities. The IEEEG1 generic steam turbine model [99] available in the global library of the Power Factory software is adopted here in this simulation study for both the CHP and CPP units. The models of steam governor, steam turbine unit and aggregated battery storage are given in Fig. B.3, Fig. B.4, and Fig. B.9 (Appendix B) respectively. The battery storage responds to frequency deviations in this study, instead of Load Frequency Control signals as presented in Fig. 4.5.

The corresponding parameters of these models given in Tables BII and BIV (Appendix B) are used here for simulations. The additional model parameters related to control strategies used in this chapter are listed in Tables CI and CII (Appendix C). The aggregated battery storage considered here is a generic model representing Vehicle-to-Grid systems in MW range. The battery model takes into account the state of charge (SOC) limits and the resultant battery power (ΔP_b) regulation capabilities. In Bornholm, at least two-third of the population owns a car [112]. If all the cars are converted to electric cars, an approximate 250MW of potential battery storage will be available for Vehicle-to-Grid contract. The SOC limits of 20-95% and storage duration of four hours are used in this study.

The generators, the aggregated electric vehicle battery storage and the load models are considered here to be connected to a single bus bar representing the Bornholm power system as shown in Fig. C.1 (Appendix C). This approach neglects all other factors affecting the operation of transmission system and focuses only on the performance of power balancing reserves for stabilising the power system frequency. Fig. 5.7 illustrates the high-level block diagram representation of frequency control model for an islanded power system operation in Bornholm. When the system frequency is nominal, the generator models are in steady state and the power outputs are constant. The power imbalance between the generation and the demand causes the frequency to deviate from the nominal.

The conventional generator units and the aggregated battery storage respond to the frequency deviation based on their assigned characteristics and settings. In the simulation cases where the Vehicle-to-Grid systems are not considered, the CHP unit always operates in an isochronous speed control mode. The CHP performs the frequency regulation using a conventional proportional and integral (PI) control loop which replaces the droop mode in the governor block of Fig. B.3. The CPP unit operation is always simulated in a speed droop control mode.

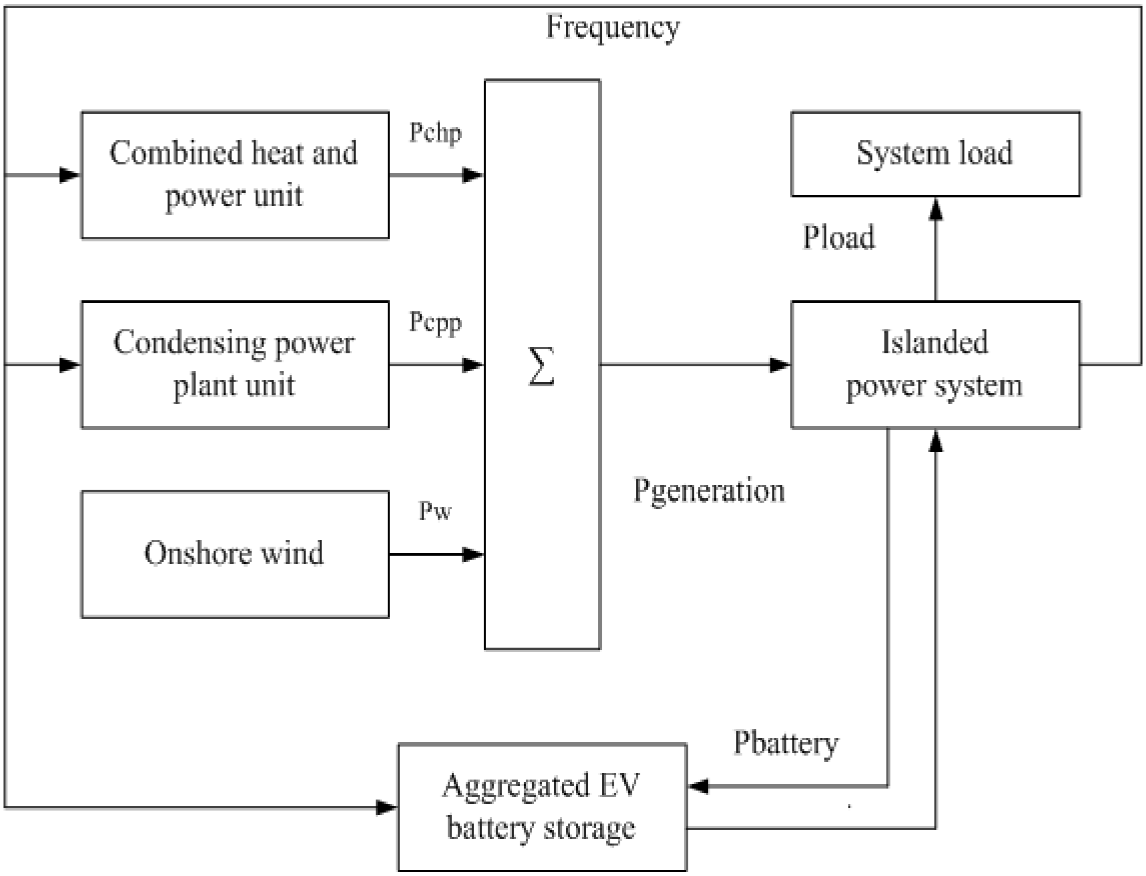

Fig. 5.7 Block diagram of frequency control model for islanded operation

Two modes of Vehicle-to-Grid regulation are used in this study which is simulated separately for all the simulation cases. The first control strategy is the droop mode as shown in Fig. 5.8, where the battery storage gain, K_b is defined by the rated battery current (I_{rated}) in kA/Hz. The CHP unit operates in an isochronous mode for V2G mode 1 strategy. A dead band of ±10mHz was applied to the frequency deviation signal so that the Vehicle-to-Grid systems will not respond to the signals below the above threshold. This prevents the battery from excessive charging or discharging on very short fluctuations, thus extending the battery life. In the second mode as shown in Fig. 5.9, the Vehicle-to-Grid systems use a PI controller for regulating the system frequency.

Here, the CHP unit is operated in a droop mode. Mostly for the V2G mode 2 simulations, the regulation capacity will be exhausted quite often for a lower battery capacity as the PI controller force the storage to operate to its SOC limits. To prevent this, a high-pass filter is added to the control loop as shown in Fig. 5.9. The high-pass filter prevents the battery storage from responding to any sustained frequency deviations, where T_f is the battery high pass filter time constant [94]. In both the regulation modes, a primary V2G activation delay factor (T_b) of four seconds is used. A limiter is used to limit the battery current within the charging and discharging capabilities of the battery storage.

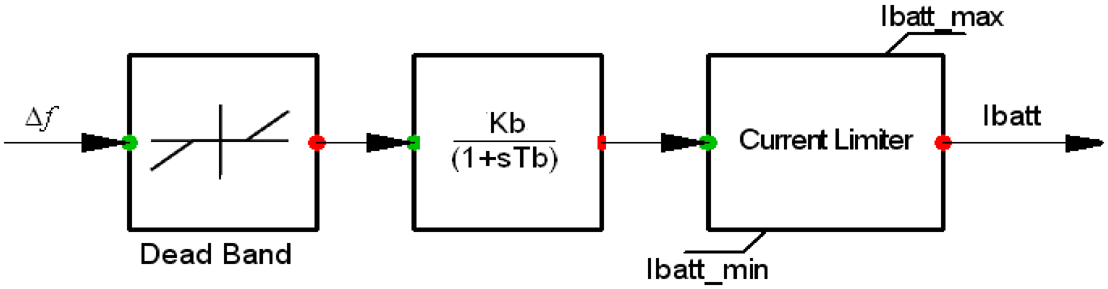

Fig. 5.8 V2G mode 1 control strategy

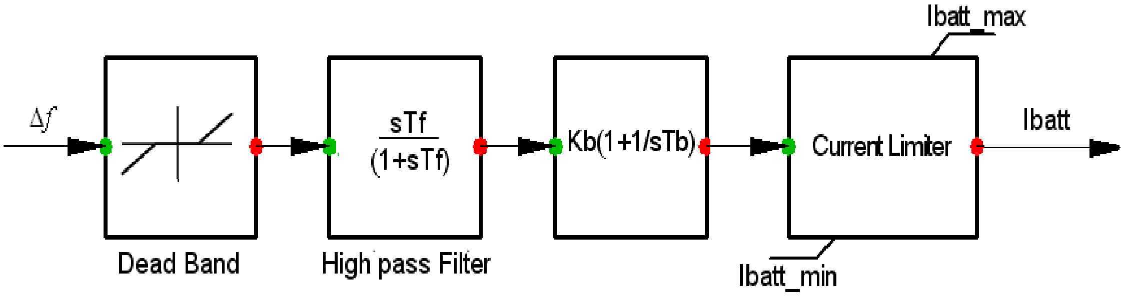

Fig. 5.9 V2G mode 2 control strategy

5.5 Simulation Results

For all the simulation cases in the Table 5.2, the simulations are conducted initially without integrating the aggregated battery storage (V2G). The results of these simulations serve as reference cases or the starting point from which the V2G power capacity are added in steps to observe the frequency regulation support. Fig. 5.10 illustrates simulation result of the frequency deviation for Case B – evening peak demand period. The frequency deviation in the reference case is very large as the regulation reserves in the power system are insufficient. To analyse the effect of using V2G grid frequency regulation, the result is compared with a simulation case using 10MW battery storage. The V2G mode 1 could not suppress the frequency deviations completely as it uses a proportional controller reacting to the frequency error. The V2G mode 2, using a PI controller is found to be effective in eliminating the frequency error. The high pass filter used in the control loop prevents the battery from losing its regulation capabilities.

Without the filter, the battery storage capacity is exhausted towards the end hours of the simulation period as shown in the Fig. 5.11 for battery storage of 8MW. The positive value of the battery power defines the battery discharging mode and battery charging mode negative value. The initial state of charge of the battery storage is assumed here as 50%. In Fig. 5.12, the battery state of charge reaches its upper limit for V2G mode 2 without the filter, beyond which the further down-regulation is not possible.

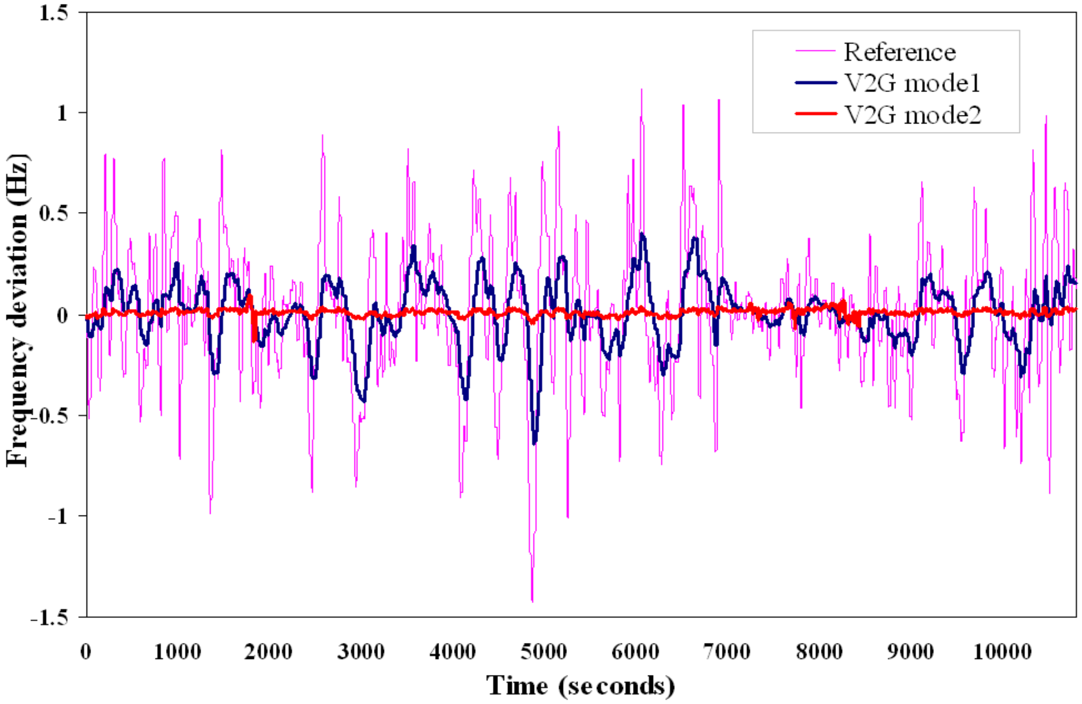

Fig. 5.10 Frequency deviation results in Case B for the evening peak demand period (10MW battery used in V2G modes)

The battery state of charge for both V2G mode 1 and V2G mode 2 with filter are within the operational limits. The contribution of frequency regulation from the V2G mode 1 is very limited which is evident from the battery power and state of charge results in Fig. 5.11 and Fig. 5.12. In this case, the CHP unit operating in the isochronous mode contributes more to the frequency regulation process. The battery storages in V2G mode 1 could contribute further higher regulation with lower values of droop (higher battery gain) or by reducing the sensitivity of isochronous controller of the CHP unit. However, the extent to which it can contribute using the proportional controller will be less than the aggressive operation strategy of V2G mode 2. The droop of the battery storage is selected in this study after several simulation tests which produced a stable output.

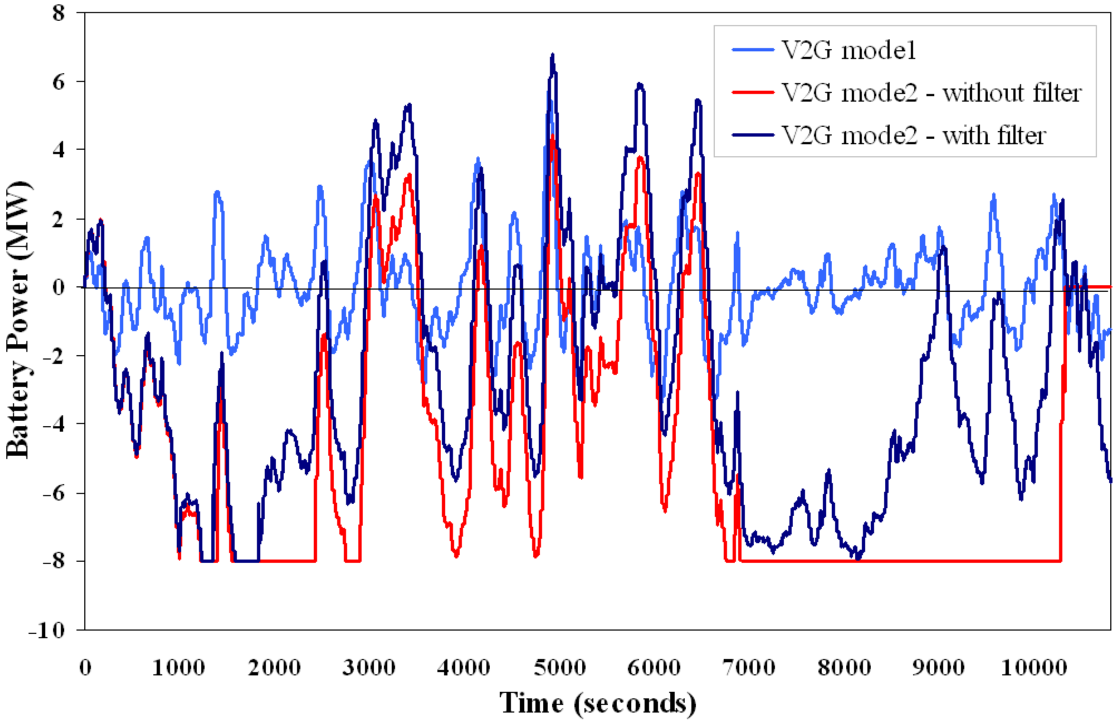

Fig. 5.11 Battery power results in Case B for the evening peak demand period (8MW battery used in V2G modes)

For a quantitative analysis of the system performance, the standard deviation of the frequency from the nominal value of 50Hz is calculated from the simulation results for all the test cases. Fig. 5.13 to Fig. 5.16 shows the standard deviation of the frequency for the simulation cases for the two system demand periods considered. It can be seen that by increasing the Vehicle-to-Grid system capacity, the frequency deviations are reduced in both modes of V2G operation. It is evident from the previous results that the V2G mode 2 requires less power capacity to minimise the frequency deviations. The normal acceptable operating frequency range in the Nordic power system control area is ±0.1Hz [113].

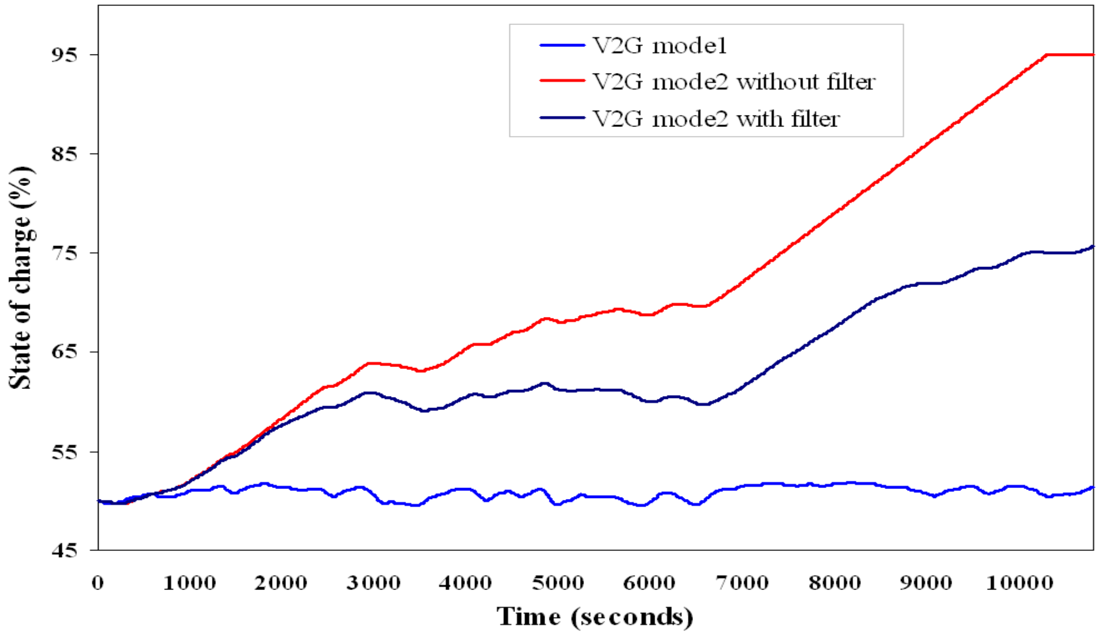

Fig. 5.12 Battery state of charge results in Case B for the evening peak demand period (8MW battery used in V2G modes)

The reference case simulation results (without V2G) of Case A shown in Fig. 5.13 and Fig. 5.15 could be considered as a base case of acceptable operational limits of frequency deviations. For case A, there is sufficient generation and reserve capacity from the conventional generators even without Vehicle-to-Grid (reference case) to ensure standard frequency regulation to accommodate the wind power and load fluctuations. For the Case B and Case C, the reserves from Vehicle-to-Grid systems become more relevant for being able to integrate a large amount of wind power and to ensure the nominal system frequency limits. As an example, from Fig. 5.13 and Fig. 5.15, it can be seen that in the Case B simulation results, the aggregated battery storage of 10MW provides satisfactory power system operation to integrate 30MW of wind power for both the morning and evening load demand periods.

From the results, the approximate Vehicle-to-Grid power required in percentage of the wind power capacity to ensure frequency stability of a wind dominated islanded Bornholm power system for the mode 1 and mode 2 operations are found to be 80-85% and 30-40% respectively. These higher percentages of battery storage power capacities are justifiable, as the worst case scenarios are analysed here in an islanded mode of operation, where the conventional generator reserves are either reduced or insufficient. The 30-40% of installed wind capacity could be regarded as a minimum storage capacity requirement to ensure the desired frequency quality.

These percentages could be representative for similar islanded or large wind power systems, where the wind farms are clustered in small geographical areas resulting in coincident high ramp system demand and wind periods. Also the wind ramp period must be predicted with some accuracy to ensure the availability of sufficient flexible online reserves.

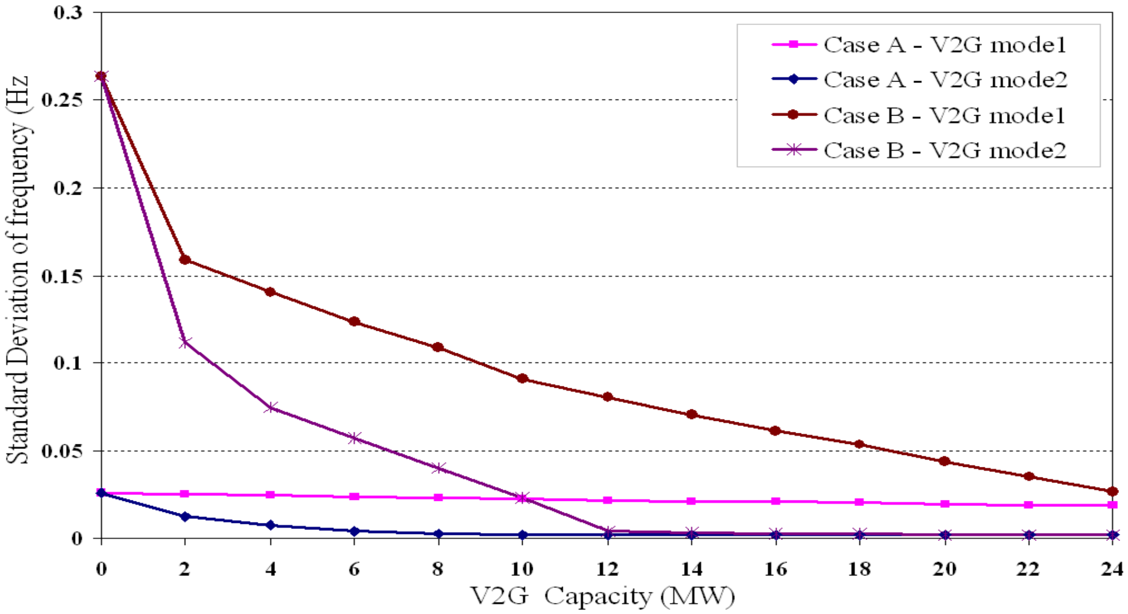

Fig. 5.13 Standard deviation of frequency for the morning up-ramp demand period (Case A and B)

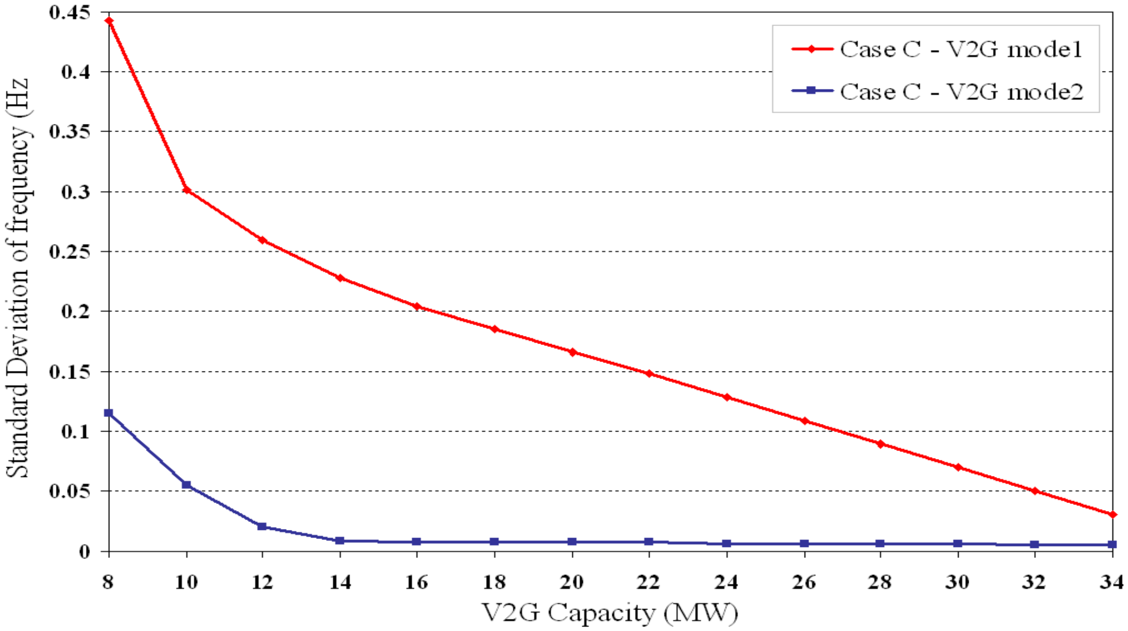

Fig. 5.14 Standard deviation of frequency for the morning up-ramp demand period (Case C)

Fig. 5.17 and Fig. 5.18 show the percentage regulation reserves (up and down) replaced by the V2G storage from the conventional generators for the two load demand periods. These results are calculated by comparing the generator regulation needs of the reference case (without the V2G) to the case of a minimum Vehicle-to-Grid integration which ensures an acceptable frequency limit. The V2G mode 1 or the droop mode of battery operation needs a large sized MW storage and is only moderate in reducing the conventional generator reserves.

On an average, the V2G mode 2 replaces more than 80% of the large conventional generator regulation reserves which is evident from the results. The quick start and high speed response of the battery storages are effectively utilised by the V2G operated in mode 2. This has resulted in a significant system regulation control capability using battery storage of a reasonable size. One major constraint of this mode could be the limit on the battery energy storage capacity. However, it is expected that the battery storage energy capacity of the electric vehicles will be increasing in the future.

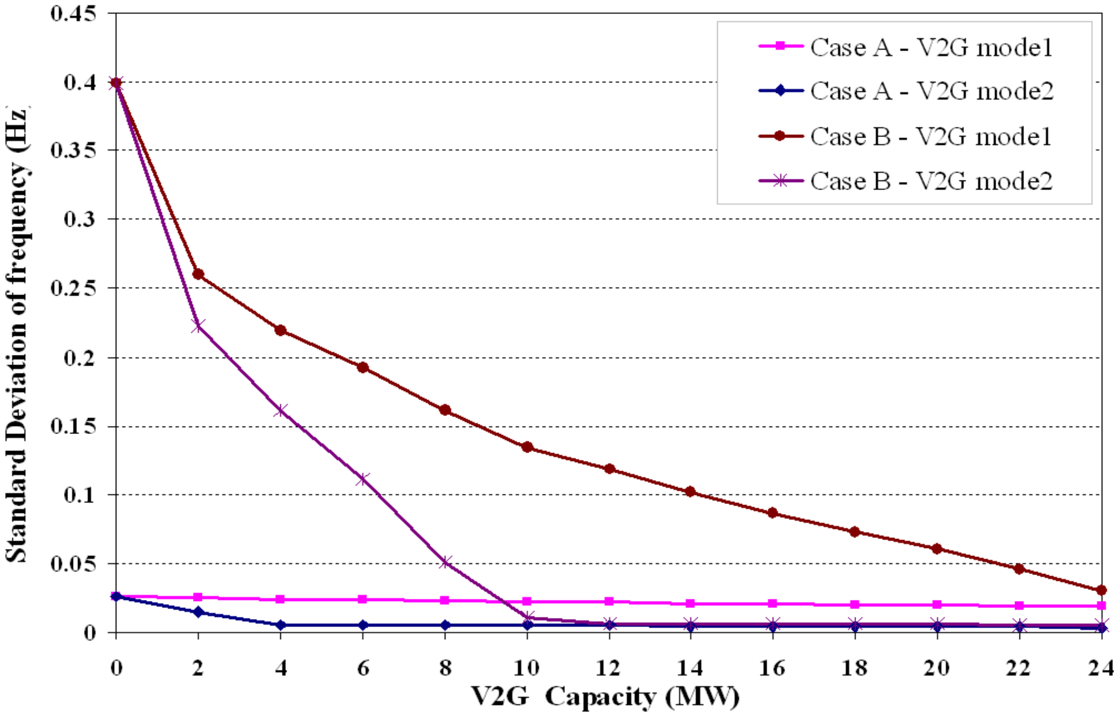

Fig. 5.15 Standard deviation of frequency for the evening peak demand period (Case A and B)

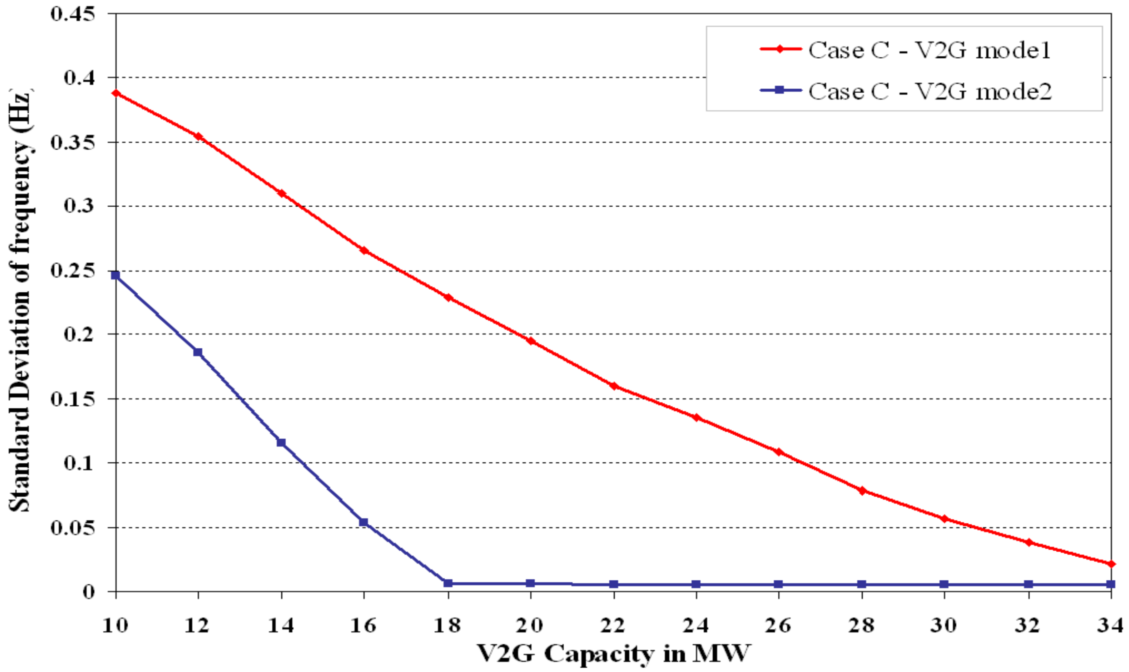

Fig. 5.16 Standard deviation of frequency for the evening peak demand period (Case C)

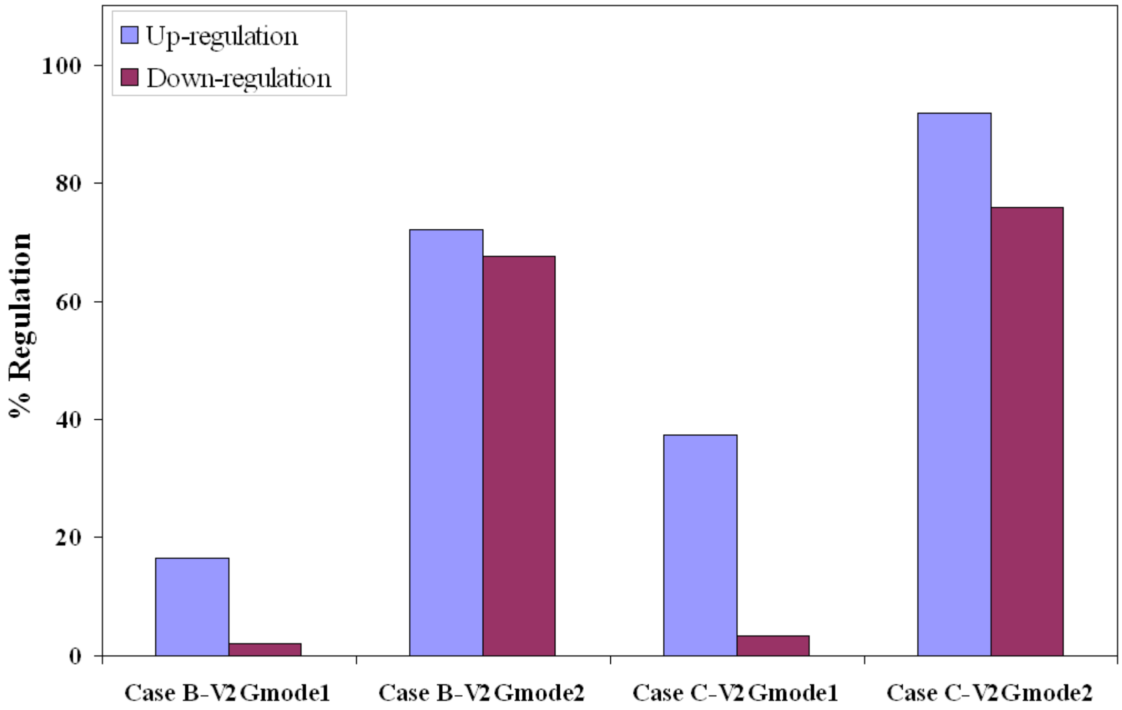

Fig. 5.17 Percentage regulation power replaced by the V2G systems from the conventional generators – morning ramp demand period

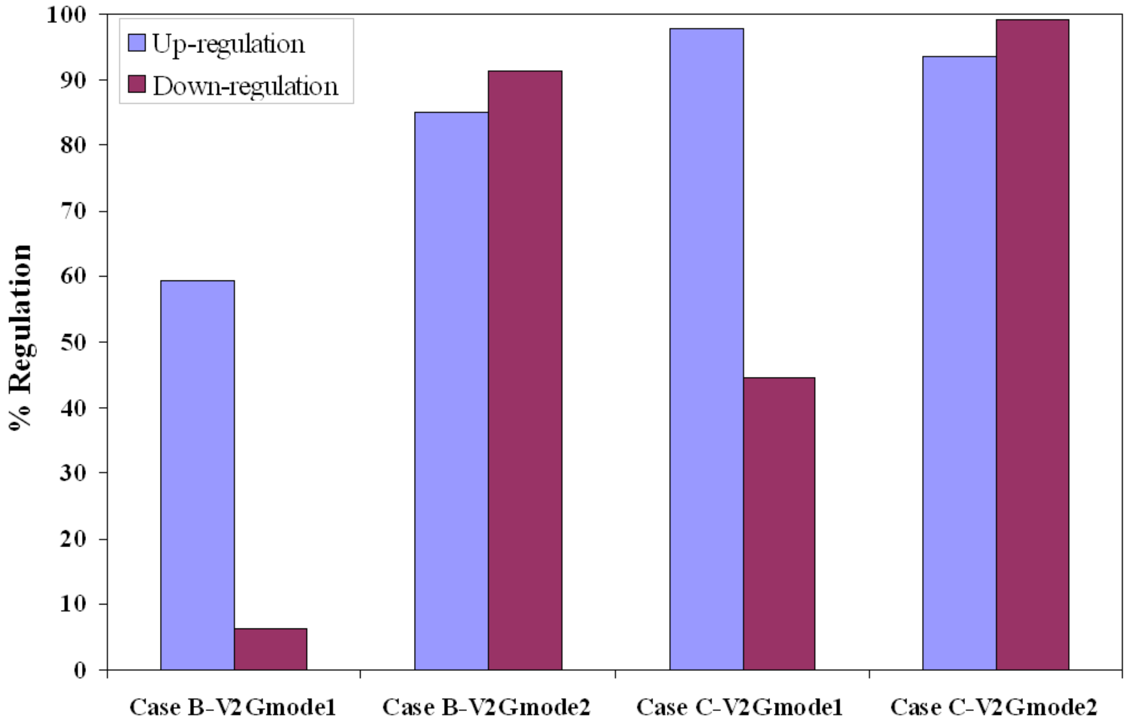

Fig. 5.18 Percentage regulation power replaced by the V2G systems from the conventional generators – evening peak demand period

5.6 Summary

In this chapter, the role of Vehicle-to-Grid systems to integrate more wind power in the Danish island of Bornholm in an isolated power system operation is presented. A single bus bar model of Bornholm power system is used for simulations which represents the dynamic interactions of generators, load and storage. The aggregated battery storage uses a long-term dynamic simulation model which is constrained by the state of charge limits. Data from two system demand periods, where many instants of the wind power ramps coincides with the load demand fluctuations were used for simulations. The simulations were performed for cases with reduced configurations of conventional generation and reserves. The Vehicle-to-Grid integration were analysed in two operating modes. The first is the droop mode using a proportional controller which needs a larger storage power capacity for maintaining the power system frequency limits. The second mode uses a conventional proportional-integral controller along with a high pass filter. For the simulated test cases, the second mode requires a battery power capacity of 30-40% of the installed wind power for ensuring standard frequency quality.

The Vehicle-to-Grid systems are able to replace an average of more than 80% of the frequency regulation reserves from the conventional generators for the studied simulation cases. These results are applicable to other similar islanded power systems with large wind power penetration, especially with less geographical spread of wind farms. This analysis is representative for the future distribution networks which intend to operate the system in a planned islanded mode. The higher sensitivity of islanded operation to demand and generation changes, strong correlation of wind power outputs resulting in coincident wind and load ramp periods, are highly challenging for the stable system operation. The overall generation control efficiency of such islanded wind dominated power systems could be improved using quick response Vehicle-to-Grid systems when compared to the conventional power plants.

Chapter 6

Impact Assessment of Electric Vehicle Loads on Distribution System Operation

6.1 Introduction

The social and economic benefits of electric vehicles have now been widely recognized by the automotive industry and the electricity sector to a point where the major auto manufactures either have or are in the process of developing both plug-in hybrid and battery electric vehicles. The transportation sector could benefit immensely from the adoption of electric vehicles which uses electricity that is cheaper than the depleting fossil-fuels. This will also improve the energy security, efficiency and sustainability. In order to reap these benefits, it is important for the electric utilities and automotive manufactures to assess the impacts of electric vehicles as additional loads on the safe and reliable operation of the electricity network.

Some of the previous studies on electric vehicle integration have focused on the availability of present and planned generation capacity to accommodate additional demands from electric vehicles, based on the assumptions that the charging of vehicles are confined to the off-peak hours [114-116]. However, such system level analysis may not address the coincident peaks of electric vehicle charging and conventional loads in the distribution system levels. The uncertainty that may result from the electric vehicle driving patterns, penetration levels and charging of electric vehicles in the electrical distribution systems could result in new system peaks and negative distribution system impacts. However, the coordination of smart charging (controlled charging) of the electric vehicles through two-way communication systems can facilitate most of the battery charging during off-peak hours [117], [118].

Some attention has been paid even during the last two decades, investigating the impacts of market integration of electric vehicles on the utility distribution load profile [119-121]. Other recent investigations have also examined the network limitations of large numbers of electric vehicles on the distribution system operation in terms of overloading, power quality and loss of life of components [117], [121-126]. However, the penetration levels of the electric vehicles cannot be generally quantified based on a specific case, as it is dependent on the load diversity, configurations of the assets and operating characteristics of a distribution network. The impacts of electric vehicle loads on the power distribution network in the Danish island of Bornholm are investigated in this chapter. The key operational parameters of the electrical distribution system like the voltage profile, distribution line loading, transformer loading, peak demand and system losses are examined here for an increased penetration of electric vehicle loads. As an ancillary service provider, the electric vehicle could deliver power back to the grid which can have effects on the protection systems and the voltage levels in the secondary distribution network. It may lead to the possible tripping of protection systems due to reverse flow and voltage rise of feeders during low loads. The impacts on the primary distribution network are only considered in this chapter as the data for the secondary distribution system of Bornholm was not available. So, this chapter addresses the primary concern of the utilities in the short and medium term planning process where the electric vehicles as aggregated electric loads are only accounted and not the discharging (generation) capabilities of the vehicles. The electric vehicles penetration in the range of 0-50% of the cars is analysed here with different power ratings of electric vehicle charging. A dump (uncontrolled) as well as a smart (controlled) charging mode of the electric vehicle is applied in this analysis.

6.2 The Bornholm Power System

The medium voltage distribution network of the Danish island of Bornholm is considered here as the test case. A brief discussion about the features and the importance of the Bornholm power system is discussed in the previous chapter in Section 5.2. It is a model region for testing electric cars where projects like “EDISON” plans to demonstrate the use of electric vehicles for supporting large scale wind power as discussed in Section 2.3. Fig. 6.1 shows the graphics of the Bornholm 60kV meshed power distribution network modelled in the DIgSILENT PowerFactory software with the distribution transformers, generators, wind turbines, shunts and aggregated loads in the 10kV system. The distribution system is a 60kV medium voltage (MV) network connected to the 132kV substation in Sweden which is considered as the external grid. The model shown in Fig. 6.1 is adopted from the reference article [105] and the other relevant data are taken from similar published articles and reports on Bornholm [106], [107], [127].

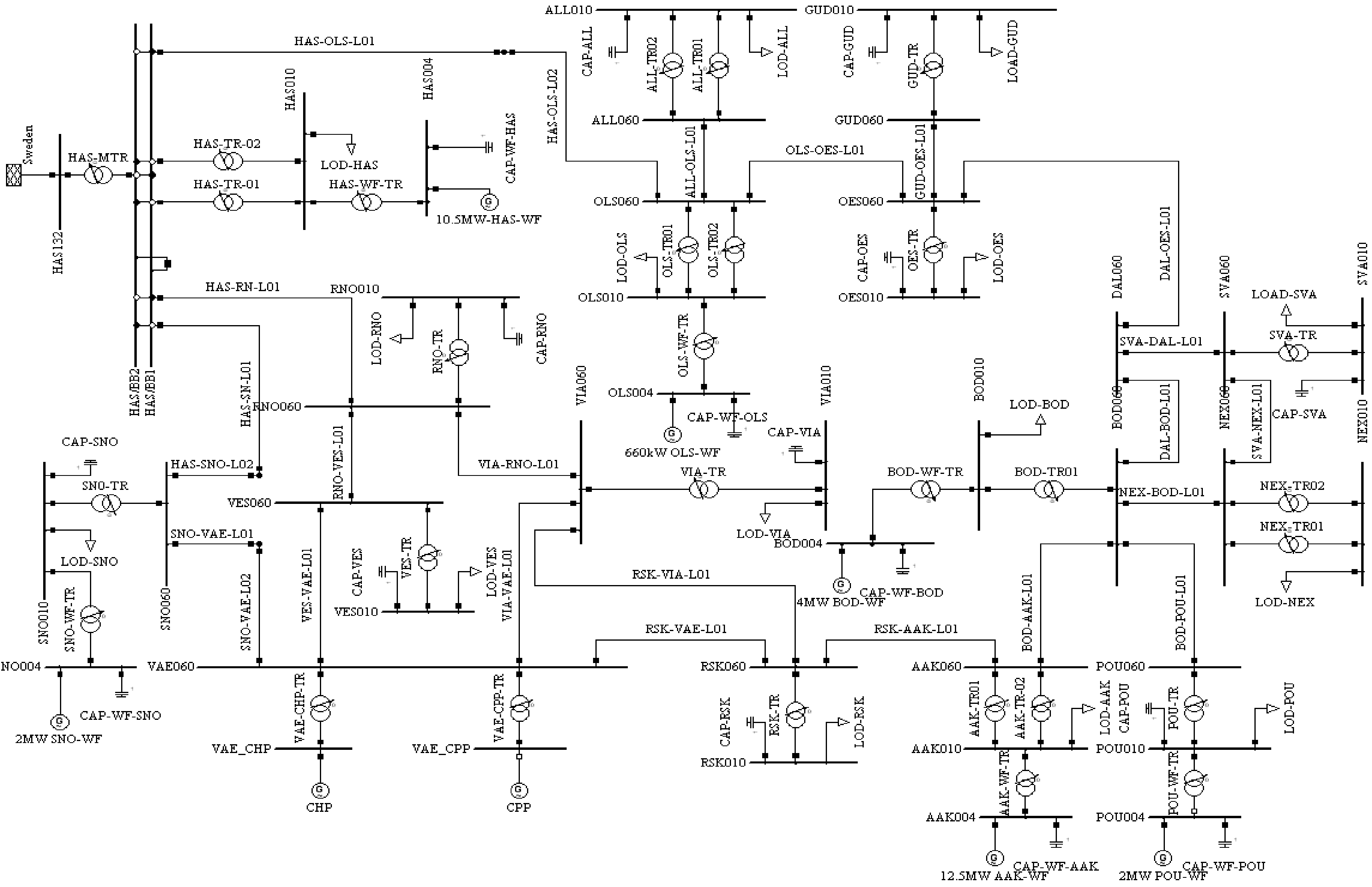

Fig. 6.1 Bornholm Power System [105]

There are 15 substations at the 60kV voltage level and 23 power transformers (60/10kV) with a total capacity of 219MVA. The map showing the 60kV network and transformer stations are shown in Fig. 6.2 and the ratings of main network components are given as tables in Appendix D (Tables DI & DII) [107]. The actual network data for the 10kV feeders and 0.4 kV secondary distribution network from Bornholm were not available for this analysis. So, a simplified radial distribution system with four feeders at 10 kV levels at each of the fifteen 60kV substations, are used in this study. Fig. 6.3 shows a case of the 10kV radial network considered here for the ALL060 (ALLINGE 60kV) substation. The aggregated system loads and EV loads are distributed across the 10kV voltage levels. The maximum and minimum demand in Bornholm reported for the year 2007 is 55MW and 13MW respectively [106]. Fig. 6.4 depicts the typical load demand curve in Bornholm used in this analysis.

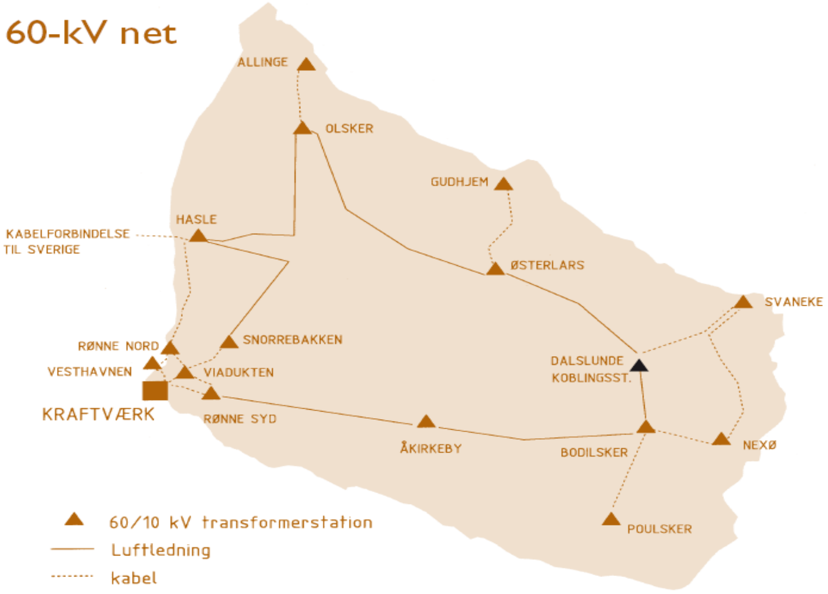

Fig. 6.2 Map of Bornholm 60kV network [107]

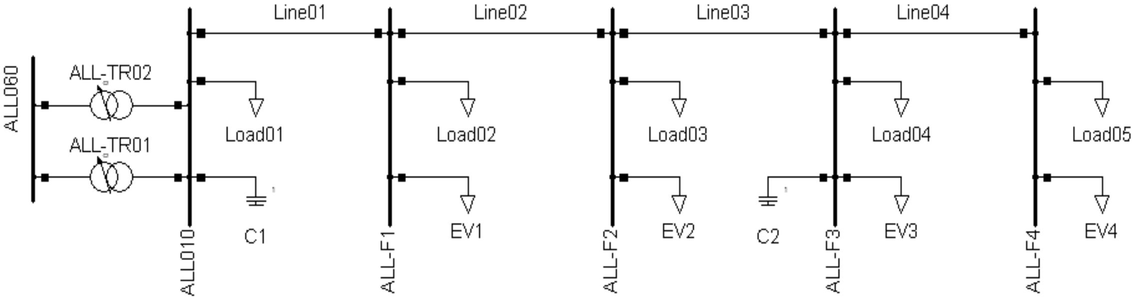

Fig. 6.3 10kV radial distribution system

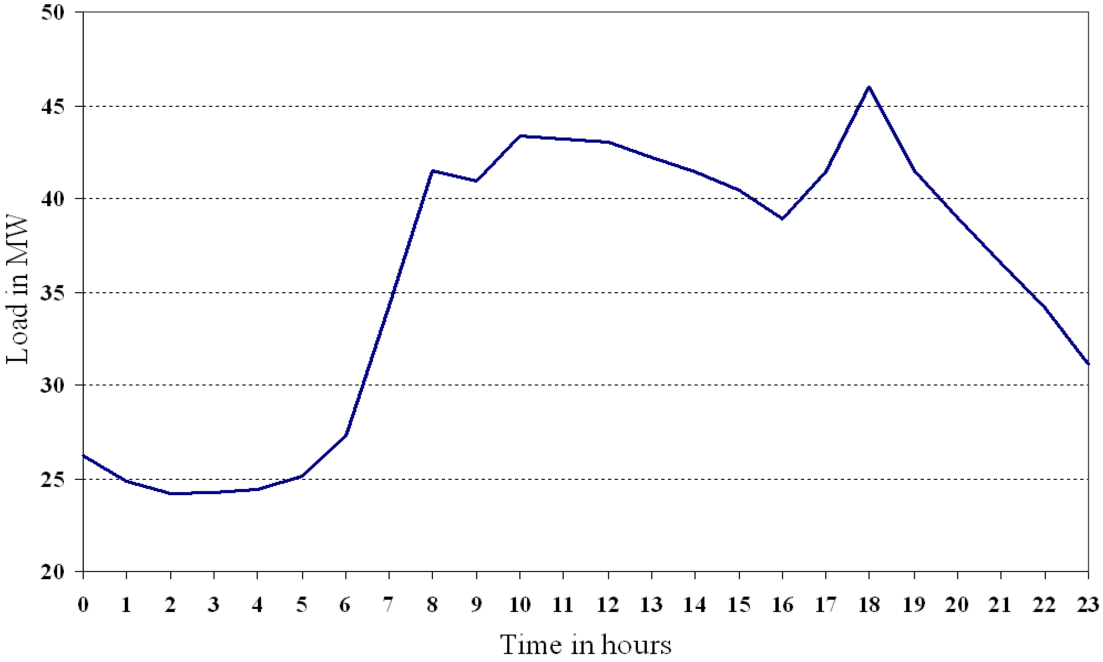

Fig. 6.4 Typical load consumption curve

6.2 Charging Profile of Electric Vehicles

In this chapter, three different types of electric vehicles are considered. They are categorized based on their rated power charging capacity (EV Type1 - 2kW, EV Type2 – 5kW and EV Type3 – 10kW) [30], [60]. The EV Type1 could be regarded as the charging power needed for a hybrid electric vehicle, where the typical battery storage capacity ranges from a few kWh to around 15kWh. The EV Type2 and EV Type3 could be considered as the charging range for medium and large battery electric vehicles respectively. The integration of the electric vehicles are analysed here in steps and as additional electrical loads integrated to the Bornholm distribution network.

Fig. 6.5 shows the distribution of the three different types of electric vehicles integrated to the Bornholm Island in steps from 0% to 50%, where the total number of cars is assumed to be 20,000. The reference scenario is represented here by the zero percentage of the electric vehicles. The scenario considers the hybrid electric vehicles to constitute a major share of the vehicles during the low penetration of electric vehicles. They are gradually replaced by the battery electric vehicles for the higher integration levels of electric vehicles. This will be realistic in the near future where the driving range of the pure battery electric vehicles becomes comparable to that of conventional gasoline and hybrid electric vehicles. This is evident from the current trends of increasing battery capacities providing reasonable driving range of 300-400km from the latest battery electric vehicle models (Section 2.2). Two types of plug-in electric vehicle charging are considered in this work 1) uncontrolled and 2) controlled. Fig. 6.6 depicts the aggregated EV charge profile used in this work, where 100% of battery charging requirement is distributed among the hours of a day. The charging profile used in this chapter is a modified version of what is available in [128].

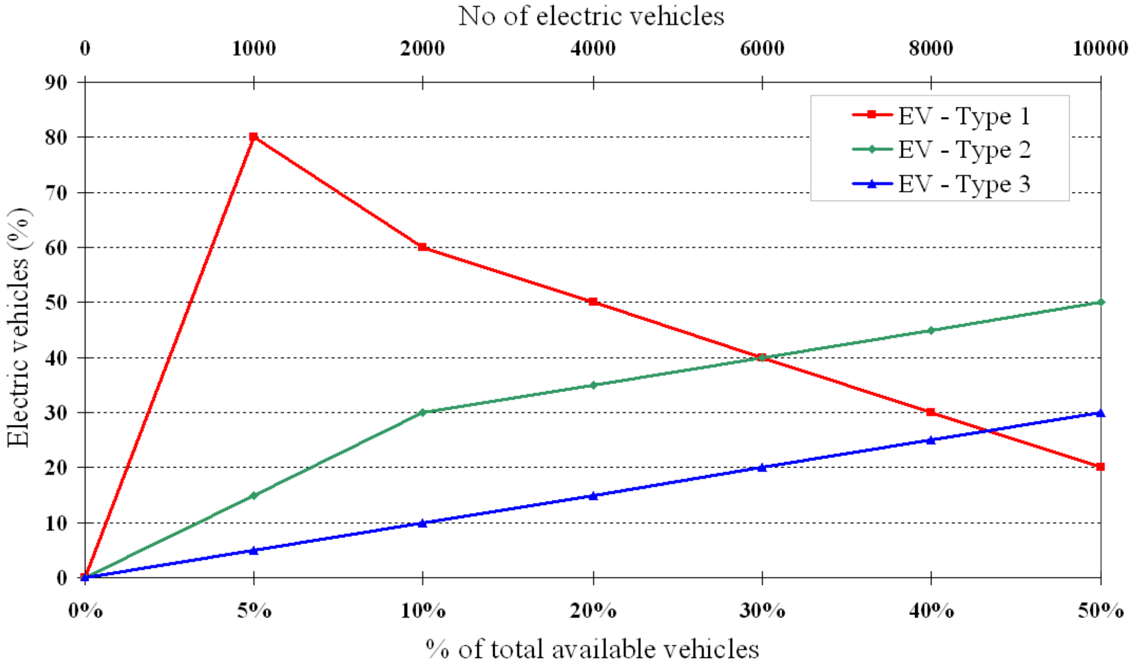

Fig. 6.5 Distribution of electric vehicles

The charging time of electric vehicles are considered here to be four hours. The uncontrolled charging mode corresponds to a dump charging mode, where the electric vehicles are charged at any time, irrespective of any constraints. In this charging mode, it is considered that the utility makes no effort to influence or control the amount of electric vehicle charging loads. In this scenario, it is assumed that most of the charging takes place in the evening after the car owner's returns home from work. The fast charging of electric vehicles (e.g. charging 50% of the battery storage capacity in half an hour) possibly by the taxis and business vehicles during the afternoon hours is also considered under the uncontrolled charging mode. This charging mode represents a scenario where 55% of the battery charging takes place during the off-peak hours (10:00 p.m. to 7:00 a.m.) and the remaining 45% is provided between 7:00 a.m. and 10:00 p.m.

The controlled charging is a flexible mode or smart charging, where the battery charging is carried out mostly during hours of low electricity price and low electricity demand (off-peak hours). This scenario assumes that the utility is successful in implementing steps like dynamic load control, pricing and incentive mechanisms to minimise the increase in the peak load demand. The electric vehicles have to be equipped with smart metering and communication interfaces to realise this scheme. This charging mode is assumed to ensure minimal plug-in electric vehicle loads during the peak electricity demand hours. The controlled charging mode creates a scenario where 75% of the EV battery charging occurs during the off peak period (10:00 p.m. to 7:00 a.m.) and the remaining 25% is provided between 7:00 a.m. and 10:00 p.m.

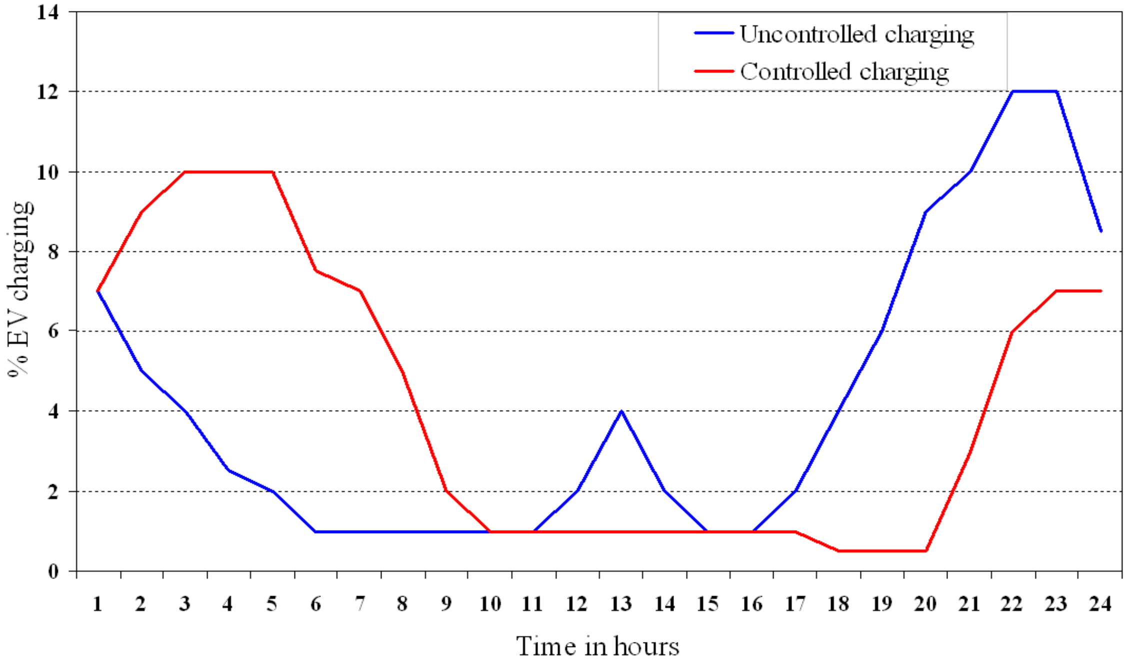

Fig. 6.6 Charging profiles of electric vehicles

6.4 Simulation Methodology

The plug-in EV loads are added to the system demand (reference scenario in Fig. 6.4) in steps of 0-50% based on the EV distribution scenario illustrated in Fig. 6.5. The impacts of these additional loads on the key operational parameters of the distribution grids are analysed using load flow studies simulated for each hour of the typical day considered. The effect on the system voltage profile per feeder, daily system losses, peak demand period and distribution line losses are investigated for an increased penetration of electric vehicle loads. A DPL (DIgSILENT Programming Language) script is developed in the PowerFactory software for using the charging profile of electric vehicles in the model and also to perform the hourly load flow analysis.

To analyse the impacts of electric vehicle loads on a low voltage (LV) distribution transformer (loading and aging factor) operation, a 250kVA transformer is considered in this work. The transformer size is based on the average size of the LV distribution transformers in Bornholm with 29 customers per unit [106]. Fig. 6.7 shows the aggregated load profile of a 250kVA low voltage distribution transformer. This demand profile is scaled from a daily residential curve presented in [129]. The peak demand for the day is 196.35kW at 17:00hrs. The average demand is 68.17kW and the daily load factor is 34.72%.

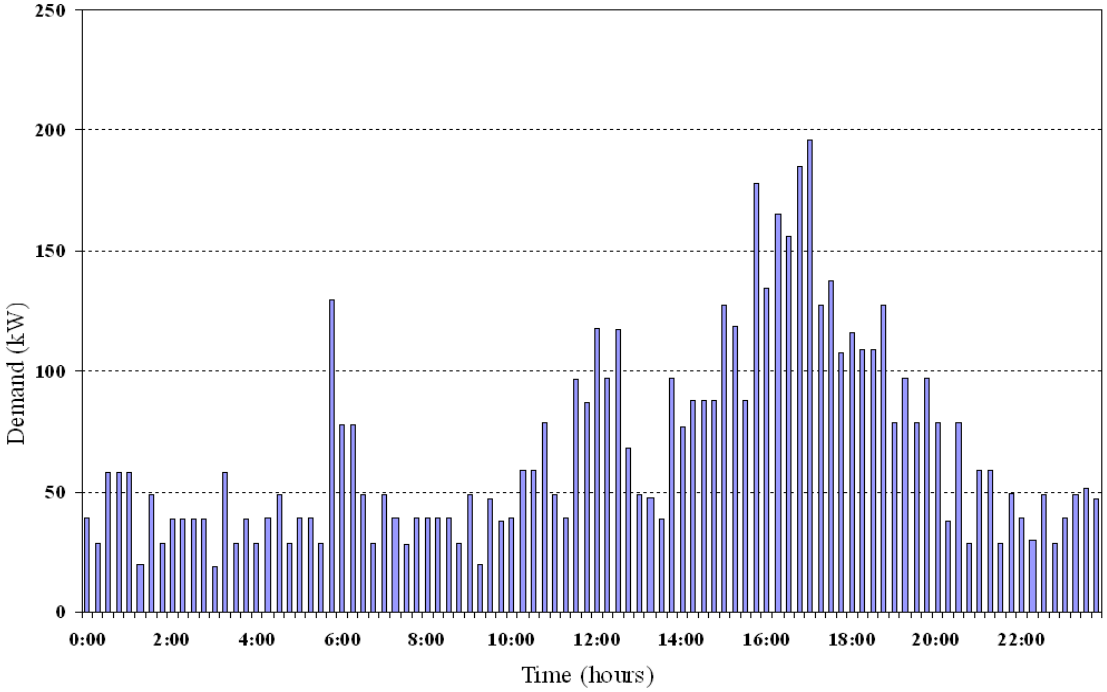

Fig. 6.7 Demand curve of 250kVA distribution transformer

6.4.1 Impacts of EV loads on the Distribution System

The average voltage drop of three critical feeders in the network for the uncontrolled charging mode of the electric vehicles is shown in Fig. 6.8. For an increasing number of electric vehicles, the voltage of these feeders drops below the reference voltage to a level beyond the normal acceptable limit of 0.95p.u [64], which is indicated by the dashed line. It is observed that the voltage limits are violated for the ALL-F4 feeder even with 10% of electric vehicle loads. The on-load tap changers of the transformers reach its limits where further voltage regulation is not possible. But for the controlled charging in Fig. 6.9, the voltages of the critical feeders give better results than for the uncontrolled case as in Fig. 6.8. The voltage falls below the nominal limit only for the feeder ALL-F4, for an electric vehicle integration of more than 40% in the distribution network. The tap changers of transformers reach their limit upon which the feeder voltage falls below the statutory requirement of 0.95p.u.

The loading profiles of the three highly congested distribution lines are shown in Fig. 6.10 and Fig. 6.11 for the uncontrolled and controlled charging modes respectively. The loading exceeds the 100% limit for two distribution lines in the uncontrolled mode of charging. The congestion level of the most critical branch is exceeded when the electric vehicle load penetration is 40% for the uncontrolled mode. If the electric vehicles are following the controlled charging mode, the line loadings for all the three lines are within the permissible loading range.

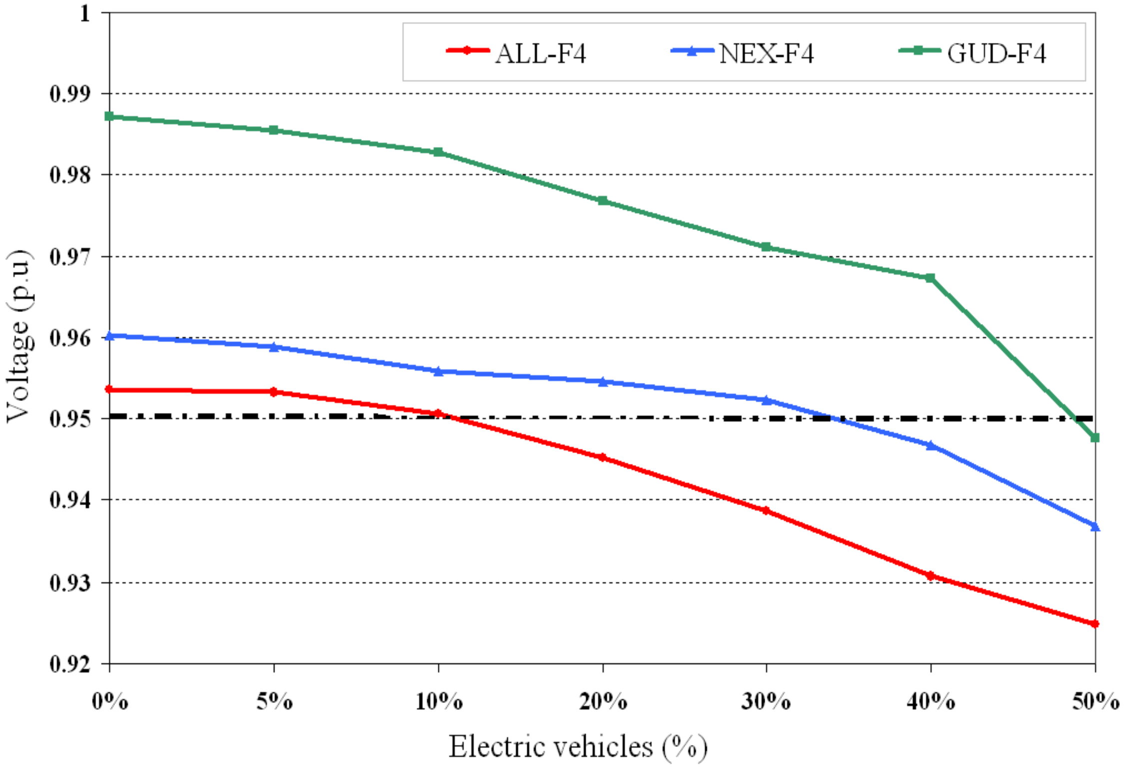

Fig. 6.8 Voltage profile of three critical feeders for uncontrolled charging

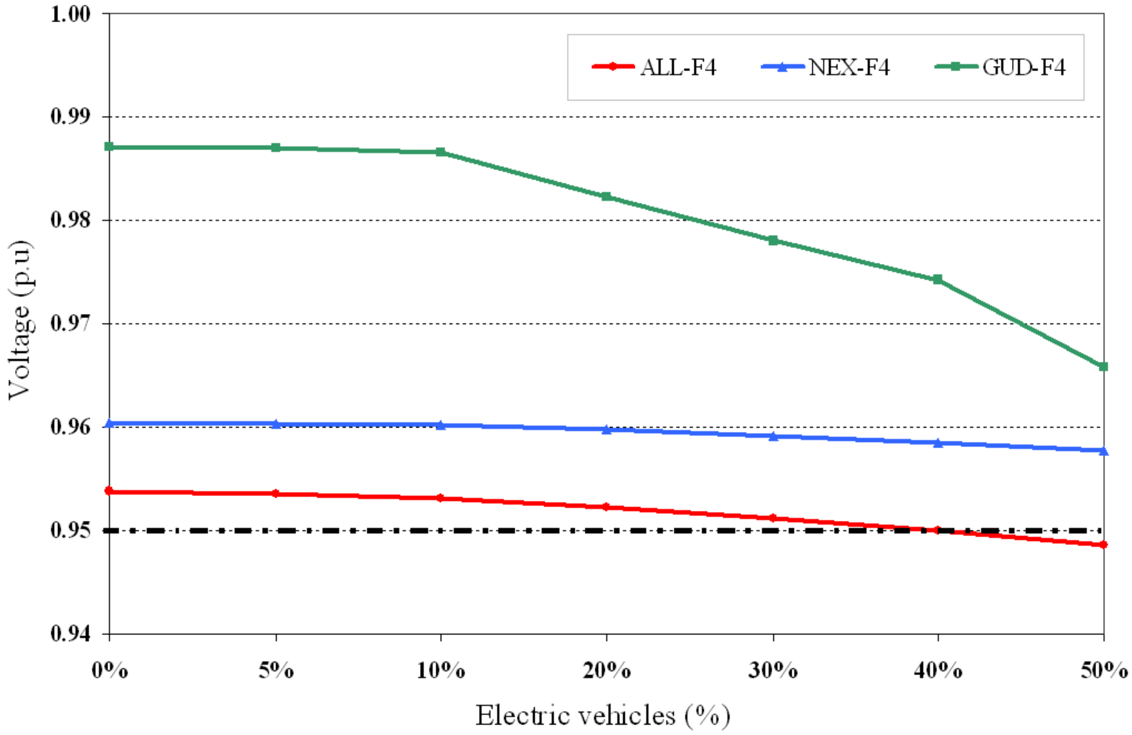

Fig. 6.9 Voltage profile of three critical feeders for controlled charging

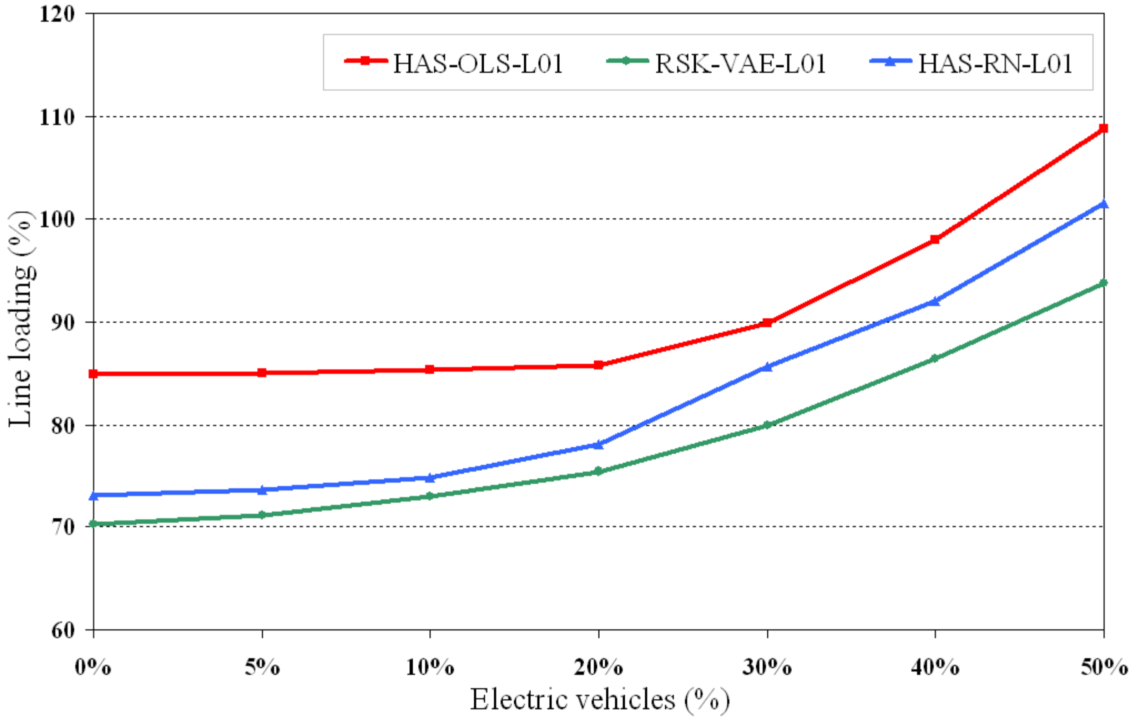

Fig. 6.10 Loading profile of three highly congested lines for uncontrolled charging

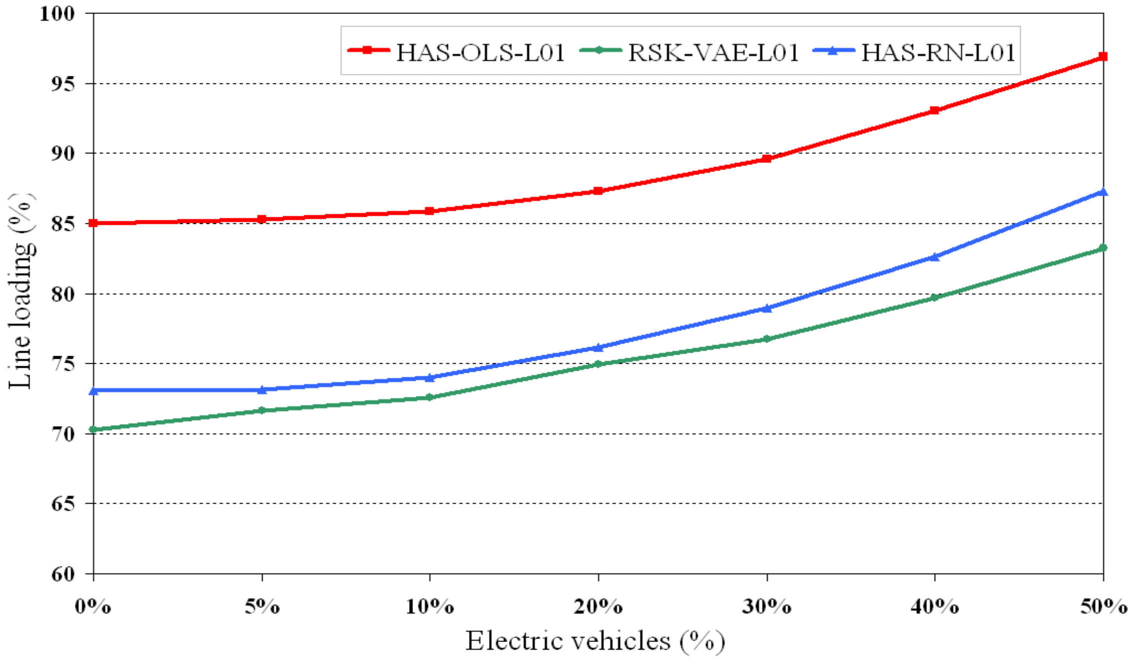

Fig. 6.11 Loading profile of three highly congested lines for controlled charging

The distribution system losses and the peak demand distribution for both the controlled and uncontrolled mode are illustrated in Fig. 6.12. The losses are increased by 40% and 30% for the uncontrolled and controlled charging mode respectively from 0% (reference scenario) to 50% of electric vehicle integration. For uncontrolled charging, the peak load is increased by 48% on integrating 50% of electric vehicles in the distribution network. The peak demand in the network for the uncontrolled charging mode is found to be 31% higher than the controlled charging for the 50% electric vehicle scenario. The resultant load demand curves obtained from incorporating additional electric vehicle loads ranging from 0-50% for the entire day are illustrated in Fig. D.1 to Fig. D.6 (Appendix D). For both modes of electric vehicle charging, new and higher system peaks are created. However, this effect is more evident for the uncontrolled charging, even for lower levels of EV penetration. For controlled charging, the peak load changes are more distinct only when the electric vehicle penetration is about 40%.

To analyse the daily load factor of the 250kVA LV distribution transformer, the EV charging profile of Fig. 6.6 is used. The load factor is a measure of load uniformity and efficiency with which the electrical energy is used in a power system. Fig. 6.13 depicts the load factor in percentage for both controlled and uncontrolled charging for an increasing number of electric vehicles. The controlled charging gives a better demand factor than the uncontrolled charging.

For an improved load factor, the demand is held minimum relative to the overall kWh consumption providing a constant rate of electricity use. A better load factor will lower the unit cost of electricity.

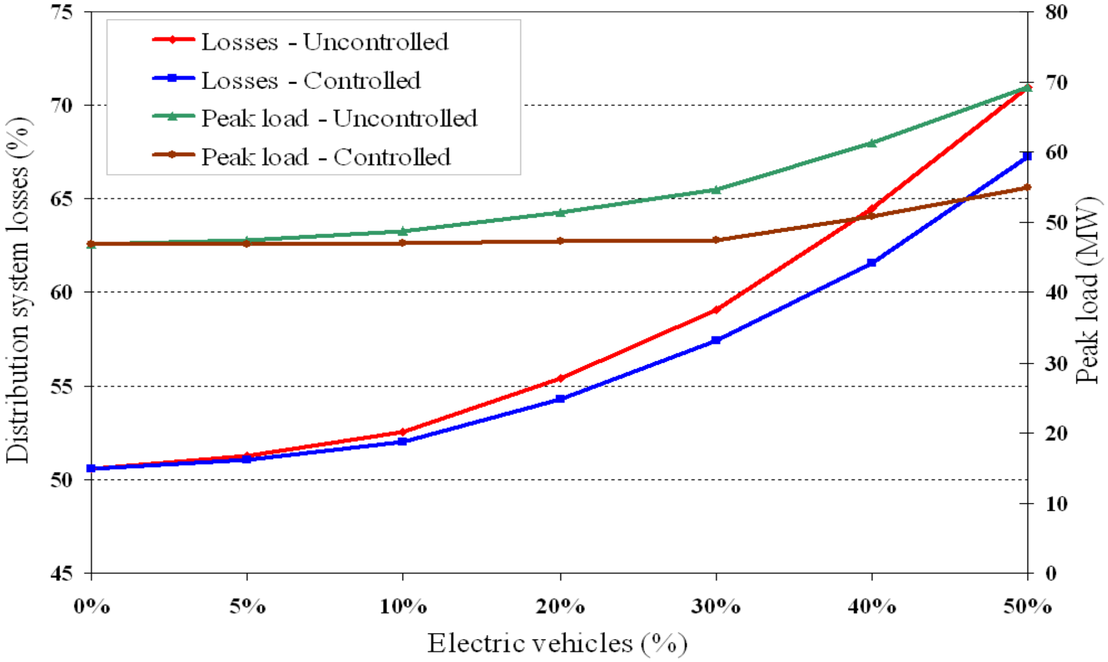

Fig. 6.12 System losses and peak demand for both uncontrolled and controlled charging modes

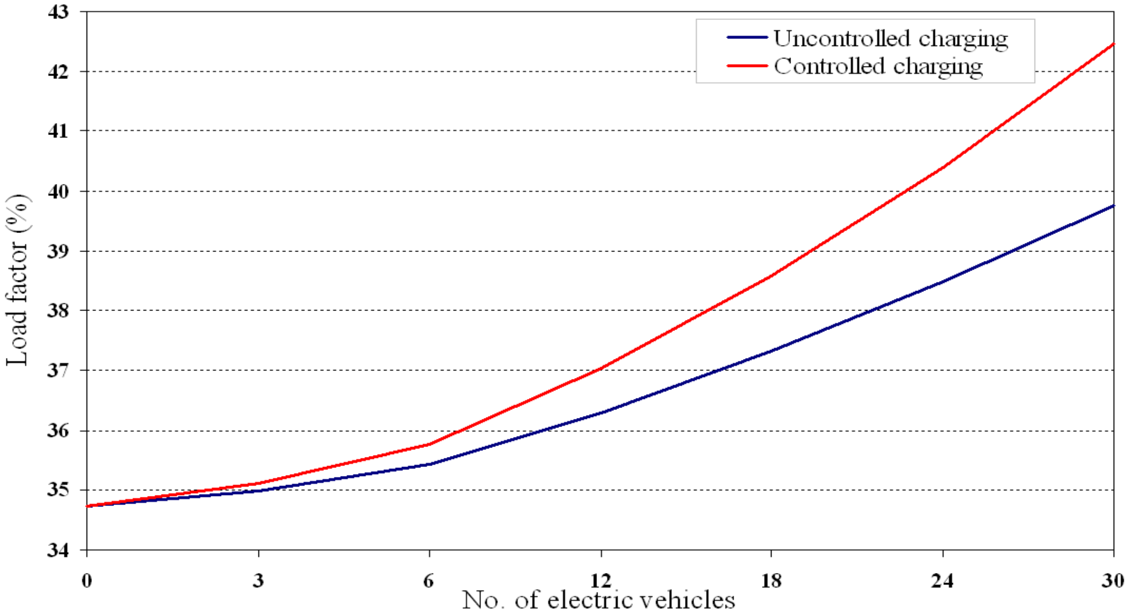

Fig. 6.13 Load factor of 250kVA LV distribution transformer

It can be inferred that the voltage drop in the network is more critical than the line loading for the same levels of electric vehicle integration as evident from the results. Thus, these network parameters analysed so far acts as limiting factors to higher levels of electric vehicle integration in a distribution network. The network utility has to increase the grid capacity in order to handle the larger peaks, higher losses and congestions resulting from the electric vehicle integration in the future. These bottlenecks in the distribution grid could be dealt to a certain extent using intelligent charging of electric vehicles with the help of information technology and smart meters. The controlled charging mode analysed here yields better results than the uncontrolled loading of electric vehicles for the operational parameters observed so far. The electric vehicle loads are more distributed across the low system demand periods for the controlled charging mode. This results in a better method of integrating electric vehicles in a distribution network.

6.4.2 Loss of life of transformer

The transformer is one of the most critical network components to be affected with the increased penetration of electric vehicles. To analyse the electric vehicle charging on a 250kVA local distribution transformer with a demand curve as given in Fig. 6.7, the peak load hour is selected. The electric vehicle charging at the peak demand hour should be considered as a worst case operating scenario for the transformer loading. The peak load charging and a large presence of electric car loads connected online could cause overloading, lower operating efficiency and a higher percentage loss of insulation life of the transformer. Fig. 6.14 illustrates a simple example of how the peak loading from increasing number of electric vehicles could exceed the rated capacity of the 250kVA transformer. The rated capacity of the transformer is exceeded with only six electric vehicles of EV- Type3 connected to the grid during the peak demand hour.

The aging of transformer with additional loads from the electric vehicle charging during the peak hour is calculated here. The method for calculating the percentage aging of the transformer is based on the IEEE standard C57.91 [130].

The aging acceleration factor (F_{AA}) for a given load and temperature is given by the following equation [130].

$$F_{AA} = EXP^{\left[\frac{1500}{383} - \frac{1500}{\theta_H + 273}\right]} \tag{6.1}$$

where θ_H is the transformer winding hottest-spot temperature in °C.

The percentage loss of life of transformer insulation is calculated based on Equation (6.2) [130]. The normal insulation life of the transformer is considered as 180,000 hours (20 years) [130].

$$\%\,Loss\,of\,Life = \frac{F_{AA} \times 24 \times 100}{Normal\,Insulation\,Life} \tag{6.2}$$

Fig. 6.16 illustrates the percentage daily loss of insulation life of the 250kVA LV distribution transformer. It is evaluated by charging the number of vehicles of different types during the peak demand hour at 17:00hrs. The corresponding transformer winding temperature for different levels of loading is determined by a polynomial interpolation of the corresponding transformer data available in [130]. From Fig. 6.15, the peak loading of the distribution transformer by plugging in six electric vehicles of Type 3 results in 0.01% loss of transformer insulation life which is equivalent to aging of 18 hours.

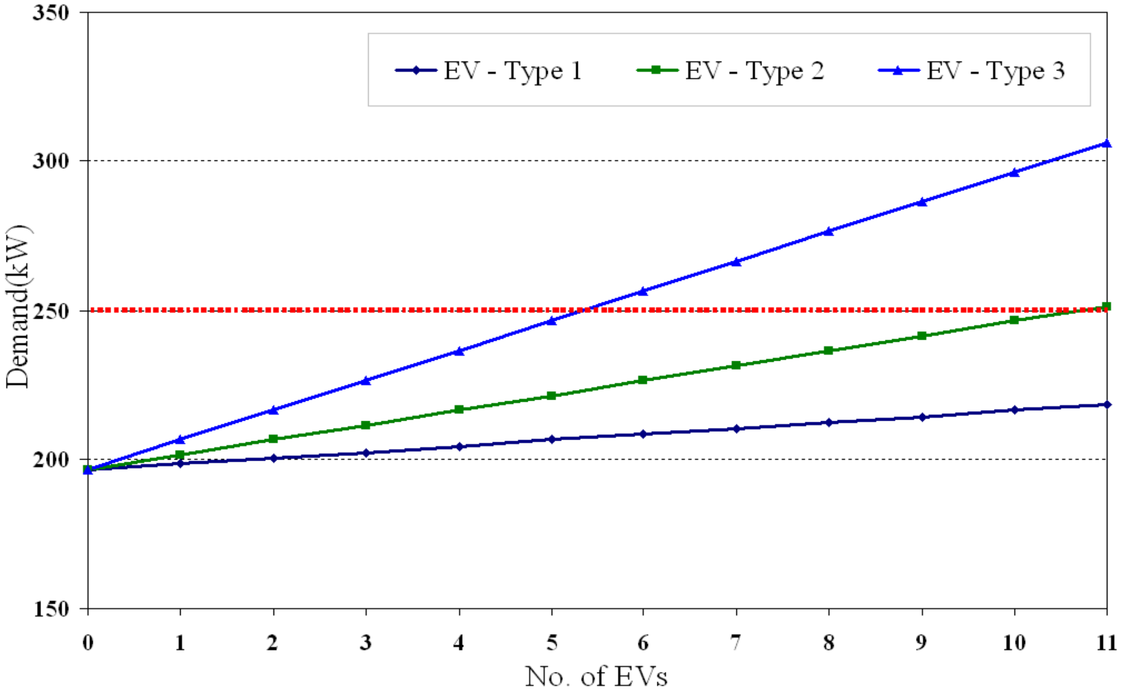

Fig. 6.14 Peak loading of the distribution transformer for different EV types

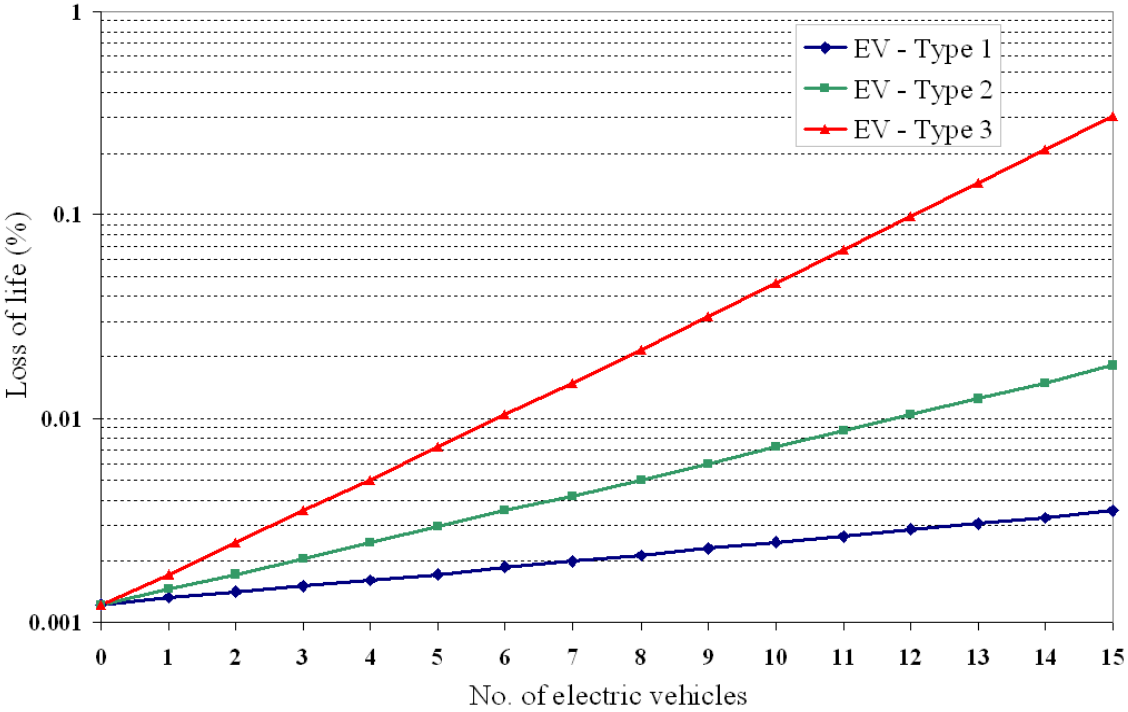

Fig. 6.15 Daily loss of life of a 250kVA LV distribution transformer from peak loading caused by EV charging

6.4.3 Demand Response & Smart Control Strategies – A Discussion

To reduce the impacts of electric vehicle charging on the local distribution transformer, the simple alternative could be upgrading of the transformer and the other network assets associated with it, which needs significant investment. Other methods include the controlled charging as examined in the previous sections and demand response (load control) possible in households. The demand response strategy is a subset of demand side management which aims to reduce the peak to average demand in the premises of the customer through automation and intelligent devices. They are time dependant strategies which either shifts or reduce the electricity use of individual households. The daily operation of the household loads like the electric cars, heaters, dryers, coolers etc. could be prioritised based on the consumer comfort and preferences. The non-critical loads could be shed, during the electric vehicle charging period. The household loads including the electric vehicles and the electricity consumption have to be monitored continuously.

If the peak load set for a household is reached, the loads could be shed in order of their lowest priority. The transformer demand needs to be monitored continuously to send control signals to a household controller to perform such demand response and load control strategy. To monitor and control the household loads and electric vehicle unit with remote control switches, an Advance Metering Infrastructure (AMI) [131] is required. The basic components of AMI are the smart meters and two-way communication interfaces. The infrastructure could monitor, measure and analyse the electricity used by sending data over the bidirectional communication network connecting the utility control systems and smart meters [132]. Fig. 6.16 depicts a ZigBee based home automation system with a smart meter and automated loads required to implement demand response strategies at the household levels [133], [134].

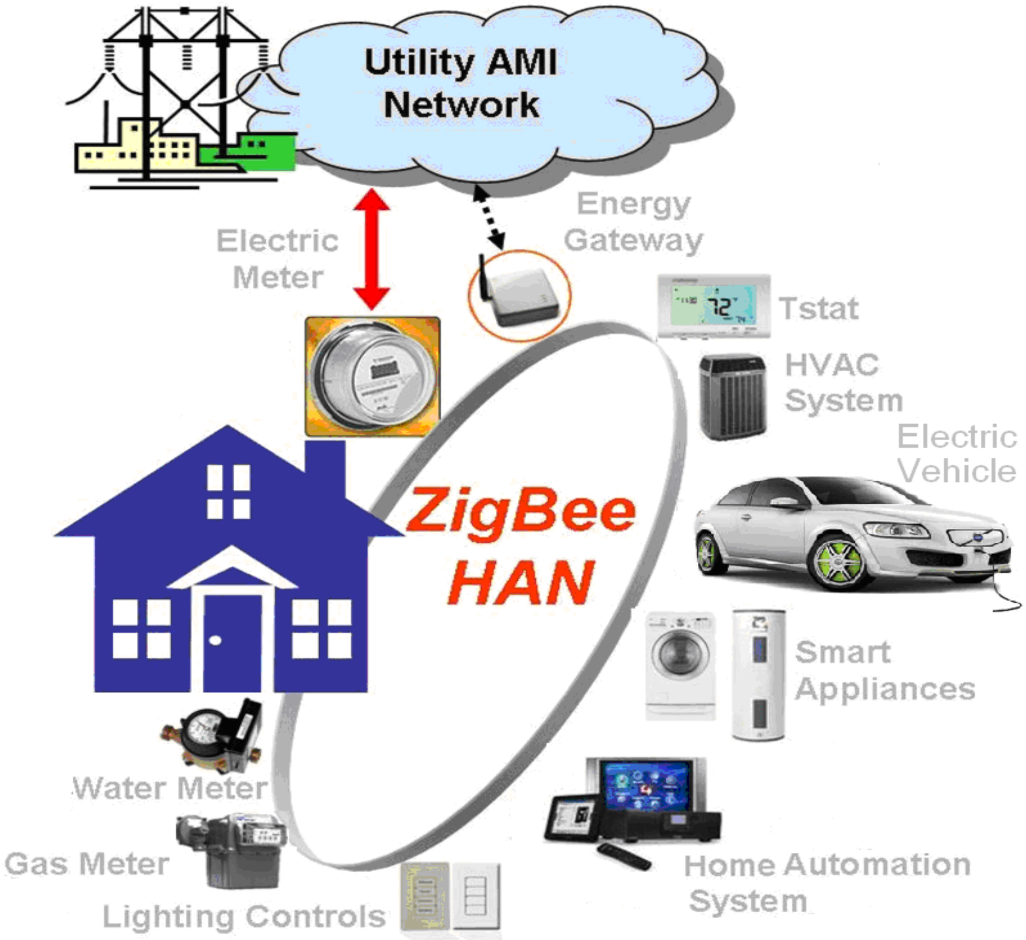

Fig. 6.16 Home Automation System [133]

This control strategy is mainly a software-based solution which is cost effective and could be implemented on the existing distribution network infrastructure without any grid reinforcement. The use of these intelligent controls and communication technologies is equally effective to counteract some of the primary issues like voltage fluctuations and reverse power flow when the electric vehicles export power into the distribution grid. Considering a case with many electric vehicles supplying power to one neighbourhood and are connected to the same distribution transformer. During periods of low demand and real power supplied by several vehicles, the power flow may reverse through the distribution transformer and the voltage may rise beyond the statutory operating limits. This could be mitigated by either limiting the amount of power generated by electric vehicles or reactive power control of the EV battery storages, when the voltage levels are near or exceeding the nominal operating limits. This voltage control functionality can be realised by coordinating the individual embedded controllers in the electric vehicles.

6.5 Summary

This chapter has investigated the impacts of integrating electric vehicle (EV) loads in a typical Danish primary distribution network. Two modes of electric vehicle charging was analysed here, i) controlled and ii) uncontrolled for an increasing penetration of electric vehicles in the range 0-50%. The results from the impact analysis show that there are adverse effects on the distribution system operation even at a lower penetration of electric vehicles, if the charging is uncontrollable. The impacts include low voltages, increased losses and overloading of conductors and transformers. Most of these impacts could be resolved by the controlled charging of electric vehicles which is more effective than the uncontrolled charging mode for integrating more electric vehicles on a moderate level. The following general conclusions could be drawn from this analysis:

- The wide-scale adoption of electric vehicles will influence the operation and design of the distribution grids. The drop in the network voltage is more critical than the overloading of conductors for the same levels of electric vehicle integration.

- Only 10% of electric vehicle integration is feasible from the uncontrolled charging in the studied test distribution network. For the controlled charging which could be realised by smart grid connection interfaces, about 40% of electric vehicle penetration is possible without violating any operating limits of the distribution system. The demand response of household loads could also be used to mitigate the peak demand loading of electric vehicles taking into account the customer's comfort levels and preferences.

- The levels of EV penetration may not be the same as for other distribution circuits. Impacts of EV integration in low voltage secondary distribution and weak networks may yield more conservative results. This can be investigated as an important topic in the future work.

- The future penetration levels of electric vehicles depend not only on the market mechanisms, the promotion policies and the improving vehicular technology but also on the safe operating limits of various electricity network parameters as well as the charging profile. The utilities must undertake an impact assessment of the penetration levels and charging patterns of the electric vehicles in the distribution grids to implement corrective actions.

Chapter 7

Dynamic Power System Simulations to Validate Energy Planning Scenarios from EnergyPLAN

7.1 Introduction

One of the important objectives of the CEESA (Coherent Energy and Environmental System Analysis) project introduced in Section 1.1.2 of this thesis is to analyse the integration of transport sector with the electricity sector to promote large amounts of renewable energy in Denmark [15]. The investigations which were conducted as static and dynamic simulation studies using Vehicle-to-Grid systems heretofore in this thesis were part of analyzing the above objective of the CEESA project. The next task defined in the analyses is to utilise the dynamic simulation models and results to evaluate the technical feasibility of the CEESA energy planning scenarios, which are investigated in this Chapter. These energy planning scenarios are based on Denmark which is studied as a “closed system” (“islanded” or self sustainable) using the EnergyPLAN model [135]. The results of the energy system analysis of these scenarios concludes that it is physically possible to integrate 50% and even 100% of renewable energy in Denmark using local or domestic resources for the years 2030 and 2050 respectively [16],[136].

The EnergyPLAN model is an energy system analysis tool which uses hourly distribution data of energy supply and demand and has the flexibility to model most of the conventional and renewable energy technologies. It also has models of different regulation strategies like Vehicle-to-Grid, heat pumps, electrolysers, energy storages etc. which can be used to negotiate energy system imbalance of the electricity system on an hourly basis. The excess electricity production is an indicator in the EnergyPLAN model to find whether the energy system is self-sustainable [137]. However, in the case of an electricity grid which is multivariable, complex and dynamic, the power system events occur in the range of seconds to minutes. Therefore, the power must be balanced on all time scales in order to ensure secure and stable operation of the electricity grid [63]. The basic indicator for the power balance in an electricity grid is represented by the power system frequency. The hourly simulation models do not consider the short-term or intra-hour events which will have a critical influence on the stability of an electricity network with large wind power penetration, especially when operated in an islanded mode. So it is important to quantify the difference this will have on the resultant energy system analysis, using the hourly simulation model on the CEESA energy planning scenarios.

This chapter intends to verify the technical feasibility of the CEESA scenarios validated by the EnergyPLAN model using the dynamic power system model. It is also intended to improve the model simplifications in the hourly model based on the outcome of this investigation. The technical evaluation here is performed by a comparative analysis of the simulation results for planning scenarios obtained from the hourly (excess electricity production) and the dynamic simulation (frequency stability) models to integrate more wind power in an islanded system. Due to the modeling differences and the large data requirement, a comparative study of energy systems with the two models for the whole of Denmark as an islanded system is not feasible. In order to simplify the analyses in this study, the small Danish island of Bornholm which has almost similar energy system features as that of the mainland Denmark (as discussed in Section 5.2) is considered. As a result, the energy scenarios defined for the whole of Denmark are interpreted and scaled to match the system capacities of Bornholm. Also due to the above limitations of simulation models, the Vehicle-to-Grid system is used in this study as the sole future flexible regulation strategy to support high wind power penetration. This restricts a complete energy system analysis involving the heat, transport and electricity sectors.

7.2 CEESA Planning Scenarios

The CEESA project aims for future sustainable energy systems in Denmark based on renewable energy as the major energy source. The combination of life cycle assessment, system modelling and market analysis methods are used in the project to meet the major challenges of integrating more renewable energy. It includes the integration of transport sector, a power system compatible for renewable energy generation and the development of public regulation in international market [15]. The energy systems developed in the CEESA scenarios for an increased production from renewable energy, demands for an effective interaction of the distributed energy sources with the entire energy systems. The high degree of power balancing flexibility that is essential for integration of large fluctuating renewable energy is facilitated by new regulation strategies and larger interaction introduced across the electricity, heat and transport sectors.

The CEESA scenarios are based on detailed system designs and energy balances for two energy target years: year 2030 with 50 per cent renewable energy as the first step, followed by year 2050 with 100 per cent renewable energy (wind, solar, biomass and wave energy). The “Energy Plan 2030” proposed by the Danish Association of Engineers (IDA) as a result of the “Energy Year 2006”, forms the basis of the CEESA scenarios. Fig. 7.1 illustrates the energy flow diagram of the IDA Energy Plan 2030 which targets energy efficient solutions for energy security, employment creation, higher energy exports and 50% CO_2 emission reduction by 2030 compared to the 1990 levels [138].

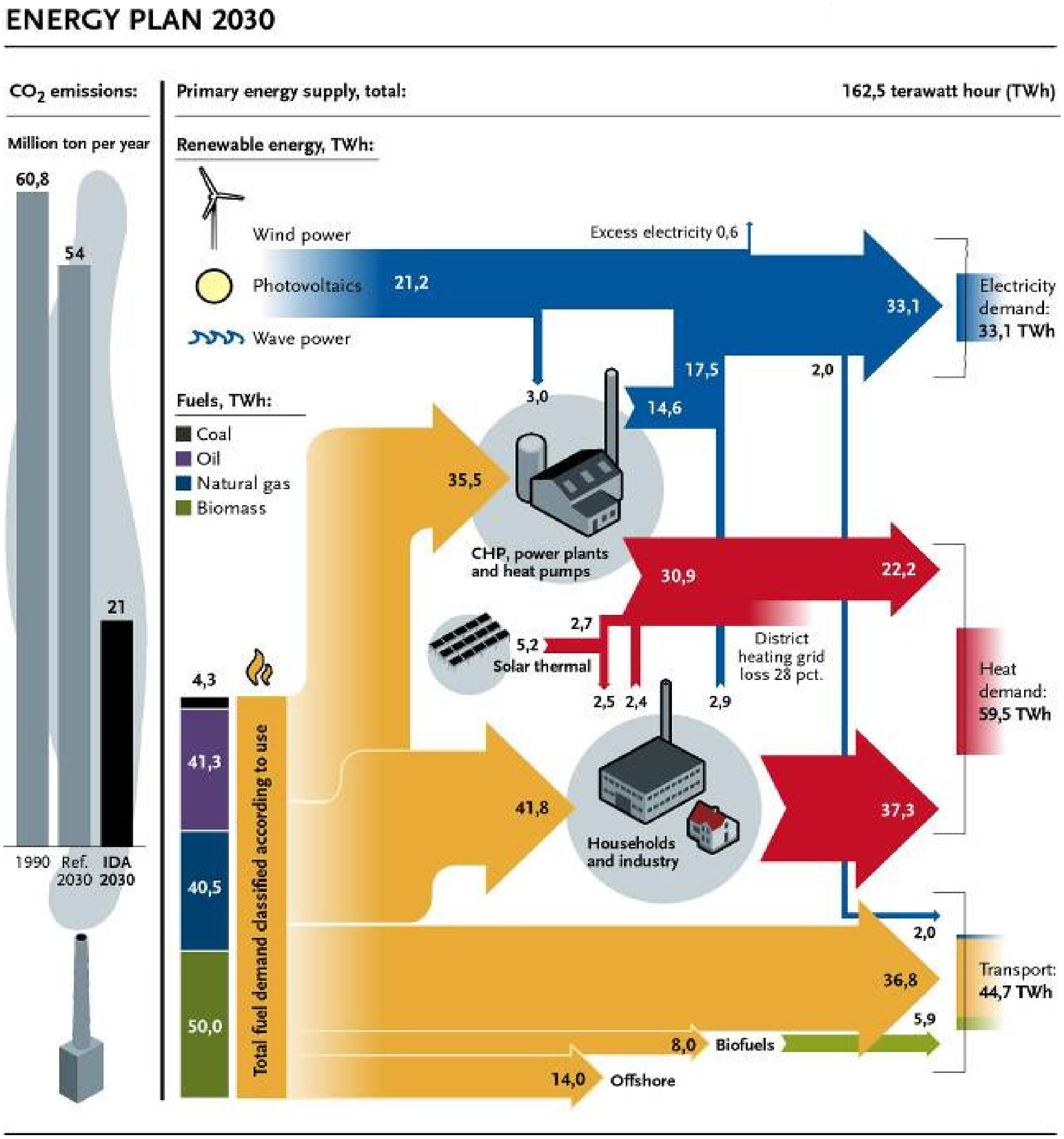

Fig. 7.1 Energy flow diagram of IDA Energy Plan 2030 [138]

Many recommendations and strategies are proposed for energy efficiency and savings in the industry, transportation, business and electricity sectors which significantly includes an estimated 6000MW of wind power installation planned for 2030 [138]. The flow diagram of 100 percent renewable energy system is already presented as Fig 1.3 in Section 1.1.2. The scenarios and energy system analysis are explained in detail in [16], [136], [139]. The results of these studies conclude that the 2030 scenarios are feasible followed by the 100 per cent renewable energy systems from the local resources available within Denmark. This implies that the future scenarios consider Danish energy system to be self sufficient, which could operate in a "connected island" mode [140]. It could be inferred that there won't be any dependence on the interconnections for energy balance in Denmark except for the international trade. The energy balance for 2030 and 2050 Danish energy systems to function as a self sustainable (closed) system were tested and verified using the EnergyPLAN model.

In order to deduce useful conclusions and simplify the comparative analysis between the hourly EnergyPLAN and the dynamic model simulations, only the 2030 scenario is considered here for the energy system analysis. Table 7.1 gives the scenarios for the whole of Denmark scaled to the island of Bornholm. The 2007 data for the Danish mainland has been collected mainly from the Danish Energy Association [141]. The 2007 data of the Bornholm energy systems as given in Section 5.2 of this thesis is used and the Denmark data for the 2030 future scenarios is obtained from the CEESA project database [16], [136], [139]. The electricity demand and generation capacity of Bornholm is found to be less than 1% of the whole of Denmark. The generation capacities and electricity demands of Bornholm for the year 2030 is scaled based on the maximum demand of Denmark 2030. The electricity demand in Bornholm for the year 2030 is assumed to increase in the same proportion as that of the Danish mainland.

The present storage capacities of the battery electric vehicle is varied between 20-30kWh for an average driving range of 100-150 km, the largest being that of TESLA Roadster which has a 53kWh storage [31], [37]. It is expected that the energy capacity of the EV battery storages will increase with time. In this study, the electric vehicles are assumed to have an average battery storage capacity of 80kWh to satisfy the higher driving ranges of 500km and a power line capacity of 10kW for the 2030 scenario [31]. The regulation strategies adopted in the 2030 scenario to incorporate 50% of renewable energy include the static models of heat pumps and flexible demand which includes the off-peak dump charging of electric vehicles in EnergyPLAN.

Out of the total electricity consumption, the heat pump contributes to 7% of the demand, while flexible demand takes 11% to balance the energy system [16], [136]. In the dynamic simulation model, the heat pumps and flexible demand like dump charging of EVs, cooling, heating etc. are added proportionally as additional demand to the reference load curve over the off-peak hours for the 2030 Bornholm scenario.

Table 7.1 Energy scenarios

	Denmark 2007 [141]	Bornholm 2007 (Reference) [106]	Denmark 2030 (CEESA) [135],[136],[139]	Bornholm 2030
Electricity Production capacity (MW)				
Centralised Power Plants	7200	64	4500	38
Decentralised Power Plants	2322	2	1726	12
Wind Power Plants	3125	30	6000	51
Electricity demand				
Total demand (TWh)	36.4	0.24	48.13	0.317
Flexible demand(TWh)	-	-	5.16	0.034
Heat pump (TWh)	-	-	3.14	0.021
Maximum Demand (MW)	6436	55	7962	68.04
Minimum Demand (MW)	2300	13	1702	9.62
Vehicle-to-Grid				
Power connection capacity (kW)	-	-	-	10
Battery energy capacity (kWh)	-	-	-	80

7.3 The EnergyPLAN Model

The EnergyPLAN model is an energy system analysis tool designed for studying energy technologies in large complex systems as well as for areas ranging from small to large national energy systems. The EnergyPLAN model is a deterministic model which provides hour-by-hour calculations of how heat and electricity demand could be met within given regulation strategies and constraints. The model provides the basis for design and evaluation of a flexible energy system that can balance energy supply and demand in electricity, heat and transport sectors. References include [140], [142-145] and the model is described in [135]. The model is available for free at www.energyplan.eu. Fig. 7.2 illustrates the combined energy system analysis model integrating electricity, heat and transport sectors.

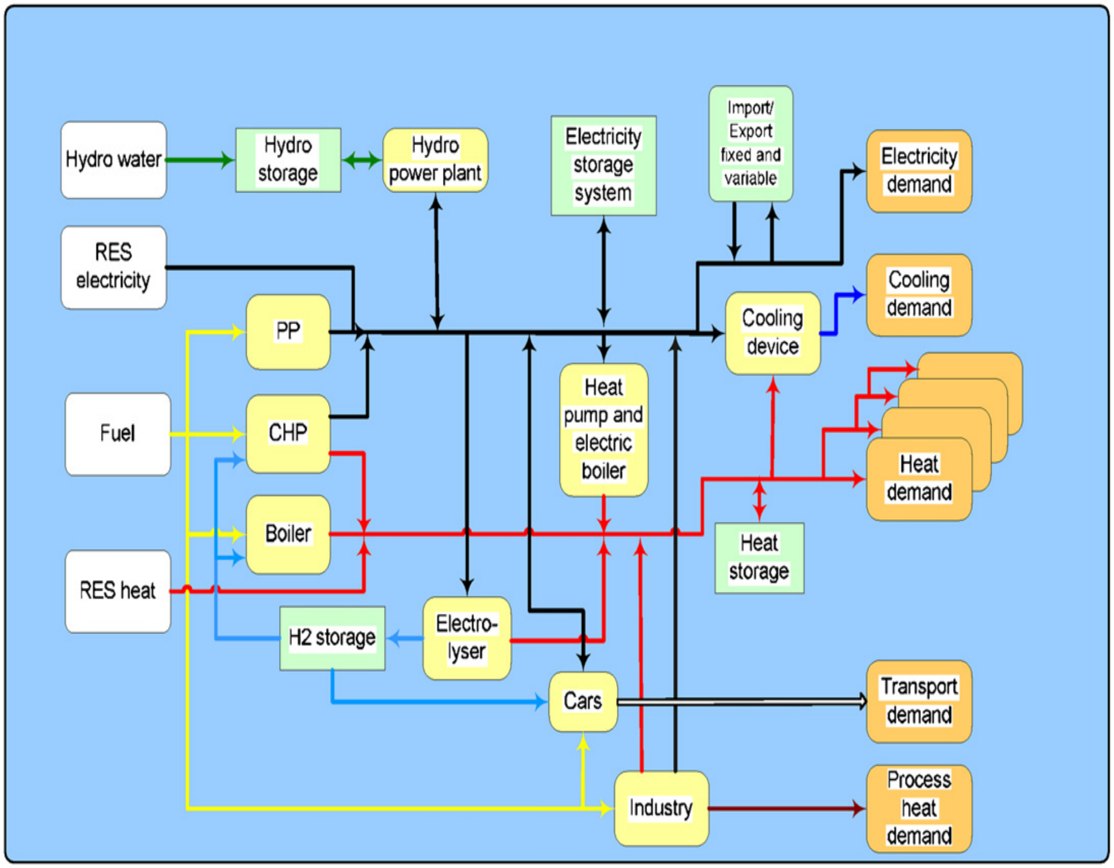

Fig. 7.2 The EnergyPLAN energy system analysis model [135]

7.3.1 Energy system analysis

The EnergyPLAN model analyses the different energy systems, regulation strategies and integrates different mix of energy technologies. Two methods of energy system analyses are available in the model with different optimisation strategies. A market-economic optimisation where the economic costs are minimised and a technical optimisation to find the least fuel-consuming solution is used. The provision of electricity exchange is available for both the strategies by allocating suitable transmission capacity. In the technical optimisation strategy, the electricity is exchanged for technical reasons, whereas for the economic optimisation, the aim is to optimize the profit by participating in external electricity market. However, the transmission capacity and the imports/exports model in EnergyPLAN are aggregated and static which does not account for scheduled power exchange flow in the interconnectors.

Both the regulation strategies give priority to heat and electricity production from the renewable energy sources like wind, solar photovoltaic, wave and geothermal (electricity and heat). The subsequent priority is given to the fuel efficient combined heat and power (CHP) units in the technical optimisation strategy, if they are used in the analyses. In the economic strategy, the priority is given to those units which have short-term marginal costs calculated based on the fuel costs, emission costs and operation and maintenance costs. If the renewable energy generators and CHP units are unable to meet the electricity and heat demand, the deficit is met by the condensing power plants and boilers respectively. In the technical regulation strategy, the model seeks to minimise the condensation power plant production by replacing them with CHP supported by heat storages [111]. When the electricity demand is lower than the electricity production from the renewable energy technologies and heat production dependant CHP, the excess electricity production is minimized by replacing the CHP heat production with heat pumps or even electric boilers or with flexible energy technologies like electrolysers, energy storages, and electric vehicles.

The technical system analysis is used in this chapter, to investigate a closed (islanded) system operation of the Bornholm energy system. The methodology starts with defining the generation capacities and energy demands in the form of heat, electricity and transportation. The hour-by-hour distribution data of load demand and wind profile which are based on actual measurements from the Danish mainland available in the EnergyPLAN data library are used in this analysis. The wind distribution data set supplying the same percentage of the load demand as that for the dynamic simulation model is selected. The result of the technical system study in EnergyPLAN gives the energy balances, CO_2 emissions, fuel consumptions and excess electricity production. The excess electricity production diagram in EnergyPLAN model expresses the ability of the electricity grid to integrate variable renewable energy technologies [137]. If the excess electricity production is zero, it indicates that energy system is capable of regulating itself. The parameter relevant in this analysis is the excess electricity production, which provides the measure of self sustainability of the Bornholm energy system operating in the islanded system.

7.3.2 Vehicle-to-Grid model in EnergyPLAN

In the technical regulation strategy, the Vehicle-to-Grid model in EnergyPLAN is used to minimise the excess electricity production and the amount of power generated from the condensing power plants in the system. The Vehicle-to-Grid model in EnergyPLAN is the key regulation tool used here in this chapter to support high penetration of wind power for the 2030 energy scenario in Bornholm. The V2G systems are modelled in EnergyPLAN as one large battery which is equal to the sum of all individual batteries of the cars which are grid connected. The aggregated battery undergoes charging based on the availability of hourly excess electricity production, available battery energy capacity and grid connection capacity. The amount of charging is dependent on the minimum of the three values mentioned above. This is represented as Equation 7.1 [135].

$$V2G_{charge} = \min(e_{CEEP}, S_{V2G} / \eta_{charge}, c_{V2G}) \qquad (7.1)$$

where e_{CEEP} is the hourly excess electricity production in GWh,

c_{V2G} is the power capacity of the grid connection in MW,

S_{V2G} is the net available battery storage capacity in GWh,

and η_{charge} is the charging efficiency of V2G.

The resultant hourly battery capacity is calculated by adding the above charging and subtracting the discharging caused by driving (E_{EV})[135]:

$$E_S = E_S - E_{EV} + (V2G_{charge} / \eta_{charge}) \qquad (7.2)$$

The charging is also forced if the transportation demand for the next few hours cannot be met by the battery storage capacity or if there is a lack of excess electricity production. The battery may discharge to the grid when required after meeting the transportation demand. In this way, the electricity production from the condensing mode power plants or imports may be substituted by the Vehicle-to-Grid. The discharging capacity is decided based on the minimum of the up-regulation demand, battery storage capacity and V2G connection capacity as given in the following equation [135].

$$V2G_{discharge} = \min(e_{PP}, (S_{V2G} - S_{V2G\_\min})\eta_{dicharge}, c_{V2G}) \tag{7.3}$$

where e_{PP} is the potential replacement of production from condensing power plants in MW, $S_{V2G\_\min}$ is the minimum battery storage capacity for transportation in GWh, and $\eta_{discharge}$ is the discharging efficiency of the V2G.

The resultant hourly battery capacity is calculated as follows [135]:

$$E_S = E_S - (V2G_{discharge} / \eta_{discharge}) \tag{7.4}$$

The initial storage content in the model is defined as 50% of the total storage capacity. The modelling of V2G control strategies are described in detail in Section 6.9 of the EnergyPLAN software manual [51], [135].

7.4 Dynamic simulation model

In an electricity network, the power must be balanced at all time scales to ensure the stable operation and security of the supply. If there is a change in real power demand at one point of the electricity grid, it is reflected everywhere in the system as a frequency deviation. The excess of power in the grid is reflected by a rise in frequency and a deficit of power is represented by frequency drop. Therefore, grid frequency is a basic indicator of power balance in an electricity grid power system. In this chapter, the system performance of the dynamic simulation model is measured and quantified based on its ability to stabilise the power system frequency. A single bus bar representation of the Bornholm power system modelled in DIgSILENT PowerFactory software as discussed in Section 5.4 is used here as the dynamic power system simulation model.

The power ratings, models and control parameters of generators and aggregated battery storage used in Chapter 5 are also applied in this chapter. The large fossil-fuel based CHP generator is operated in isochronous mode for simulations. The Vehicle-to-Grid aggregated storage and other fossil-fuel based generators are operated in the droop mode. The real time series data for short time frame were not available from the Bornholm power system for simulations. Therefore, the load demand and wind power profile of five minutes time resolution for a typical winter day in January which was available from the Danish mainland, is scaled to the Bornholm power system, is used here for simulations.

7.4 Comparing Energy PLAN and Dynamic Simulation Tools

Table 7.2 gives an overall general comparison between the two simulation models. Out of the important characteristics and technical limitations of the two simulation models listed, the main focus in this study is the simulation time-step. As a cut-off criterion for comparing the performance of the two models, the excess electricity production parameter in the EnergyPLAN model and the standard deviation of the frequency in the dynamic power system model is considered. To validate the technical feasibility of the power balance from the EnergyPLAN and dynamic power system model for an increasing penetration of wind power in an islanded system operation, the Bornholm scenarios defined in Table 7.1 is used in this analysis. The power regulation service from the Vehicle-to-Grid system is evaluated for the Bornholm 2030 scenario.

Table 7.2 Comparison of hourly and dynamic simulation models

Characteristics	EnergyPLAN model	Dynamic simulation model
Time-step	Hourly	Seconds
Model type and balancing mode	Deterministic, energy balance in heat, transport and electricity	Deterministic, energy balance in electricity sector only
Generator models	Aggregated and static	Aggregated and dynamic
Grid Interconnection	Single aggregated transmission capacity	Several interconnections possible.
Regulation strategies	Static models of heat pumps, electrolysers, Vehicle-to-Grid systems and flexible demand.	Vehicle-to-Grid model is dynamic, others strategies could be modelled as an additional demand if the short-term consumption profiles are known.
Vehicle-to-Grid regulation	Aggregated battery storage model, meets transportation demand and electricity power balance	Aggregated battery storage model, meets electricity power balance

7.4.1 Technical energy system analysis - EnergyPLAN

The 2007 energy mix of Bornholm as given in Table 7.1 is used here as the reference case for simulations. A reference energy system provides the existing system characteristics which will serve as a benchmark to develop appropriate future energy scenarios. Such a scenario can be used to quantify the ability of future energy technologies and regulation strategies to accommodate high wind penetration in the excess electricity diagram [137]. For both Bornholm 2007 and 2030 scenarios, the impact of Vehicle-to-Grid regulation for increasing wind power penetration is simulated in the EnergyPLAN model. The excess electricity diagram in Fig. 7.3 shows that the annual excess electricity production increases when the wind power capacity exceeds beyond 20MW for the reference scenario.

An excess electricity production is an indication that large wind power is not able to integrate to an energy system without the help of an interconnected power transmission system with neighbouring countries. The 2030 energy systems, including the regulation strategies of heat pumps and off-peak charging of electric vehicles, can accommodate 33MW of the wind as shown in the Fig. 7.3. Next by applying the Vehicle-to-Grid regulation strategy to the 2030 scenarios in steps of different battery power capacities (4MW, 10MW, 16MW), more wind power can be integrated. The actual simulations are performed here by adding battery storages in steps of 2MW which is presented as Table EI in Appendix E. The relevant results are only plotted in Fig. 7.3 to give more clarity to the results and to simplify the simulation cases, so that it can be compared using the slower dynamic simulation model. The aggregated vehicle battery storage of 16MW was found to support 42MW of wind power production in an islanded energy system operation.

7.4.2 Power balancing studies – Dynamic Simulation Model

The nominal acceptable frequency range in the Nordic power system is in the order of 49.9Hz to 50.1Hz [113]. As Bornholm is part of the Nordic power system, it is assumed here that these frequency limits are also followed in the islanded operation. For a quantitative analysis of the power system performance, the standard deviation of the frequency from the nominal 50Hz is calculated using the dynamic power system simulation model for all the scenarios evaluated in the previous section. Fig. 7.4 illustrates the standard deviation (SD) values of system frequency for the 2007 reference, 2030 scenario without V2G regulation and 2030 scenario with 4MW, 10MW and 16MW V2G regulation for an increasing wind power penetration. A standard deviation of not more than 0.1Hz is considered as unacceptable level for a stable and reliable power system operation. The standard deviation of frequency is 0.09Hz for the 2007 scenario with a wind power capacity of 10MW, which is within the acceptable value of 0.1Hz. For 15MW wind power penetration, the SD of frequency has increased to an unacceptable operating level of 0.35Hz. So, the 2007 reference scenario could accommodate 10MW wind into the islanded power system without any additional regulation reserves apart from the conventional fossil fuel based generators.

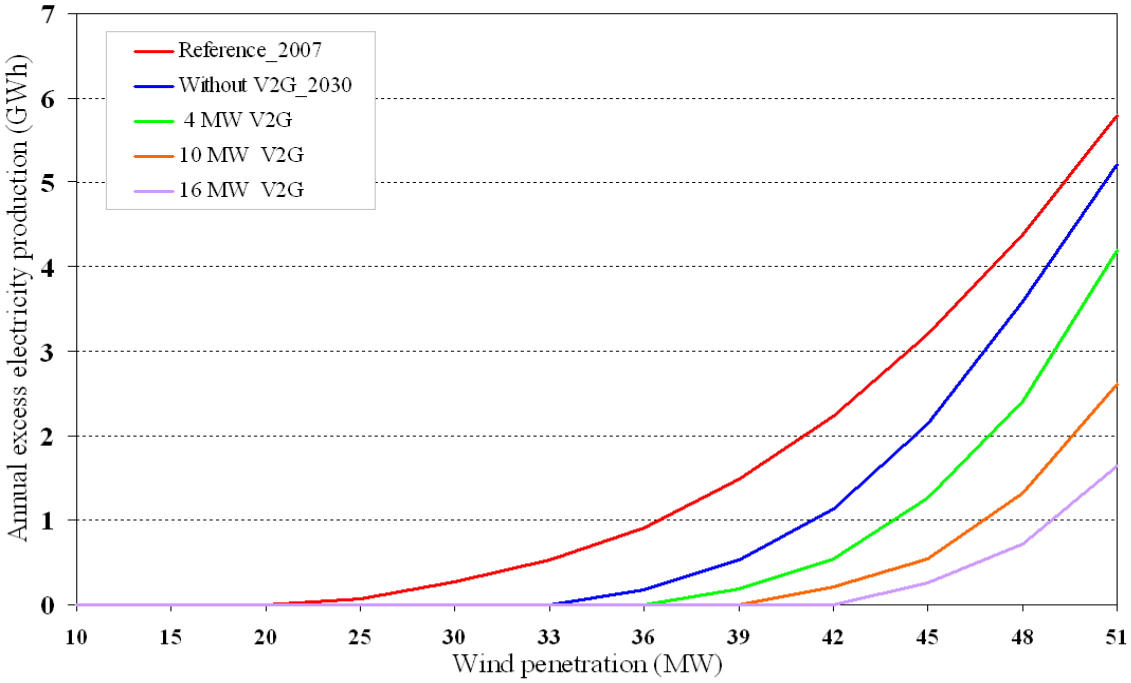

Fig. 7.3 Excess electricity diagram from EnergyPLAN simulations

The 2030 scenario without V2G regulation could integrate a wind power capacity of 20MW. Additional 10MW wind integration in the power system is possible for the 2030 reference scenario due to the increased electricity demand produced by the heat pump regulation and off-peak hour charging loads from the electric vehicles which offsets some of the extra wind power produced. A wind power capacity of 25MW, 30MW and 36MW could be integrated in an islanded power system by maintaining the desired frequency quality by applying the frequency regulation from Vehicle-to-Grid systems of 4MW, 10MW and 16MW power capacity respectively. Fig. 7.5 shows the state of charge of the 10MW dynamic aggregated battery storage for different wind penetration levels. The battery state of charge profile simulated for one day period shows the battery charging process during the off-peak hours of the day. The power system requires down-regulation reserves from the Vehicle-to-Grid storage due to the surplus wind power production during these hours.

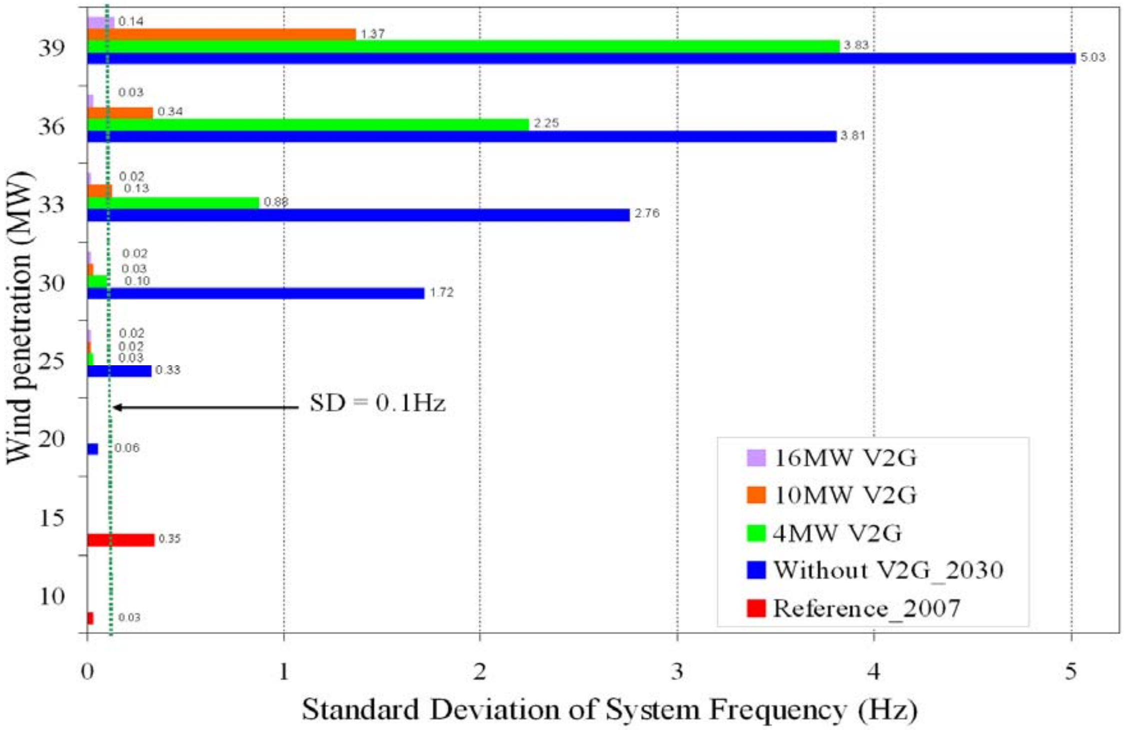

Fig. 7.4 Standard deviation of power system frequency for increased wind penetration

The drop in battery state of charge during the peak demand period indicates the battery discharging mode to provide up-regulation requirement. The battery state of charge remains constant during other periods where the isochronous generator has sufficient regulation reserve to negotiate any power imbalance. The 10MW V2G could integrate 30MW wind in the isolated system as the state of charge remains within the acceptable limits of 20-95%. This result is also evident from the SD of frequency for the 10MW battery storage in Fig. 7.4, where the system frequency is within the operational limits. For a wind power penetration of 33MW, in Fig. 7.5, it can be seen that the upper state of charge limits are reached which in turn exhausts the regulation down capabilities of a 10MW V2G. This is also reflected in the standard deviation of frequency value of 0.13Hz which exceeds the nominal value of 0.1Hz.

To illustrate a comparative analysis of the results obtained so far from the hourly EnergyPLAN and the dynamic simulation model, Fig. 7.6 is plotted for different storage power capacities of Vehicle-to-Grid systems to support increasing levels of wind power penetration for both 2007 and

2030 scenarios. For the 2007 reference scenario, the dynamic simulation results shows that the power system could accommodate 33% of the installed wind capacity which is 50% less when compared to the EnergyPLAN simulations.

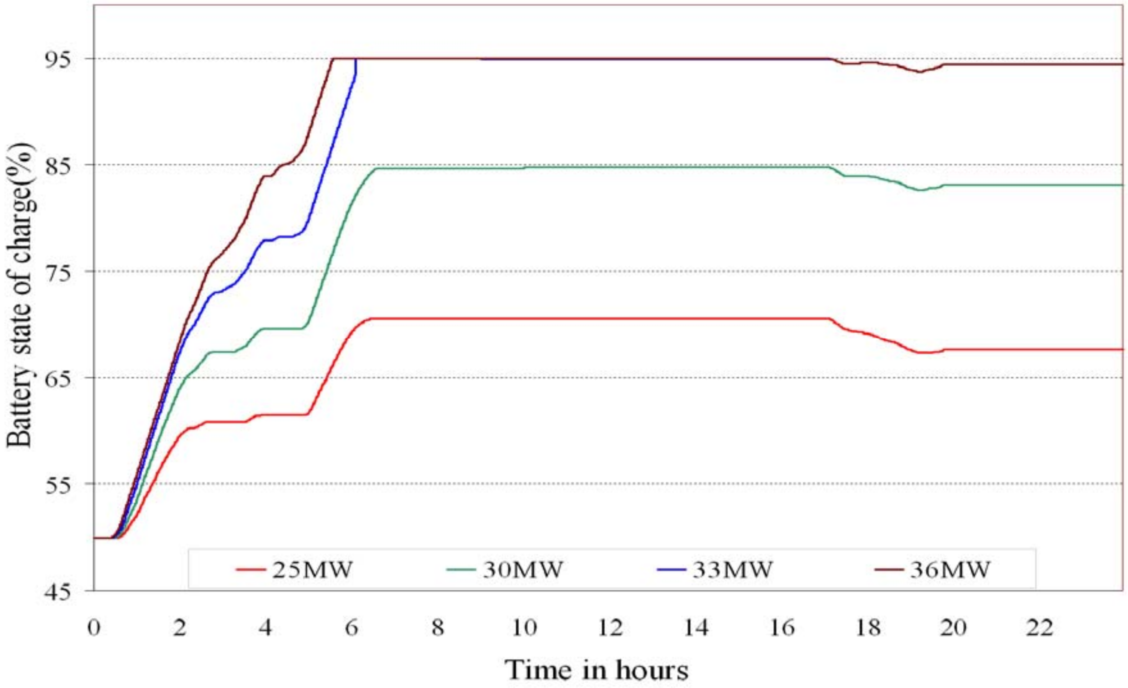

Fig. 7.5 State of charge of 10MW aggregated battery storage from power system simulations – 2030 scenario for different wind penetration

For the 2030 scenario without V2G, the additional electricity demand from the heat pumps and off-peak charging of electric vehicles provide 65% and 39% of wind power capacity utilisation for the hourly and dynamic simulations respectively. When applying the regulation from Vehicle-to-Grid systems, both the models were able to integrate more wind power into the islanded system. For a Vehicle-to-Grid capacity of 16MW, the simulation results from EnergyPLAN supports 82% of the wind penetration, while the dynamic simulation results enable 70% of wind power capacity utilisation in the studied islanded system.

There is a significant difference if we compare the hourly and dynamic simulation results for the scenarios analysed for Bornholm. The islanded system examined in hourly model from EnergyPLAN is based on the criteria of excess electricity production and that using dynamic simulations is based on a larger system frequency deviation (SD>0.1Hz). To conduct similar comparative studies for interconnected systems, the excess electricity production in EnergyPLAN could be compared with power exchange deviations in the dynamic simulation model. However, for such an investigation, the provision for representing different scheduled power exchanges has to be included as a modification to the EnergyPLAN model, instead of the existing single aggregated interconnector. The wind power that could be integrated in the Bornholm scenarios is much lower for the dynamic simulations than from the hourly simulations. The hourly simulations thus provide insufficient criteria to ensure the feasibility of an energy planning scenario. The results show that scenario evaluation tools like EnergyPLAN need to be taken conservatively if used for islanded system operation. The dynamic simulations even in seconds are crucial to ensure stable power system operation and control. The simulations in this work used only five minute average values for the wind data. Thus, short-term power system dynamic characteristics have not been accounted for. The use of time series data with higher time-resolution would provide more accurate simulation results for the islanded system and it is expected that the wind integration capacity will be even more conservative.

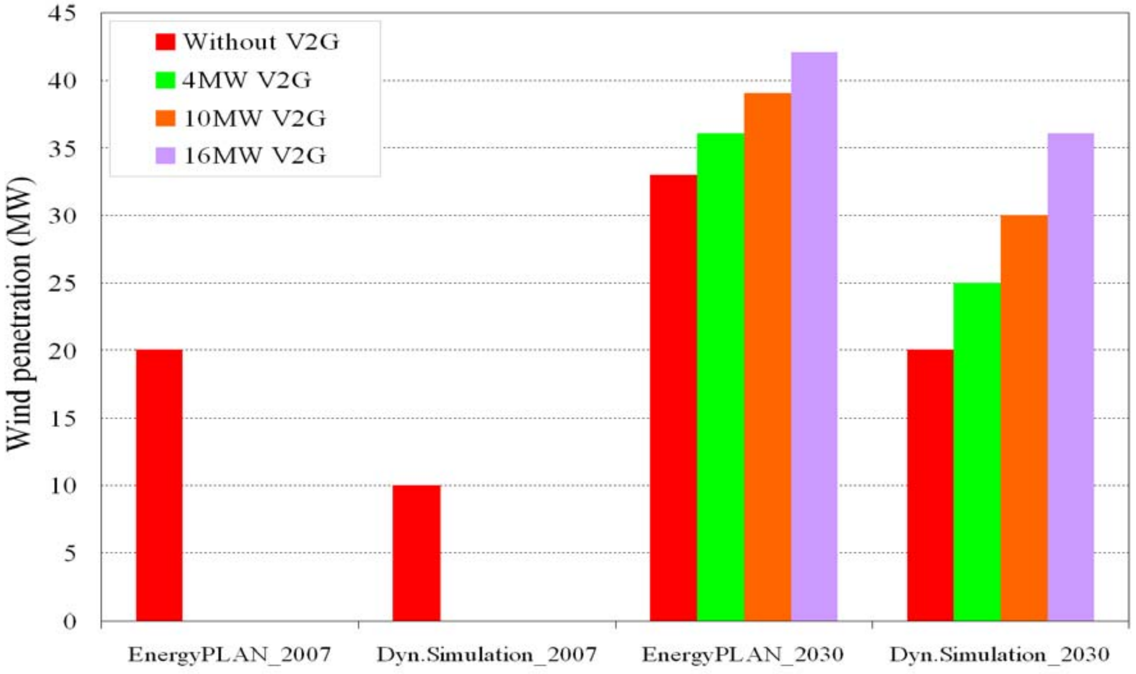

Fig. 7.6 Energy plan vs. dynamic simulations results for Bornholm scenarios

The difference between the results from the two models is reduced with the use of power balancing support from the Vehicle-to-Grid systems. This is because the short-term wind power fluctuations are taken care by the faster dynamics of the Vehicle-to-Grid systems in the dynamic model which continuously balance the wind power variations. This indicates that the electric vehicles will have an important role in future energy system scenarios due to their fast response in comparison to the conventional generators which at present are the main source of balancing power. To improve the intra-hour regulation capability of the EnergyPLAN model, instead of technical optimisation strategy, a grid stabilisation share must be allocated to the energy storage capacity of the Vehicle-to-Grid systems. This share would depend on the storage capacity, energy mix and the system interconnection type.

7.5 Summary

This chapter has compared the power balancing results from two different simulation models for an islanded system operation of Bornholm to integrate large amounts of wind power. The first model, EnergyPLAN considers power balancing on an hourly scale. However, in a real power system, the operation and control is highly dynamic and complex due to very short-term events that occur in electricity consumption and generation. This necessitates the power balancing to be maintained in all time frames. The second model uses a dynamic simulation model of Bornholm power system which takes into account the intra hour variations in wind power and system demand. To compare the results of the two models the excess electricity production parameter in the EnergyPLAN model and the standard deviation of power system frequency in the dynamic models were used.

The 2007 energy mix of Bornholm was considered as the reference scenario in this study to validate the right energy balance in EnergyPLAN. As the next step, the future 2030 (CEESA) scenarios representing high penetration of wind power supported by the power balancing services (regulation) from the Vehicle-to-Grid systems were analysed. The wind power capacity integration from the dynamic simulation results is around 50% less than what is achieved from the hourly simulation results for the scenarios analysed without V2G regulation. If the V2G regulation is implemented, more wind power production is feasible. As a resultant case, a wind power penetration of 82% and 70% is possible with the support of 16MW V2G for the simulation results of the hourly and the dynamic models respectively.

However, there is a large mismatch between the results from the two simulation models, where the levels of wind power integration is much lower for the dynamic model. It could be inferred that the technical feasibility of the future energy planning scenarios cannot be validated or justified by the hourly simulation models which does not include any system dynamics. The criterion becomes more conservative for the islanded systems like Bornholm with large amounts of wind power where the system stability is more sensitive to smaller changes of demand or generation. The use of power regulation support from the Vehicle-to-Grid systems has reduced the difference between the results of the two models. This illustrates the ability of faster Vehicle-to-Grid systems in improving the short-term power balancing with large wind power variations in the dynamic power system model. To improve the capability of the EnergyPLAN model in representing the intra-hour balancing from Vehicle-to-Grid systems a grid stabilisation share must be allocated to the battery storage capacity. Similarly, this feature could also be applied to other flexible regulation solutions like heat pumps, electrolysers and other storage types which could provide short-term balancing of renewable energy technologies.

Chapter 8

Conclusions and Future Work

8.1 Summary

This thesis has analysed the use of battery storage of electric vehicles which is represented as Vehicle-to-Grid systems to provide one of the important ancillary services like active power balancing reserves in the future power system operation with large amounts of wind power in Denmark. The future power systems will be characterised by lesser conventional generation reserves and higher variability and unpredictability of power generation from large amounts of wind power. The objective of the whole investigation in this thesis is to validate the performance of Vehicle-to-Grid systems over the conventional generators in providing grid power regulation. This is analysed in this research work as different case studies listed below, by performing static and dynamic simulations in the DIgSILENT Power factory software.

1. Vehicle-to-Grid systems as primary reserves to maintain the frequency stability of a distribution network operating in an islanded mode.
2. Vehicle-to-Grid systems as secondary reserves to minimise the power exchange deviations between two control areas in an interconnected power system.
3. An analysis to quantify the reserve power replacement by the Vehicle-to-Grid systems from the conventional generators and the battery storage capacity for a stable islanded wind power system operation.
4. Evaluation of the potential impacts of the new electrical loads like electric vehicles on the stable operation of a distribution network.
5. Validation of hourly based energy planning tools and future scenarios in a renewable energy dominated energy system by dynamic power system simulations.

8.2 Conclusions

The different case studies in this thesis have been analysed on typical Danish power and distribution networks which are characterised by high penetration of wind power generation. In the present Danish power system, the strong interconnections with neighbours, efficient international trading and large power plants have so far accommodated the massive power in-feed from the variable and uncertain power generation from the wind turbines. However, this remains challenging and a cause of concern for the power markets and the stable and reliable operation of the power system. The introduction of more wind power replacing the large conventional power plants in Denmark and the limited expansion of interconnections, demands for new solutions of managing such large intermittent power generation. To integrate a higher share of wind power, the electrical infrastructure and energy systems should be made flexible and intelligent. The decision making and active control has to be decentralised to several intelligent sub-grids coordinated by information and communication technology.

The sub-grid structures planned at the distribution levels with local intelligence can ensure efficient use of local distributed energy resources. In addition to the intelligent grid, flexible distributed generation, consumption and storage units utilised across the heat, electricity and transport sectors with smart controls can facilitate the efficient operation of these sub-grids. The transport sector utilising electric vehicles and heat pumps in heat sector can offer this flexibility when integrated with the electrical grids. To verify these concepts, there is an increased interest among utilities, industries and scientific community for testing and operating the electrical distribution networks as self-sustainable systems with the support of local balancing solutions. The interdisciplinary planning projects like CEESA estimate that Denmark can be self-sustainable with renewable energy systems based on distributed and local resources. This research work is a part of the CEESA project where the use of electricity storage capacity and demand response of electric vehicles are investigated to support large scale integration of wind power in Denmark.

In this thesis, the role of Vehicle-to-Grid systems to act as a power balancing source to support large amounts of wind power is verified in both interconnected mode and islanded mode of power system operation. Some worst case simulation scenarios are analysed in different case studies in this thesis which were defined to differentiate the flexibility of Vehicle-to-Grid systems over the conventional generator reserves in providing power regulation services. The aggregated battery storage model of electric vehicles is developed in this thesis to represent Vehicle-to-Grid systems in the simulation case studies. A static generator model representing the battery storages and the CHP models in the Power Factory software are modified in this thesis to operate in droop and isochronous modes respectively for islanded operation. The long-term dynamic simulation model of aggregated battery storage developed in this project has the capability to represent state of charge limits and storage duration. A conventional Load Frequency Control (LFC) model is modified to integrate the Vehicle-to-Grid systems for interconnected operation. The steam and gas turbine models used in short-term dynamic studies are modified to provide the generation rate constraints in the LFC model.

From the simulation results of the case study on an islanded Danish distribution network, it has been shown that the Vehicle-to-Grid systems provide a faster and a more stable frequency control than the conventional generation units. The case study was analysed with 48% and 65% of wind power penetration scenarios and power systems events like step load change and loss of generation. The Vehicle-to-Grid systems working as primary reserves can operate as either controllable load or as generation based on the balancing power requirement. It is observed that this flexible solution of the Vehicle-to-Grid systems for frequency stabilisation provides a lower rate of change of frequency and frequency nadir when compared to the case operated with conventional generators alone for the different scenarios simulated in the case study.

The application of Vehicle-to-Grid systems as secondary regulation reserves were examined for both low wind and high wind scenarios in the strongly interconnected Western Danish power system. The scenarios were characterised by large power exchange deviations and continuous up-regulation or down-regulation power requirements. The integration of Vehicle-to-Grid systems in the Load Frequency Control has demonstrated that it could substantially minimise the power exchange deviations between West Denmark and the UCTE control areas (within acceptable limits of ±50MW) when compared to the case using the conventional generators alone. The regulation power requirements from the conventional generators are also greatly reduced with the integration of a V2G systems participating in Load Frequency Control. This reiterates the fact that the operating characteristics like fast ramping and quick start capabilities of battery storages can give a better performance than that from the conventional generators for providing power system ancillary services. If a storage duration of four hours and a power connection capacity of 10kW per electric vehicle is assumed, then less than 10% of the total Danish vehicle fleet when converted to V2G based vehicles is sufficient enough to satisfy the regulation needs of the examined scenarios.

To determine the qualitative and quantitative analysis of the power system performance using the Vehicle-to-Grid systems, a simulation case study for an islanded power system of Bornholm was considered. The worst case operation scenarios of high reserve power requirements, battery storage constraints, periods of coincident system peak demands and wind ramps were analysed. A droop control and a conventional PI control with a high pass filter are the two control strategies applied for the Vehicle-to-Grid systems. It was inferred from the results that a battery power capacity of 30-40% of the installed wind power capacity is the minimum requirement for a stable power system operation for the studied case. This approach could be applied for similar islanded power systems or distribution systems planned for intentional islanded operation, where wind farms are clustered in small geographical areas. More than 80% of conventional generation reserves could be replaced by the V2G systems in the studied case performing the power system regulation services. The overall generation control efficiency can be improved in a wind dominated power system like Bornholm using a quick response V2G frequency regulation as compared to the conventional power plant reserves.

In order to evaluate the impacts and penetration levels of electric vehicles in a distribution network operation, a case study was simulated by adding electric vehicles in the order of 0-50% of total vehicle fleets as additional loads in the primary distribution network of Bornholm. It was observed that the integration levels of electric vehicles depend on the various safe operational limits of power system network parameters and methods employed for battery charging from the grid. The voltage drops in the network is more critical than the line loading for the same level of electric vehicle (EV) integration as obtained from the simulation results. The controlled charging is more effective than uncontrolled charging for integrating more electric vehicles. Only 10% integration of EV was possible with uncontrolled charging in the studied distribution network. The controlled charging can integrate 40% of the electric vehicles in the studied case which could be implemented by utilising smart grid infrastructure. The levels of EV penetration may vary for other networks, especially when analysed in low voltage secondary network which may yield more conservative results. The other intelligent strategy include the use of home automation networks, where the demand response of household loads could control the electric vehicle charging without overloading the local distribution system. It is important for the utilities and distribution companies to conduct distribution level analyses to identify the integration levels and charging patterns of electrical vehicles that may need remedial actions.

The last case study in this thesis was to conduct a comparative analysis of the results obtained from hourly and dynamic simulation models to validate future energy planning scenarios. The percentage wind power that could be integrated in the Bornholm scenarios is much lower for the dynamic power system simulations than for the hourly simulations from the EnergyPLAN software tool. The wind power integration feasible from the dynamic results is about 50% lesser than what is obtained from the hourly simulation results for the scenarios analysed without V2G regulation. Hourly simulations thus provide insufficient criteria to ensure the feasibility of an energy scenario. If the V2G regulation is implemented, more wind power production is feasible. A wind power penetration of 82% and 70% is possible for a case with Vehicle-to-Grid power capacity of 16MW, as obtained from the simulation results of hourly and dynamic models respectively. The difference of results between the two models for the wind penetration levels has reduced when the fast and quick start Vehicle-to-Grid systems are applied which accounts for the intra-hour power balancing of the wind variations. Considering this significance of Vehicle-to-Grid systems in the future flexible energy system, a grid stabilisation share must be allocated to the energy storage capacity of the Vehicle-to-Grid model in the EnergyPLAN software. This will provide the EnergyPLAN model with intra-hour regulation capability to accommodate short-term power balancing of the variable wind power, thus improving the model performance in validating future renewable systems based energy planning scenarios.

The results of the case studies (1-3 and 5) have shown that the Vehicle-to-Grid systems gives better performance than the conventional generation sources for balancing the power system with high levels of variable wind power. The Vehicle-to-Grid systems possess fast, quick start and flexible characteristics to provide smooth and robust grid regulation services which could be considered as one of the attractive alternative for replacing the conventional power reserves. The Vehicle-to-Grid systems can operate both as a flexible generation and consumption unit ensuring stability and reliability of the electricity grid. The methods, scenarios and control strategies used in this thesis on selected Danish electricity networks can be representative in applying the ideas to other similar small and large power systems, where large amounts of wind power integration is desired. The Western Denmark and Bornholm power systems used as test cases in this thesis could be regarded as the ideal electricity systems to validate the interconnected and islanded system operation with large wind penetration respectively. However, the analyses could differ for electrical networks which has major share of power generation from other conventional generation like hydro, nuclear etc. and storage units like pumped hydro storages.

The various percentages obtained as results of the case studies in this thesis are more specific or dependent on the selected Danish electricity networks. It is hard to generalize the results as it may vary or may produce more conservative outcome when analysed on different networks. Some of the limitations implied in the case studies like the use of aggregated models, time-series data resolution of five minutes, primary distribution network analyses could also limit very accurate results. Instead, it could provide fairly reasonable results and trends which can act as "working tools" to simplify the complexity of multivariable and dynamic power system analyses. This could act as a base or reference case for final synthesis of future power system planning and operation. The driving patterns, storage capacity and charging/discharging patterns of electric vehicles are uncertain and are difficult to predict accurately. A very detailed study is necessary on several electricity networks, especially in local distribution networks not only to find the impacts of Vehicle-to-Grid systems, but also to study the diversity of electric vehicles in a geographical area. The extent of electric vehicle penetration as a load or a generator also depends on the robustness and the type of electrical networks. In a weak network, if many cars are grid connected at once, it can cause relatively large changes in the voltage levels which could exceed statutory operating limits. On the other hand, such large load and generation changes will have less effect in a strong network. This constraint on the weak networks could be solved by the phased switching of electric vehicles utilising smart grid infrastructure. The impacts of integrating more electric vehicles on the radial distribution type could potentially be greater than on the meshed networks. The net amount of vehicles that will be available during a particular time for demand response or generation in an area are thus dependent on the type and limits imposed by the electricity networks as well as the uncertainties caused by both spatial and temporal diversity of the EVs . Considering the above constraints, an effective optimisation methodology has to be fully developed on behalf of the aggregators and utilities to efficiently coordinate and use the Vehicle-to-Grid systems to provide the desired grid-scale regulation services.

8.3 Future Work

Some other interesting and relevant topics were identified during the course of this thesis work. The important research topics that could be considered for further investigation are listed as follows.

1. To develop a probabilistic model of the electric vehicles based battery storage for grid balancing services taking into account the transportation statistics, battery storage constraints, temporal and spatial diversity of the electric vehicles. An optimal control strategy to coordinate a fleet of electrical vehicles by the aggregator to meet the grid ancillary services requirement.

2. A study to analyse the degradation of the Vehicle-to-Grid battery storages participating in ancillary services and the impact of large penetration of electric vehicles on the power regulating market.
3. A stochastic analysis on the impact of Vehicle-to-Grid systems on secondary low voltage distribution networks. The investigation must include the load estimation of electric vehicles based on different charging profiles and vehicle usage.
4. Algorithms to utilise demand response strategies to accommodate smart control of household loads including electric vehicles to maintain the power system stability of the distribution system.
5. Investigation of other applications and issues of electric vehicle integration in the distribution network which includes the voltage control capability of Vehicle-to-Grid systems, short circuit studies, power quality issues like harmonics and unbalancing, reassessment of protection schemes resulting from reverse power flow and islanding.

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List of Publications

1. Jayakrishnan R. Pillai, Kai Heussen and Poul Alberg Østergaard, "Comparative analysis of hourly and dynamic power balancing models to validate future energy scenarios," *Energy*, 2010, EGY-D-10-00628, (Status: *Submitted*).

2. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Impacts of Electric Vehicle Loads on Power Distribution Systems," in *Proc. IEEE Vehicle Power and Propulsion Conference*, Lille, 01-03 Sept. 2010.

3. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Vehicle-to-Grid Systems for Frequency Regulation in an Islanded Danish Distribution Network," in *Proc. IEEE Vehicle Power and Propulsion Conference*, Lille, 01-03 Sept. 2010.

4. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Vehicle-to-Grid for islanded power system operation in Bornholm," in *Proc. IEEE PES General Meeting*, Minnesota, 25-29 July 2010

5. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Integration of Vehicle-to-Grid in Western Danish Power System," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 1, pp. 12-19, Jan. 2011.

6. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Electric Vehicle based Battery Storages for future power system regulation services," in *Proc. Nordic Wind Power Conference*, Bornholm, 9-10 Sept. 2009.

7. Jayakrishnan R. Pillai and Kai Heussen, "Bornholm as a Model for 100% renewable Energy Scenarios in Denmark," in *Proc. Nordic Wind Power Conference*, Bornholm, 9-10 Sept. 2009.

8. Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Vehicle-to-Grid in Danish Electric Power Systems," in *Proc. International Conference on Renewable Energies and Power Quality*, Valencia, 15-17 April 2009.

Appendix A

Table AI Generator data

Parameters	**CHP1**	**CHP2**
Type of generator	Synchronous	Synchronous
Number of Parallel Machine	2	1
Generator Transformer	25 MVA, 50/10.5 kV	10MVA,50/10.5kV
Rated Power, (MW)	10	4
Rated Voltage, (kV)	10.5	10.5
Stator resistance, (p.u.)	0.002	0.05
Stator reactance, (p.u.)	0.05	0.1
Synchronous reactance d-axis, (p.u.)	2.33	1.5
Synchronous reactance q-axis, (p.u.)	2.1	0.75
Transient reactance d-axis, (p.u.)	0.173	0.256
Sub-transient reactance d-axis, (p.u.)	0.159	0.168
Sub-transient reactance q-axis, (p.u.)	0.159	0.184
Transient time constant d-axis, (sec)	0.822	0.53
Sub-transient time constant d-axis, (sec)	0.03	0.03
Sub- transient. time constant q-axis, (sec)	0.013	0.03
Inertia time constant, (sec)	4	2
Isochronous gain constant, (p.u.)	10	-
Isochronous time constant (sec)	1	-
Governor droop, R , (p.u.)	-	0.047
Fuel system lag time constant 1, T1, (sec)	0.4	0.4
Fuel system lag time constant 2, T2, (sec)	0.1	0.1
Load limiter time constant, T3, (sec)	3	3
Ambient Temperature Load Limit (p.u.)	1	1
Temperature control loop gain, Kt, (p.u.)	2	2
Minimum valve positions, Vmin, (p.u.)	0.3	0.3
Maximum valve positions, Vmax, (p.u.)	1	1
Turbine damping factor, Dturb, (p.u.)	0	0

Table AII Load data

	Load 1	Load 2	Load 3	Load 4
P (MW)	7.67	4.83	7.9	2.0
Q (Mvar)	4.25	2.85	2	0.6

Table AIII Wind turbine-generator data

Parameters	**WTG**
Type of generator	Asynchronous
Generator Transformer	10 MVA, 10.5/0.7 kV
Rated Power, (kW)	2000
Rated Voltage, (kV)	0.7
Stator resistance, (p.u.)	0.01
Stator reactance, (p.u.)	0.1
Mag. Reactance, (p.u.)	3
Rotor Resistance , (p.u.)	0.01
Rotor Reactance, (p.u.)	0.1
Inertia Time Constant, (sec)	1.5

Table AIV Line data

Parameters	**Line 1,2 &3**
Voltage, (kV)	50
Pos. Seq. Resistance, (Ω)	0.890
Pos. Seq. Reactance, (Ω)	1.330
Pos. Seq. Capacitance, (μF)	0.582
Zero Seq. Resistance, (Ω)	3.020
Zero Seq. Reactance, (Ω)	3.450
Zero Seq. Capacitance, (μF)	0.599

Table AV Static generator data

Parameters	**V2G**
Total active power (MW)	1
Dead band (Hz)	0.01
Droop (MW/Hz)	2
Initial load (p.u.)	0.4
Maximum power limit, P_max (p.u.)	1
Minimum power limit, P_min (p.u.)	-1
Active power controller gain, Kp (p.u.)	0.75
Active power controller time constant, Tp (sec)	1

Appendix B

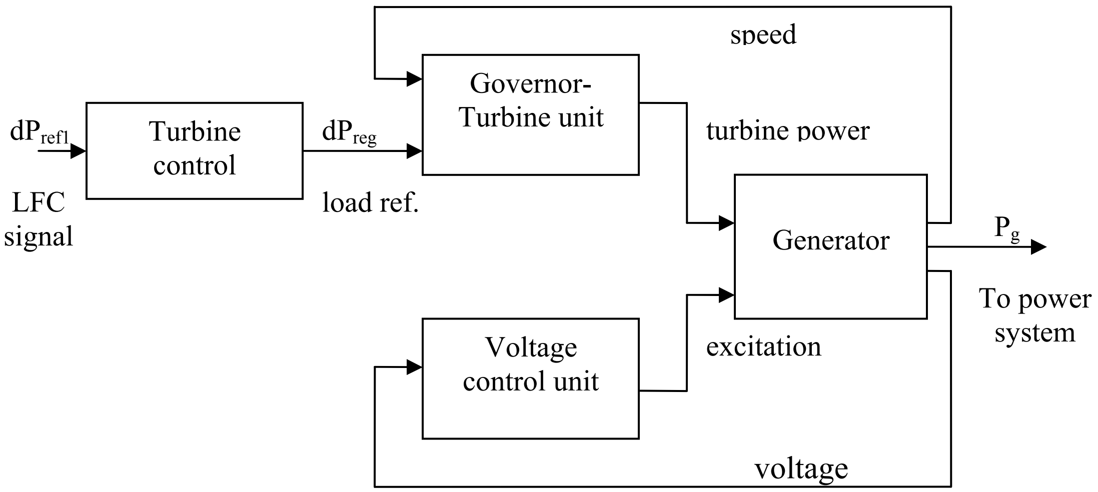

Fig. B.1 Aggregated model of generator participating in Load Frequency Control

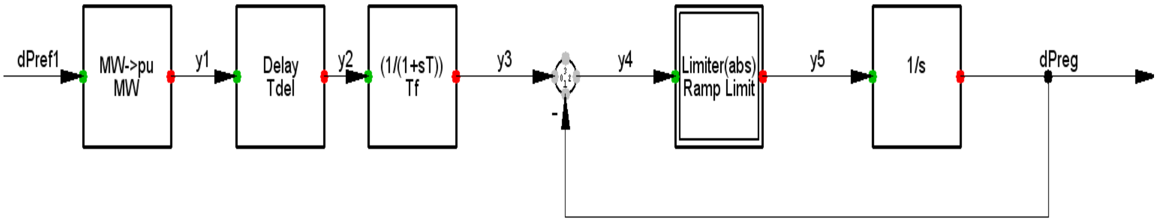

Fig. B.2 Turbine control block in DIgSILENT

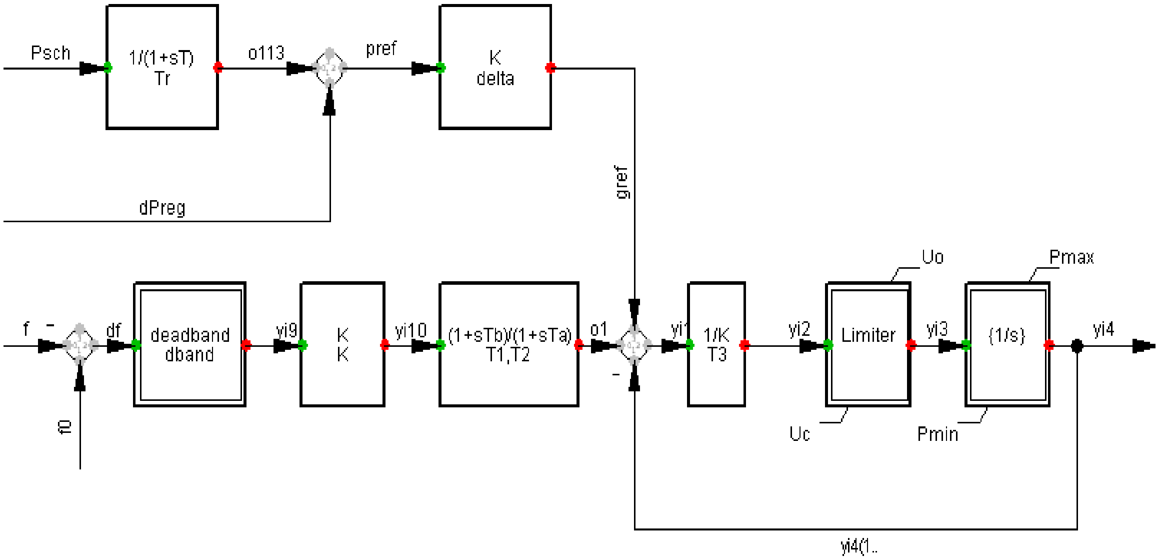

Fig. B.3 Generic IEEEG1 governor model – Centralised steam turbine power plant

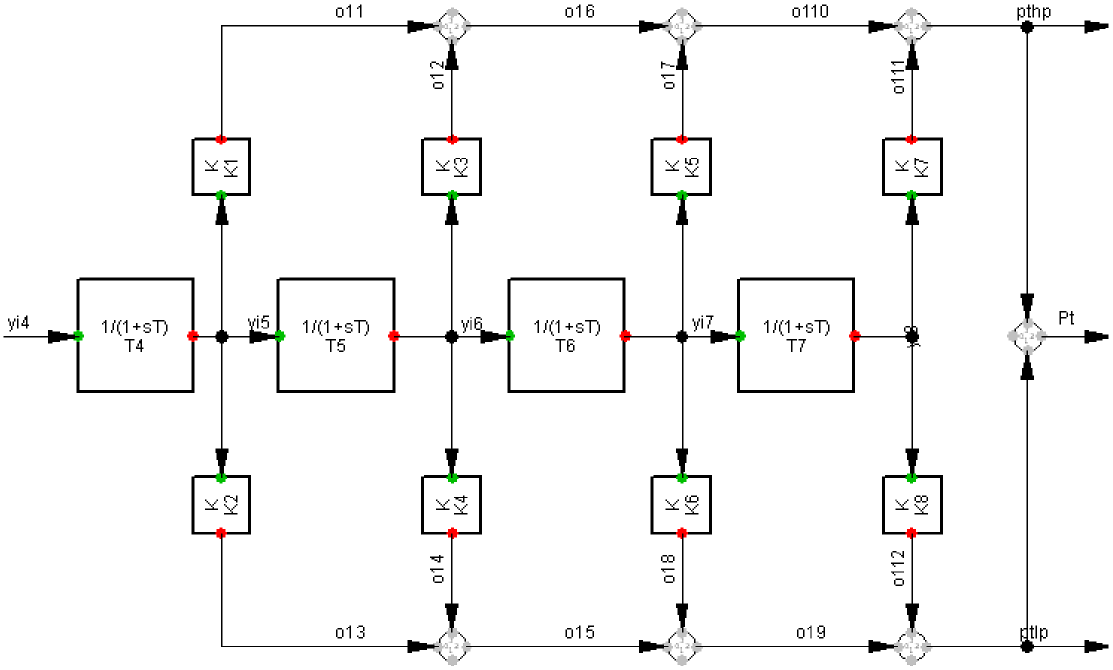

Fig. B.4 Generic IEEEG1 turbine model – Centralised steam turbine power plant

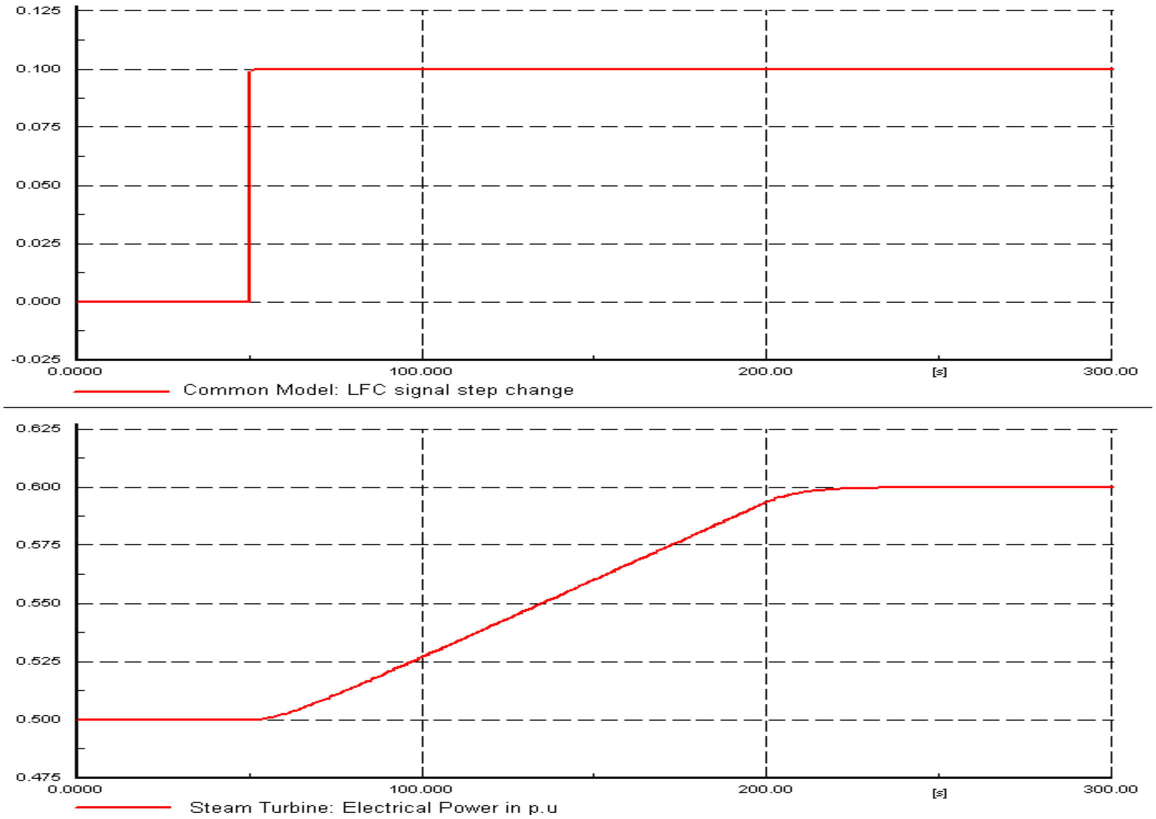

Fig. B.5 Steam power plant response to a step LFC signal of 0.1 p.u.

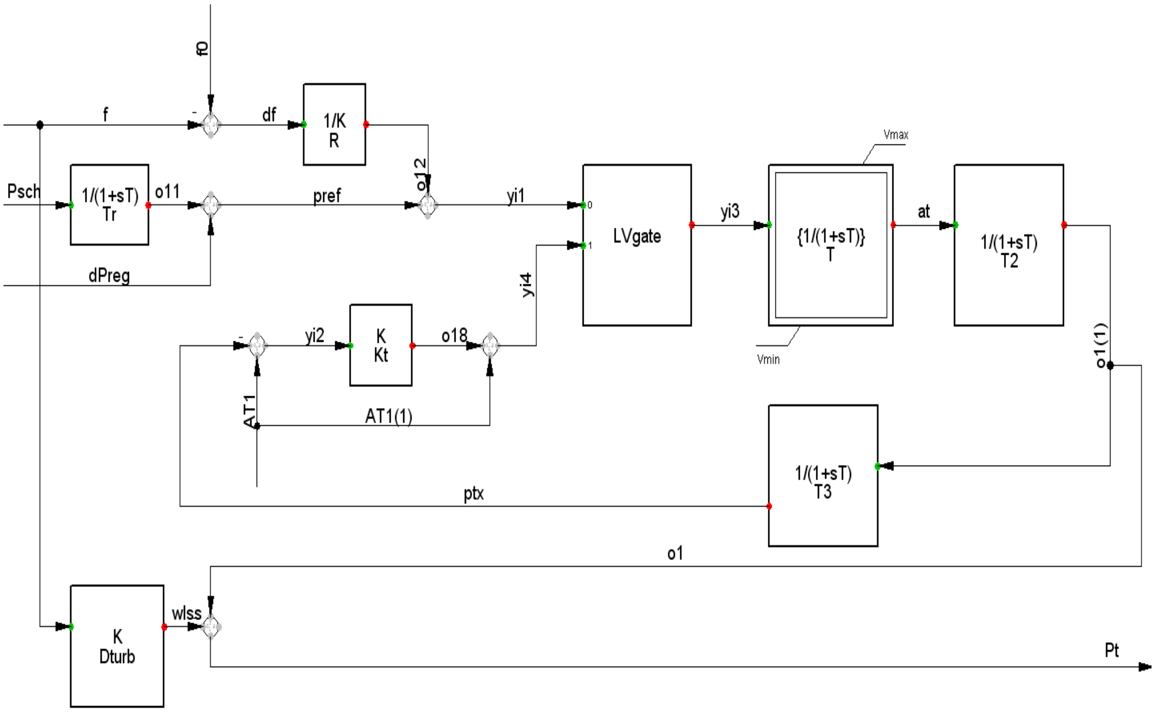

Fig. B.6 Generic GAST Governor-Turbine model – Decentralised Gas Turbine Power Plant

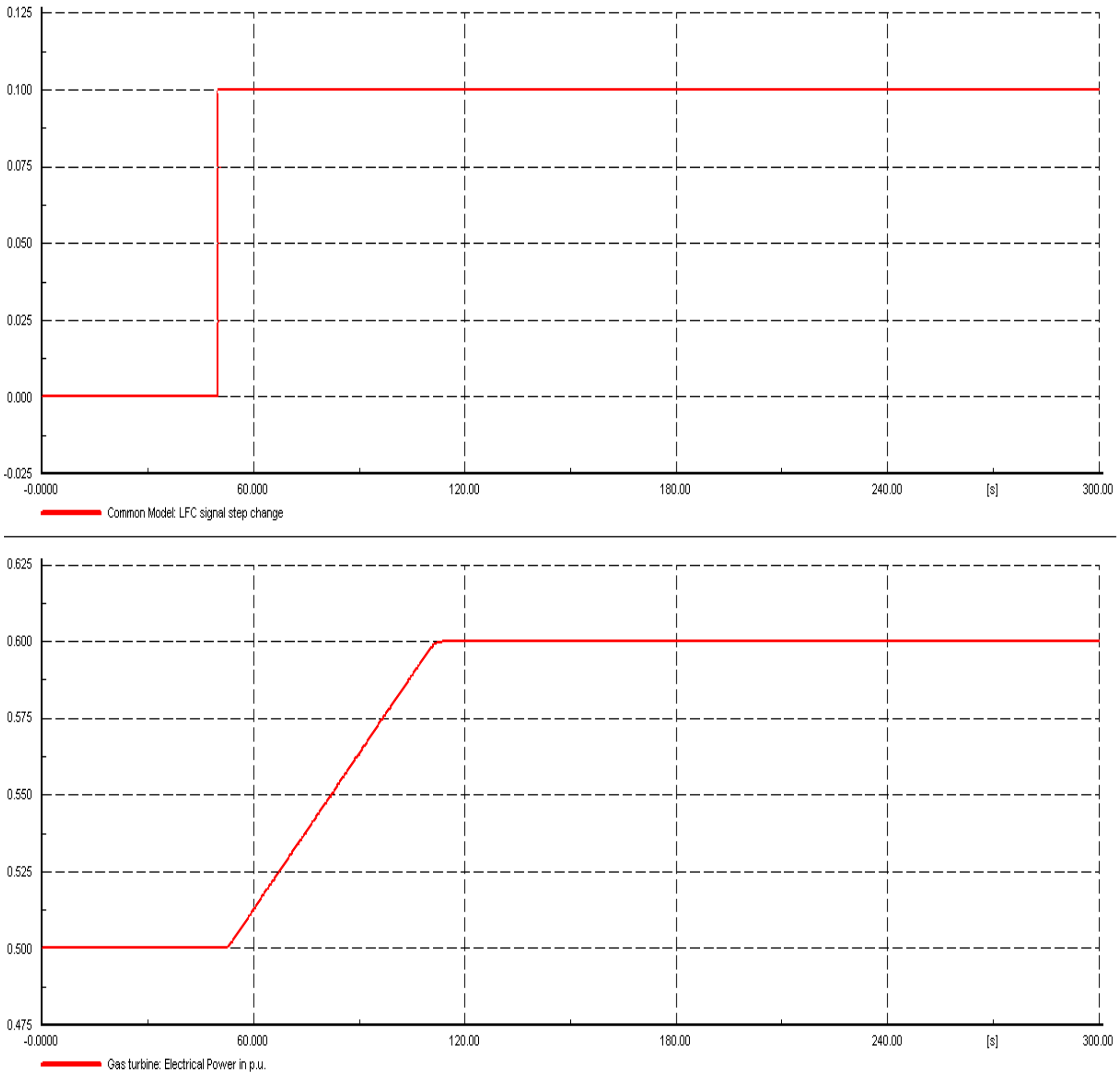

Fig. B.7 Gas power plant response to a step LFC signal of 0.1 p.u

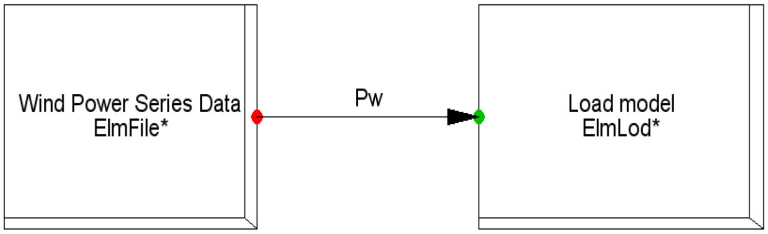

Fig. B.8 DSL Model - Aggregated Wind Power

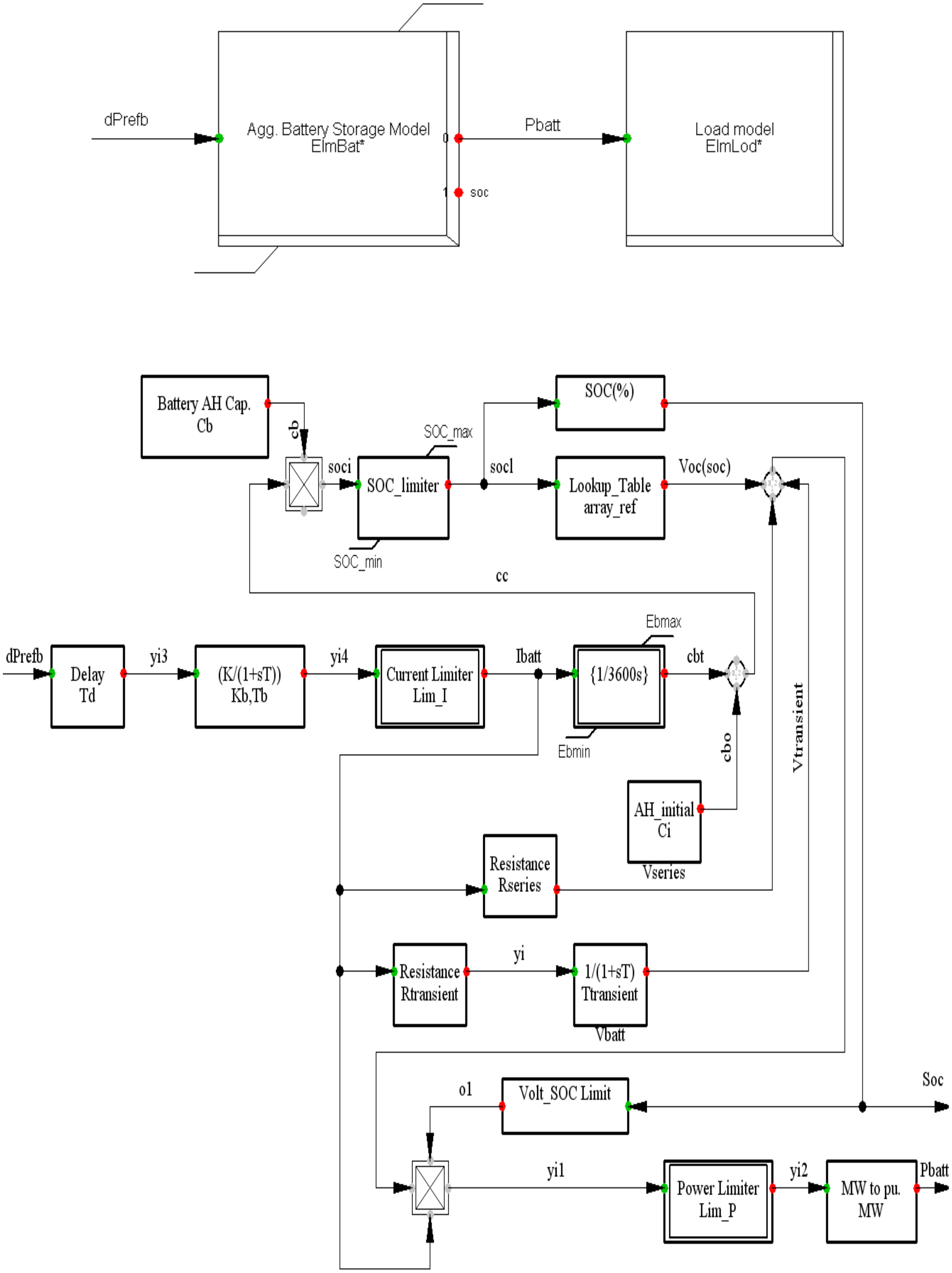

Fig. B.9 DSL Model - Aggregated Battery Storage model

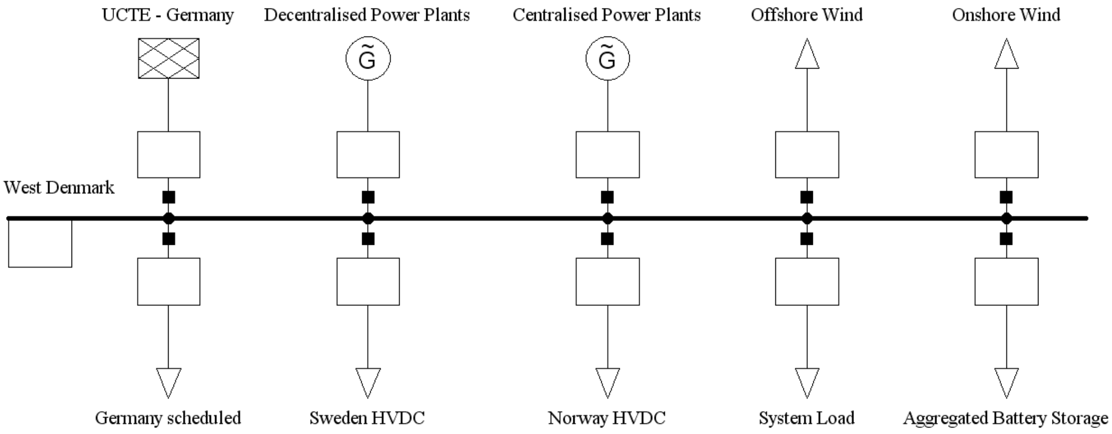

Fig B.10 Single bus bar model – West Denmark power system

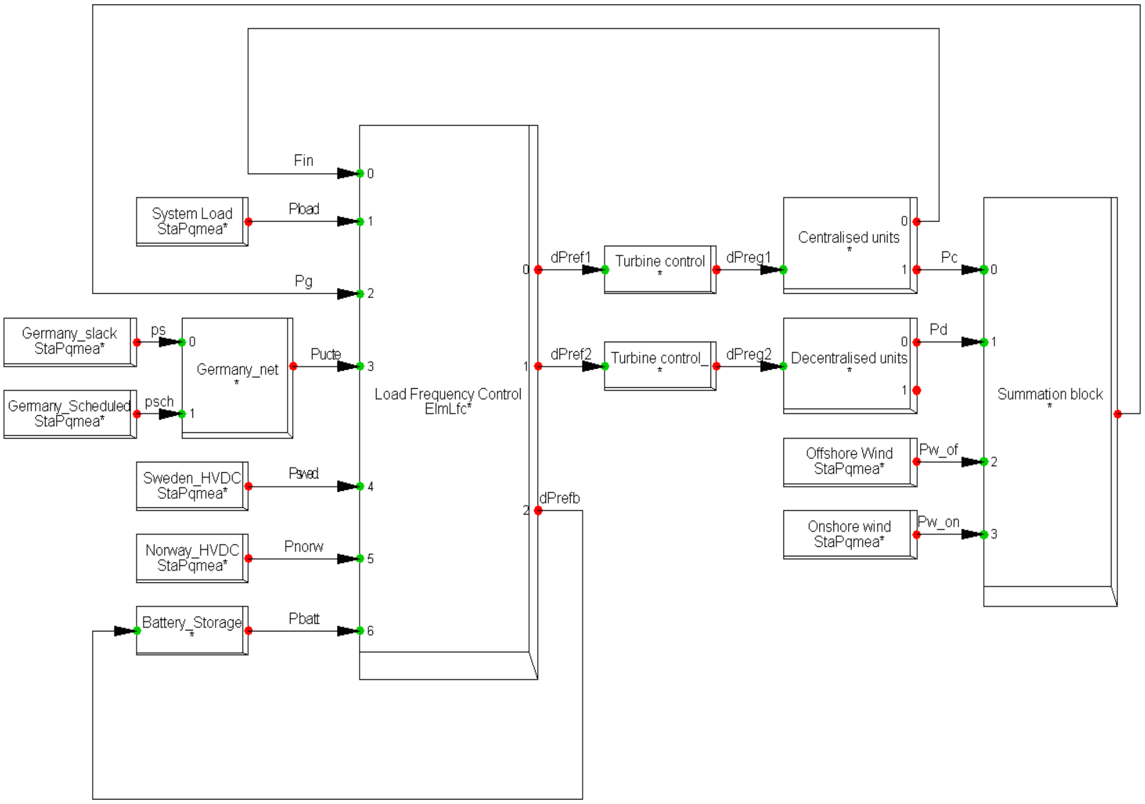

Fig. B.11 Composite model of Load Frequency Control in DIgSILENT PowerFactory

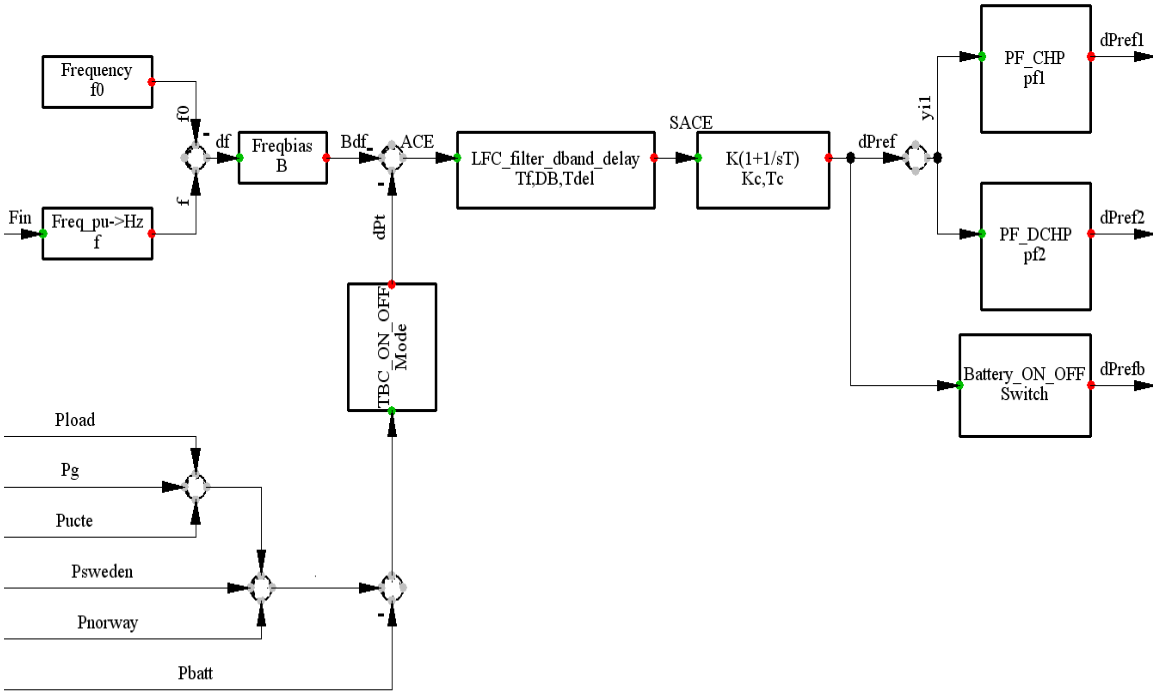

Fig. B.12 Common model of the Load Frequency Controller in DIgSILENT

Table BI Parameters of LFC model

Parameters	Value
Frequency bias factor, B (MW/Hz)	200
LFC proportional gain, K_c	0.4
LFC integrator time constant, T_c (sec)	180
LFC deadband (MW)	10
Reference Frequency, f0 (Hz)	50
Frequency, f (Hz)	50
LFC filter time constant (sec)	1
LFC time delay (sec)	2
Centralised power plant participation factor, pf1	0.9
Decentralised power plant participation factor, pf2	0.1

Table BII Parameters of Centralised Steam Turbine Power Plants

Parameter	**Value**
Governor controller gain, K (p.u.)	25
Governor Time Constant, T_1 (sec)	0.25
Governor Derivative Time Constant, T_2 (sec)	0
Servo Time Constant, T_3(sec)	0.1
Valve Opening Time, U_o (p.u./sec)	-0.1
Valve Closing Time, U_c (p.u./sec)	0.1
Maximum Gate Limit, P_{max} (p.u.)	1
Minimum Gate Limit, P_{min} (p.u.)	0.3
High Pressure Turbine Time Constant, T_4 (sec)	0.3
High Pressure Turbine Factor1, K_1 (p.u.)	0.3
High Pressure Turbine Factor2, K_2 (p.u.)	0
Intermediate Pressure Turbine Time Constant, T_5 (sec)	10
Intermediate Pressure Turbine Factor, K_3 (p.u.)	0.4
Intermediate Pressure Turbine Factor, K_4 (p.u.)	0
Medium Pressure Turbine Time Constant, T_6 (sec)	0.4
Medium Pressure Turbine Factor, K_5 (p.u.)	0.3
Medium Pressure Turbine Factor, K_6 (p.u.)	0
Low Pressure Turbine Time Constant, T_7 (sec)	0
Low Pressure Turbine Factor, K_7 (p.u.)	0
Low Pressure Turbine Factor, K_8 (p.u.)	0
Hourly ramp time constant, Tr (sec)	250
Participation Factor, delta (p.u.)	1
Frequency deadband, dband, (Hz)	0
LFC signal time delay, T_{del}, (sec)	5
Ramp rate, ramp limit (p.u./sec)	0.00067
LFC signal filter time constant , T_f, (sec)	1

Table BIII Parameters of Decentralised Gas Turbine Power Plants

Parameters	**Value**
Speed Droop, R , (p.u.)	0.047
Controller Time Constant, T1, (sec)	0.4
Actuator Time Constant, T2, (sec)	0.1
Compressor Time Constant, T3, (sec)	3
Ambient Temperature Load Limit, AT, (p.u.)	1
Turbine Factor, Kt, (p.u.)	2
Controller Minimum Output, Vmin, (p.u.)	0.3
Controller Maximum Output, Vmax, (p.u.)	1
Frictional losses factor, Dturb, (p.u.)	0
Hourly ramp time constant, Tr (sec)	150
LFC signal time delay, T_{del}, (sec)	3
Ramp rate, ramp limit (p.u./sec)	0.0016
LFC signal filter time constant , T_f, (sec)	1

Table BIV Parameters of a 90MW aggregated battery storage model

Parameters	**Value**
V2G activation delay, T_d (sec)	4
Battery gain, K_b (kA/LFC signal)	5
Battery current limit, Lim_I (A)	450000
Initial Ampere-hour, Ci (Ah)	900000
Battery power limit, Lim_P (W)	90000000
Battery converter time constant, T_b (s)	1
Tranisent Time constant, $T_{transient}$ (sec)	0.001
Battery Ampere-hour, Cb (Ah)	1800000
p.u. to MW conversion, MW	1000000
Series resistance, R_{series} (ohms)	0.013
Transient resistance, $R_{transient}$ (ohms)	0.001
Ampere-hour limits, Ebmax(Ah)	810000
Battery SOC lower limit	0.2
Ampere-hour limits, Ebmin(Ah)	-540000
Battery SOC higher limit	0.95

Appendix C

Table CI IEEEG1 Governor and Turbine Model Data

Parameter	Value
Governor controller gain, K (droop mode) (p.u.)	25
Controller gain (isochronous mode), K_i (p.u.)	0.25
Controller time constant, T_i (isochronous mode) (s)	1

Table CII Battery model parameters

Parameter	Value
Battery gain, K_b (kA/Hz)	I_{rated}
V2G primary delay time, T_b (sec)	4
Battery high pass filter constant, T_f (sec/rad)	160
V2G mode dead band (mHz)	10

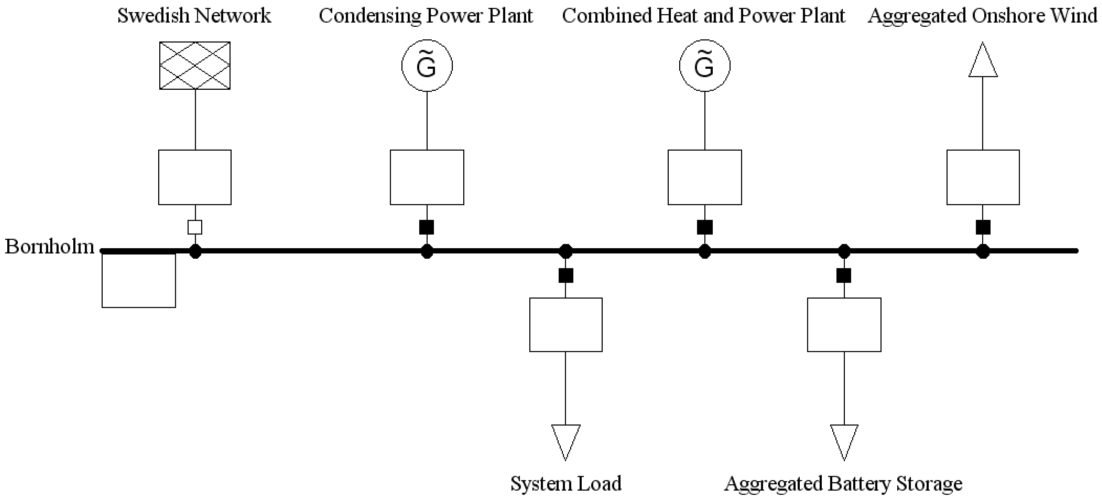

Fig. C.1 Single busbar model – Bornholm power system

Appendix D

Table DI Bornholm Substations

Abbreviation	**Substation Name**	**No. of Transformers**	**Transformer (MVA)**
OLS	Olsker	2	8
BOD	Bodilsker	2	14
AAK	Aakirkeby	2	16
ØST	Østerlars	1	6.3
SNO	Snorrebakken	1	10
HAS	HASLE	2	20
NEX	Nexø	2	20
RØN	Rønne Syd	1	10
ALL	Allinge	2	20
SVA	Svaneke	1	10
VIA	Viadukten	1	10
RN	Rønne Nord	1	10
POU	Poulsker	1	10
VES	Vesthavnen	1	10
GUD	Gudhjem	1	4
VAE	Værket	2	41
Total		23	219.3

Table DII Generation Units in Bornholm

Substation Name	**Capacity (MW)**	**Type of generation**
Olsker	0.66	Wind
Bodilsker	4	Wind
Aakirkeby	12.5	Wind
Snorrebakken	2	Wind
HASLE	10.5	Wind
Poulsker	2	Wind
Værket	37	Combine Heat and Power (CHP) - Steam Turbine unit
	27	Condensing Steam Turbine unit

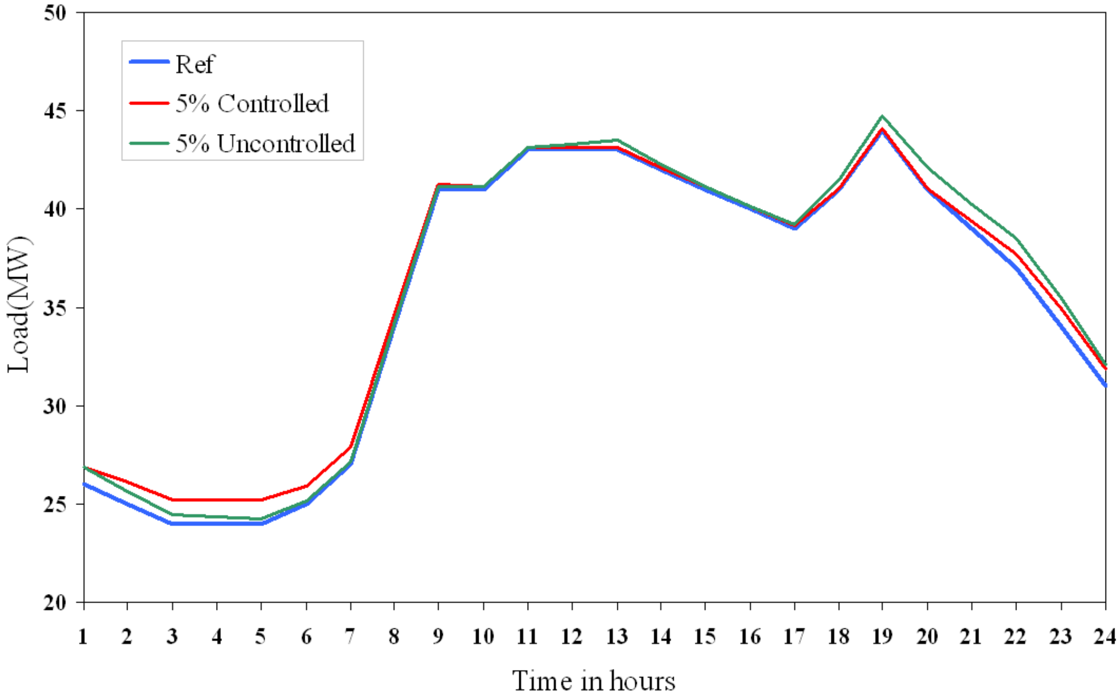

Fig. D.1 Load demand curve with 5% electric vehicle penetration

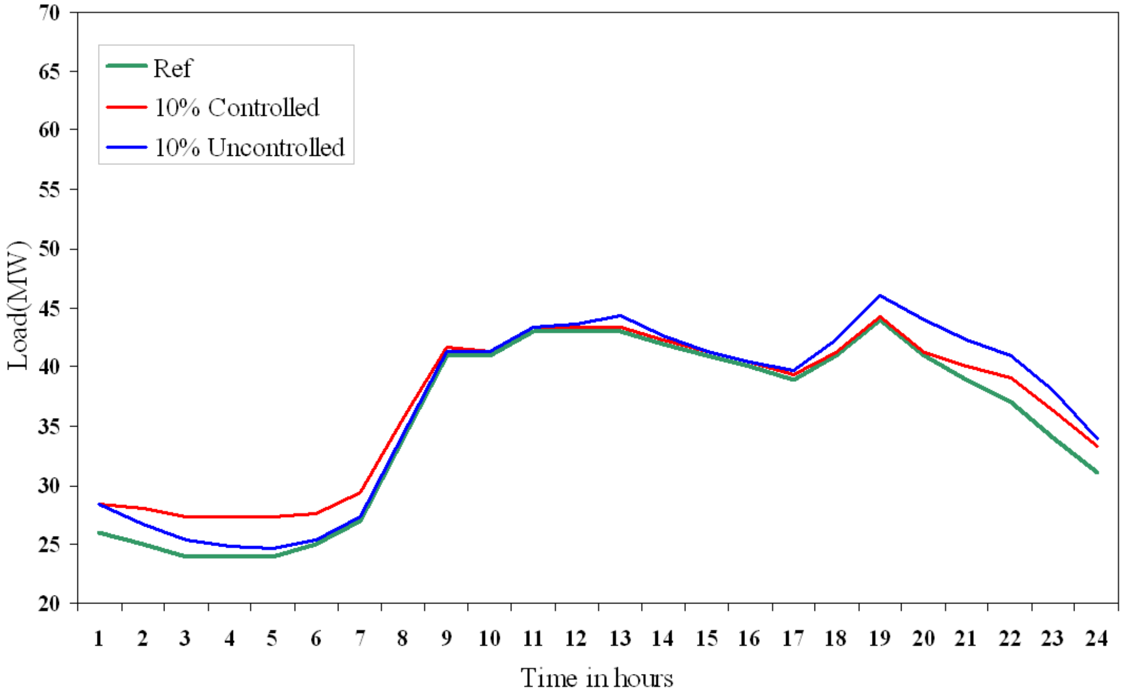

Fig. D.2 Load demand curve with 10% electric vehicle penetration

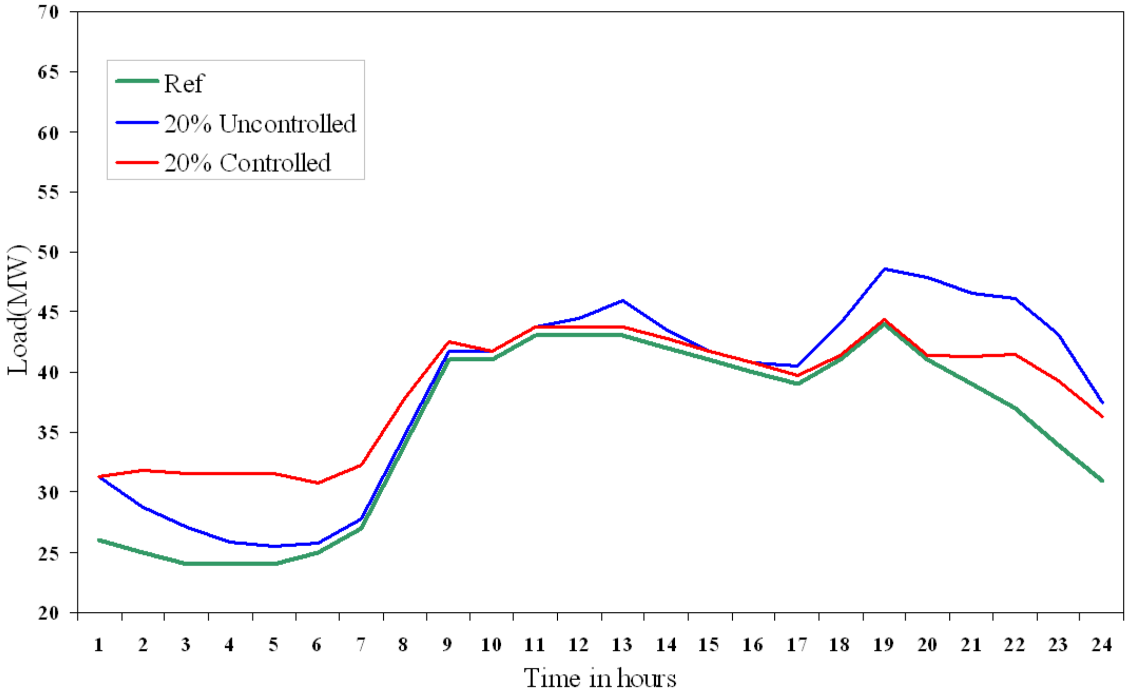

Fig. D.3 Load demand curve with 20% electric vehicle penetration

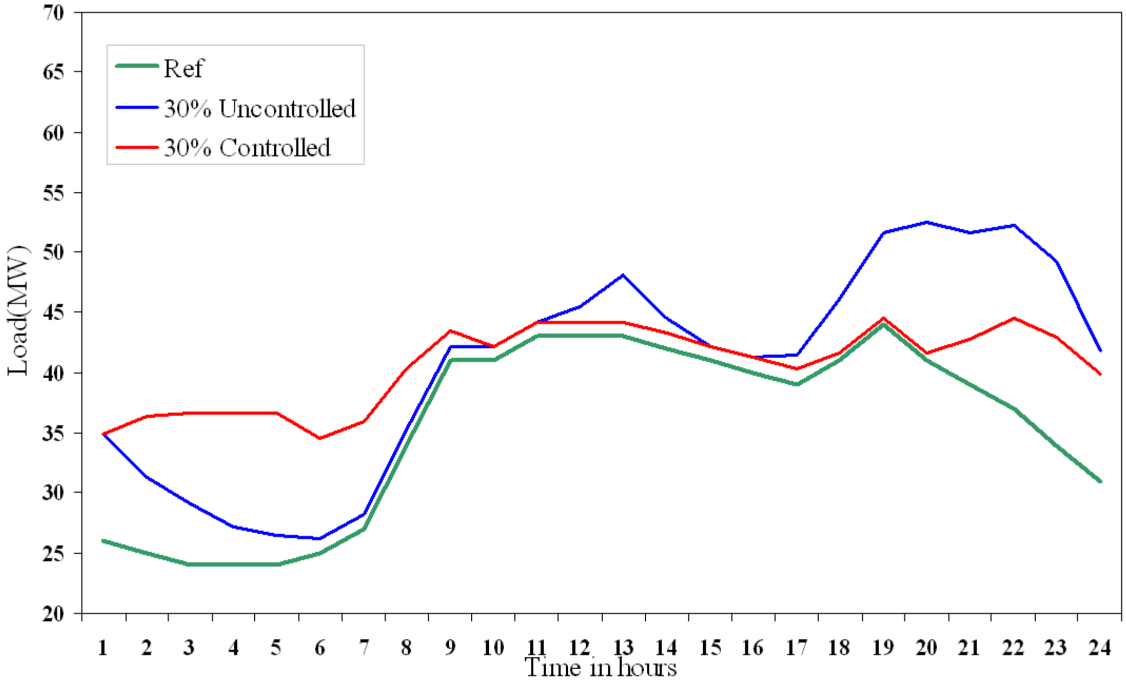

Fig. D.4 Load demand curve with 30% electric vehicle penetration

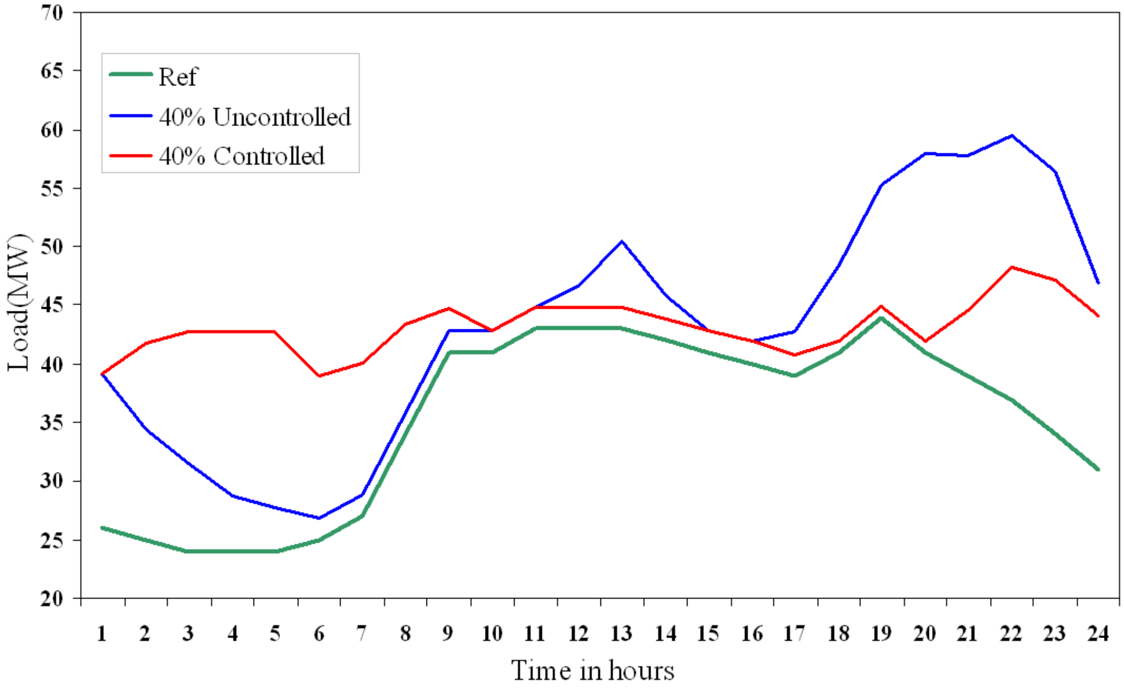

Fig. D.5 Load demand curve with 40% electric vehicle penetration

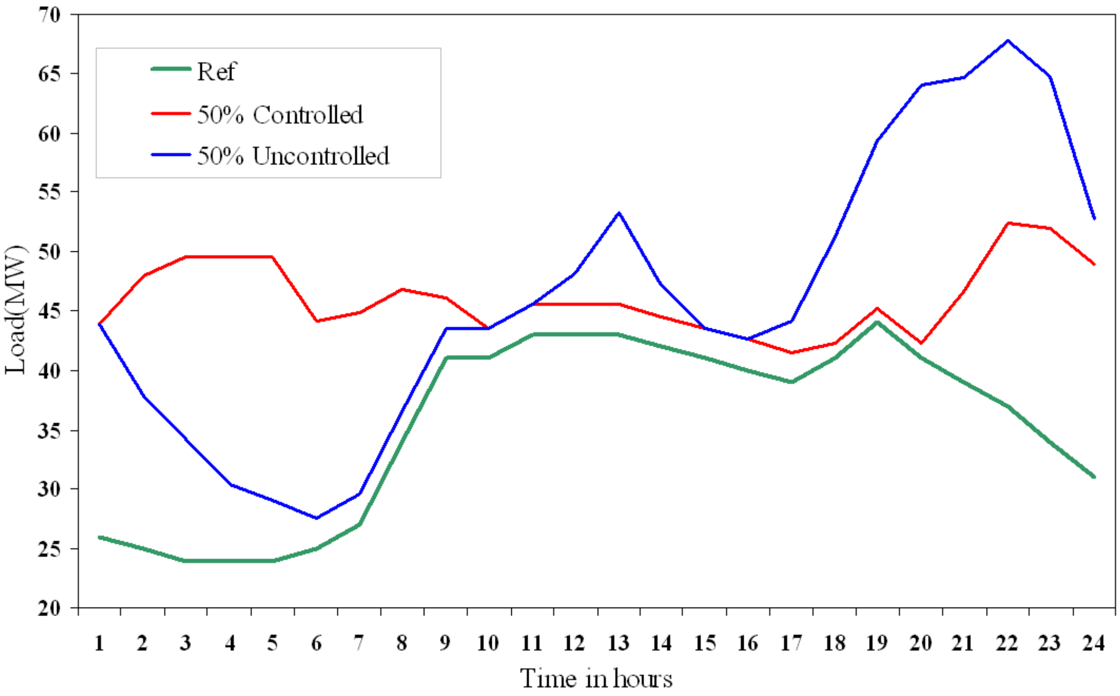

Fig. D.6 Load demand curve with 50% electric vehicle penetration

Appendix E

Table EI EnergyPLAN results of Bornholm scenarios

Excess Electricity Production (GWh)												
Wind (MW)	Ref 2007	2030- No V2G	2MW V2G	4MW V2G	6MW V2G	8MW V2G	10MW V2G	12MW V2G	14MW V2G	16MW V2G	18MW V2G	20MW V2G
0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
25	0.07	0	0	0	0	0	0	0	0	0	0	0
30	0.27	0	0	0	0	0	0	0	0	0	0	0
33	0.52	0	0	0	0	0	0	0	0	0	0	0
36	0.91	0.17	0.07	0	0	0	0	0	0	0	0	0
39	1.48	0.52	0.32	0.19	0.11	0.04	0	0	0	0	0	0
42	2.24	1.13	0.79	0.55	0.38	0.28	0.2	0.12	0.04	0	0	0
45	3.21	2.14	1.63	1.26	0.96	0.71	0.55	0.44	0.35	0.26	0.19	0.12
48	4.39	3.59	2.94	2.41	1.98	1.63	1.33	1.07	0.87	0.72	0.6	0.49
51	5.79	5.21	4.83	4.19	3.6	3.08	2.62	2.23	1.92	1.65	1.41	1.2