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Vehicle-to-Grid Power in Danish Electric Power Systems

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Abstract. The integration of renewable energy systems is often constrained by the variable nature of their output. This demands for the services of storing the electricity generated from most of the renewable energy sources. Vehicle-to-grid (V2G) power could use the inherent energy storage of electric vehicles and its quick response time to balance and stabilize a power system with fluctuating power. This paper outlines the use of battery electric vehicles in supporting large-scale integration of renewable energy in the Danish electric power systems. The reserve power requirements for a high renewable energy penetration could be met by an amount of V2G based electric vehicles less than 10% of the total vehicle need in Denmark. The participation of electric vehicle in ancillary services would earn significant revenues to the vehicle owner. The power balancing services of electric vehicles in an electricity network with a large variable renewable generation in Denmark seems feasible and realistic.

Key words

Ancillary services, Regulation, Renewable energy, Reserves, Vehicle-to-grid

1. Introduction

Renewable energy plays a vital role in ensuring global energy and environmental sustainability. To meet the environmental standards set up in the Kyoto Protocol, many countries have proposed specific targets for the share of renewable energy. Denmark has always promoted the use of renewable energy and is one of the pioneers in producing electricity from renewables like wind energy. The share of wind in electricity generation in Denmark is more than 20%, which is one the largest in the world. As part of the future Danish energy policy, it is planned to integrate 30% of energy consumption from renewable energy by 2025 and a 50% wind production share of the electricity generation by 2030 [1]. However, it is obvious that the renewable energy sources are intermittent in nature. For example, the electricity from wind energy is produced only when the wind blows, not when the power is demanded.

During high winds, the electricity generation may be more than the electricity demand. In that case, so far the surplus electricity is either exported to the neighbouring countries or the generation is reduced by curtailing the conventional generator supply. Similarly during low winds, the energy imbalance due to the deficit of power supply will be compensated by increasing the power supply from other generators or by imports. This power imbalance is highly challenging for a power system operation and control point of view. It is estimated that, for every 10% wind penetration, a balancing power from other generation sources equivalent to 2-4 % of the installed wind capacity is always required for a stable power system operation [2]. So, with more penetration of intermittent renewable energy like wind power, the system operation will be more complex and it will require additional balancing power. Installation of new conventional generators and dependence on more power exchanges with neighbouring countries may be limited by the promotion and substitution of conventional generation by renewable energy in Denmark as well as across its borders. One of the viable solutions for the energy balance is thus the energy storage technologies which is complementary to the stochastic nature of the renewables. The energy storages can store energy during low demand period and supply when power is required.

The storage systems of electric vehicles are one of the emerging technologies, which can act as a load reacting to the change in power supply. The concept of environmental-friendly vehicles has encouraged many car manufacturers to develop clean vehicles, especially vehicles powered from electricity. Electric vehicles when coupled to an electricity network (Vehicle-to-grid (V2G)) can act as a controllable load and energy storage 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. With fleets of electric vehicles, the balance between the supply and demand could be achieved by the load reacting to change in generation. Vehicle-to-grid power could provide back up electricity storage as well as quick response generation to the changes in power balance of the electricity grid. V2G systems uses the electric vehicles to transfer power with the grid when they are parked and plugged in to the charging stations at parking lots, at offices or at homes and 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. The Transmission System Operator (TSO) could request for a power transfer with an individual vehicle or fleet of vehicles in a parking lot through control signals in the form of a power line carrier, radio signal, internet connection or mobile phone network [3].

In general, the utilisation factor of vehicles is less than 10%, compared to an average 40-50% utilisation of central power plants. The light motor vehicles are idle almost 90% of the time or for a period 20-22 hours a day [4]. The average daily vehicle miles travelled in Denmark is 36km/day. Thus, if the 2 million light motor vehicles (less than 2 tons) in Denmark supply an average power of 15kW each, they could provide 30GW of electricity. This implies that the power capacity of 13% of the above vehicle fleet is equivalent to the total average power requirement of 4GW in Denmark. Many models of electric cars are now commercially available in the market operating with highly efficient lithium-ion batteries. The 2008 model battery electric vehicle, Tesla Roadster has a vehicle efficiency of 5.65 miles/kWh and energy storage capacity of 53kWh [5]. From a calculation based on equation (3) in the reference article [3], the net energy available in the battery after the daily driving requirements by this battery electric vehicle in the Danish context is approximately 45kWh. This paper analyse the use of battery electric vehicles as a provider of ancillary services (regulation and reserves) to support large-scale integration of renewables in the Danish electric power systems.

2. The Danish Power System

The Danish power system is connected to two separate synchronous areas. West Denmark is interconnected to Germany to the UCTE system and East Denmark is connected to Sweden to the Nordel system. A Great Belt HVDC Link connection between West and East Denmark is planned for operation by 2010. The Danish electricity market is part of the Nord Power exchange market (Nord Pool). This market can be generally categorized as day-ahead spot market (Elspot) and intra-day regulating power market (Elbas). The transmission system operator in Denmark, Energinet.dk purchases the regulating power, controls and manages the grid.

Table 1 gives the power generation and consumption profile of Denmark and the strong transmission ties with the neighbouring countries. About one half of the electricity production capacity in Denmark is installed in the form of dispersed generation units. They are equally dominated by the local CHP and wind farm units which are connected to the distribution system at levels below 100kV. The distribution of electricity production units are seen in Figure 1. The total installed wind capacity in Denmark is around 3200MW which accounts for an approximate 20% of the annual electricity generation. 75% of these wind turbines are installed in West Denmark.

Table 1 Power system capacity details of Denmark

	West Denmark (MW)	East Denmark (MW)
Generation capacity		
Centralized CHP units	3400	3800
Decentralized CHP units	1750	650
Wind turbines	2400	750
Consumption		
(Minimum - Maximum)	1250 - 3700	880 - 2600
Interconnections		
Norway	1000 (HVDC)	-
Sweden	740 (HVDC)	1700
Germany	1500	600 (HVDC)

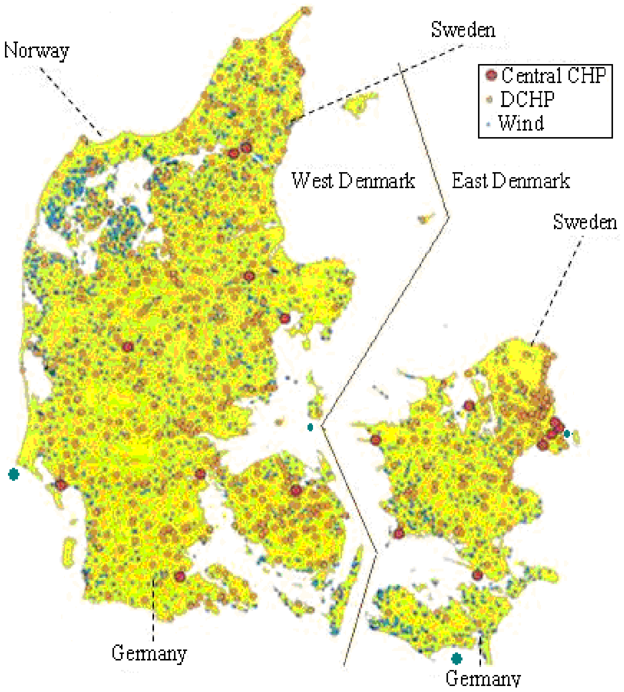

Figure1. Distribution of generation units in Denmark [6]

However, in Denmark the high wind power production is responsible for more than half of the power imbalances [7]. At instances when the wind power exceeds the demand, they are either exported or curtailed. Hereafter, even if the generation exceeds the demand, it results in transmission congestion. This will cause a high regulating price and a low market price which may sometimes even reduce to zero. This happens many hours in a year in Denmark. To restore the energy balance, the conventional power generators reduce their power production. On the other hand, when the wind power is less than forecasted, market price will be higher and the other conventional generators have to supply more power. In both the cases, the wind farm owners have to incur additional costs (penalty) which are settled through the regulating power market. This provides the wind power producer a lower price for electricity production than the spot market price. This situation could become critical when the proposed grid integration of wind is increased to 50% by 2030 in the Danish power system. In order to ensure better regulation of electricity prices and power balance in the future, a feasible solution could be provided by the battery storages of electric vehicles. The electric vehicles could charge and store energy during high winds and discharge when required.

3. Ancillary services from V2G

Various studies [3],[8] and [9] have reported that the V2G connected vehicles are best suited for electricity balancing markets to provide services like regulation and manual reserves. These two functions are the mandatory ancillary services required in any power system for its reliable operation [10]. The regulation service is the automatic generation control which tunes the power system frequency and voltage to satisfy the energy balance. The regulation may be regulation up or down. Regulation up is necessary when the demand exceeds the supply, causing the voltage and frequency to drop and if the supply exceeds demand, a regulation down is desired for a stable operation of the system. The regulation process occurs many times a day and requires fast response from the V2G vehicles (less than a minute) and may be required only for a short duration of few minutes. The generators used as manual reserves (spinning and standby reserves) must be able to supply balancing power to the system within few minutes. These instants happen possibly 20 times a year for an average duration of one hour each [9].

For the above ancillary services, the electric vehicles are paid a fixed cost (capacity cost) for their individual power rating based on the amount of time they are available and plugged in. It will also be paid a variable cost (energy cost) for the actual energy consumed during the reserve or the regulation operation. Table 2 shows the typical reserve power requirements in Western Denmark (DK-West), the reserve capacity and energy costs [11].

Table 2. Reserve power capacities and costs

Ancillary services	Reserve power requirement	Average capacity cost	Average energy cost
Regulation	+/- 140MW (15 minutes)	100,000/MW per month	100 DKK/MWh
Manual reserves	+520MW/ -160MW (1-3 hours)	50,000/MW per month	420 DKK/MWh

1 Euro = 7.45 Danish kroner (DKK)

A battery electrical vehicle with power capacity similar to the Tesla Roadster providing ancillary services could possibly provide significant annual payments to the electric vehicle owner as listed in Table 3. The results show that the earnings from the regulation services are higher than the manual reserves. This is because; the regulation services are used quite often in a day to match the grid fluctuations and are offered a higher capacity price. The total earnings from the vehicle storage are dependent on the total plug-in time, state of charge, power line capacity, and hourly market prices. Here, the calculations are based on the assumptions that the vehicles are plugged-in 20 hours a day, daily utilisation for regulation as 10% and the average costs which are considered from the table 2. Also from the results in table 3, it is evident that the revenue is increased for the V2G service with a higher 20kW power line connection.

The modelling of generic battery energy storage and a suitable dispatch strategy of utilizing the electric vehicles for ancillary services in a typical Danish power system network are currently being investigated as part of this research work. In a real situation, the ancillary services supplied by the electric vehicles will be a mix of large number of small different units. To analyse the performance of such units in a power system network, aggregate models of vehicle storages are considered which will reduce the complexity and computation time of the evaluation.

Table 3. V2G ancillary service payments

Ancillary services	Power line capacity	Possible annual payment from V2G services		
		Capacity DKK	Energy DKK	Total DKK
Regulation	15kW	15330	1095	16425
	20kW	20440	1460	21900
Manual reserves	15kW	7655	126	7791
	20kW	10220	168	10388

4. V2G for renewable energy support

The vehicle-to-grid power using battery electric vehicles are analysed here for the ancillary service operation in Denmark to incorporate a larger penetration of wind energy and solar photovoltaic (PV). The V2G vehicles supporting grid-solar PV integration for peak load management is realised by storing power from the solar peak and supply to the system peak. The battery electric vehicle like Tesla Roadster has the ability to store or release 45kW over one hour period. A solar plant planned for 1 MW peak power supply for an hour requires only 23 such electric vehicles for dedicated storage. Assuming that 10% peak power were utilised from solar PV in the Danish power system of 13GW capacity, then the 1.3GW has to be supported by approximately 86,667 battery electric vehicles (assuming line capacity of 15kW). This corresponds to 4.3% of the current vehicle fleet available in Denmark. If one-half of the vehicles are available on demand, 8.7% vehicle fleets must be under the V2G power contract.

Considering the utilisation factor of the Danish power utility to be 50% of the installed electric capacity of 13GW, then to generate half of the electric power from wind energy (capacity factor – 35%), will require 9.29GW of wind energy. Assuming regulation service requirement equivalent to 6% of the wind capacity [12], 557MW has to be met by battery V2G. With a maximum power that could be plugged in to the domestic power line assumed as 15kW, approximately 37,134 battery electric vehicles should take part in this regulation services. This accounts to 1.9% of current vehicle fleet in Denmark. The

Table 4. V2G power for renewable energy support in Denmark

Renewable Power	Application	Capacity (GW)	V2G Support type	V2G support needed	V2G availability	% of current fleet
Solar PV	Peak load (10%)	1.3	Dedicated storage (1 hour)	1.3GW	50%	8.7%
Wind	Base load (50%)	10.83	Regulation (15 min.)	557MW	50%	3.8%
			Manual reserves (1 hour)	1.02GW	50%	6.8%

V2G contract has to be offered to 3.8% of the total amount of vehicles, considering one-half will be available on demand. Considering the manual reserve requirement of a power system equivalent to 11% of the wind capacity [12], the same battery electric vehicle for hourly operation requires approx. 68,134 (3.4% of fleet) battery electric vehicles to support 1.02GW. Considering one-half of the vehicles are made available for the manual reserves, 6.8% of the Danish fleet of vehicles must be contracted. From the summary of results in the Table 4, it is obvious that the vehicle-to-grid power could play a major role in providing ancillary services to power systems integrated with 50% of electricity production by renewable power generation in Denmark. This is achievable with an amount of V2G based electric vehicles less than 10% of the total vehicle need in Denmark. The rapid development of high storage capacity batteries will increase the net power capacity of the electric vehicles rendering V2G power in the future. This will in turn demands less number of electric vehicles to provide ancillary services for such large-scale grid integration of renewable energy.

5. Conclusion

The increased share of renewables in the future electric power systems will limit the number of conventional generators which has the ability to provide the necessary ancillary services. The introduction of alternative technologies for providing ancillary services is inevitable for a renewable energy dominated power systems to prevent instability of the electricity network. In future power systems, vehicle-to-grid based reserve power could effectively negotiate supply imbalance and fluctuations. With less than 10% of electric vehicles used for V2G power, a stable operation of electricity grid could be ensured with a large-scale grid integration of renewables in Denmark. The V2G vehicle supplying ancillary services could deliver significant revenues to the vehicle owner, especially by providing regulation services. With the use of higher capacity power line connection in V2G system, the earnings could be increased further. The cheap storage and backup support from electric vehicles will encourage an optimal and increased utilisation of local renewable energy resources. This also creates a social synergy between renewable energy and the electric vehicles to provide carbon dioxide free electricity and transportation.

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