Electric Vehicle Based Battery Storages for Future Power System Regulation Services

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Abstract— **The large grid integration of variable wind power adds to the imbalance of a power system. This necessitates the need for additional reserve power for regulation. In Denmark, the growing wind penetration aims for an expedited change of displacing the traditional generators which are currently supplying the reserve power requirements. This limited regulation services from conventional generators in the future power system calls for other new reserve power solutions like Electric Vehicle (EV) based battery storages. A generic aggregated EV based battery storage for long-term dynamic load frequency simulations is modelled. Further, it is analysed for regulation services using the case of a typical windy day in the West Denmark power system. The power deviations with other control areas in an interconnected system are minimised by the faster up and down regulation characteristics of the EV battery storage.**

I. INTRODUCTION

The share of total electricity consumption in Denmark covered by wind power is more than 20%, which is the largest in the world. By 2025, it is planned to integrate 50% of wind power into the Danish electric power system [1]. However, the major constraint of such large scale integration of renewables lies in its variable nature and poor load following characteristics. This especially is highly challenging for a stable power system operation and control. Many options to negotiate the variable renewable power are studied and explored in the form of heat pumps, demand response, electrolysers and energy storages [1]. The battery energy storages are one of the most efficient and compatible technology for an improved power system operation and control. The operation of storages is complementary to stochastic nature of renewable energy. They can charge whenever there is excess of electricity in the connected system and discharge when required.

The battery storages could also provide many other power utility support functions like power quality improvement, load following, peak shaving, frequency and voltage stabilisation. Even though the battery storage is a matured technology, it is still under the research stages to develop more efficient, high power and energy capacity battery types. Some of the largest battery storage plants installed and operating include a 20MW, 14MWh (lead-acid) at Puerto Rico, a 40MW, 14MWh (nickel cadmium) at Alaska typically used for spinning reserve, voltage and frequency control applications [2]. The more 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 battery storage of electric vehicles is 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 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. This could be considered as a large aggregated MW battery storage which is termed as "Vehicle to grid" (V2G) system. 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 systems could provide back up electricity storage as well as quick response generation to the changes in power balance of the electricity grid.

This paper analyse the dynamic response of electric vehicle based battery storage to power system regulation signals. This is realised by incorporating an aggregated battery storage model to a load frequency control model. The simulations are examined in a typical Danish power system context with a large proportion of variable wind energy production. The various sections in this paper are organised as follows. Section II discusses the vehicle-to-grid concept in detail. The applications of vehicle-to-grid and its benefits are also discussed. Modelling of generic battery storage for regulation services are discussed in Section III. The dynamic response of an aggregated EV storage model to power system regulation signals for a typical windy day in West Denmark is analysed in Section IV. Section V discusses the load frequency control model with V2G and the simulation results are presented and concluded in Section VI.

II. VEHICLE TO GRID SYSTEMS

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. The Transmission System Operator (TSO) can request for a power transfer through an aggregator (intermediate entity) who manages the individual vehicle or fleet of vehicles through control signals in the form of a power line carrier, radio signal, internet connection or mobile phone network [3]. The aggregator appears to the TSO as a large battery storage with regulation capabilities.

The V2G connected vehicles are reported to be best suited for electricity balancing markets to provide services like power regulation ([3], [4]). This is considered as a mandatory ancillary service required in any power system for its reliable operation. The regulation service is the load frequency control which tunes the power system frequency and voltage to satisfy the energy balance. The regulation may be regulation up or regulation 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. The electric vehicles participating in V2G will be paid a capacity cost for availability and an energy cost based on the activation. The earnings gained by the electric vehicle owner from the regulation services are higher than manual reserves as the former services are required quite often in a day to match the grid fluctuations and are offered a higher capacity price [5].

The average daily vehicle miles travelled in Denmark is 36km/day. The light motor vehicles are idle almost 90% of the time or for a period 20-22 hours a day [6]. In general, the utilisation factor of the vehicles is less than 10%, compared to an average 40-50% utilisation of central power plants. With less than 10% of electric vehicles under V2G mode, it could support grid regulation services in a power system with 50% wind power integration ([3], [5]). 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 [8]. From a calculation based on equation (3) in the reference article [7], the net energy available in the battery after the typical daily driving requirements by this battery electric vehicle in the Danish context is approximately 40kWh.

Considering the energy storage potential offered by the V2G system to support the growing wind power capacity, V2G projects have already been initiated in Denmark. The "EDISON" project plans to demonstrate electric cars based smart grids in the Danish island of Bornholm which is characterised by large proportion of wind. It is also reported that the Danish utility company DONG energy plans to implement a full-scale V2G infrastructure by 2011 to provide wind power support. The scope for dedicated battery storage power stations for power system operational support is limited in their capacity due to technical and cost constraints. But by aggregating the large number of distributed mobile storages of electric vehicles, a significant storage or generation capacity is available through a well coordinated V2G system. The distributed storage could also provide local power system support. Other feasible enlarging applications of V2G include manual reserves, back-up power supply, peak load management, micro-grid and local voltage support.

The uncertainties of the electric vehicle management system, power regulation effects on the battery life are not considered in this paper. Instead, the dynamic response of aggregated electric vehicle battery storage to regulation signals with charging and discharging limits is analysed here.

III. BATTERY STORAGE MODEL FOR ELECTRIC VEHICLES

The Thevenin-based model is the most commonly used electric-circuit based representation of a battery in published research works. This model consists of an ideal voltage source in series with an internal resistance and a parallel RC networks. The inaccurate estimation of the battery state of charge is the drawback in using this model. The model in [9] discusses a combination of a typical Thevenin model with a run-time model which could accurately provide the state of charge of the battery. Figure 1 shows such a modified Thevenin equivalent representation of a battery. For power system stability and frequency regulation studies, simple transfer functions blocks are also used to represent battery energy storages [10]. The combination of the Thevenin equivalent circuit and converter models are also suggested for dynamic power system stability studies [11]. In this paper, aggregated electrical vehicle based battery storage is modelled for V2G regulation services responding to load frequency control signals. The model is used for long-term power system dynamic simulations in load frequency control (LFC). It is represented by a model equivalent to that in the Figure 1 which could provide the battery capacity and state of charge capabilities. The block diagram of a generic aggregated battery storage model representing V2G service used in load frequency simulations in this work is shown in the Figure 2.

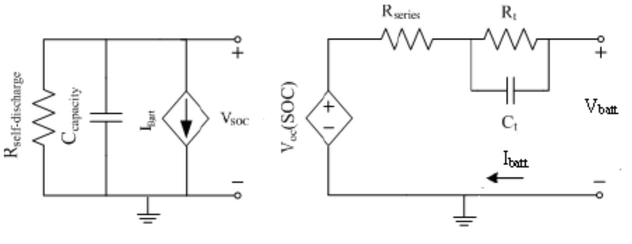

Fig. 1 Electrical battery model

The aggregated battery output is controlled based on the load frequency control signal. The input signal is passed through a first-order filter to remove noise and further the signal is applied with an activation and communication delay. From experimental field tests conducted on a V2G system as reported in [12] the wireless communication delay between a vehicle and the aggregator is less than 2 seconds and that between the aggregator and TSO is less than a second. As a worst case a delay of 4 seconds is assumed in this work for simulations.

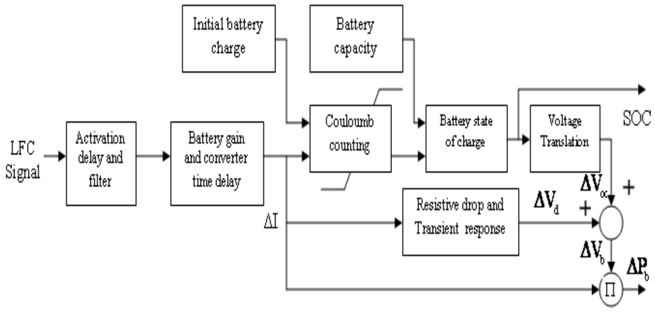

Fig. 2 Block diagram of aggregated battery storage model

The state of charge of the battery is calculated based on "coulomb counting". The current in to or out of battery is integrated to give a relative charge which when added to the initial charge gives the current state of charge of the battery as shown in equation 1.

$$Soc(t) = Soc(t_0) + \int i(t).dt \tag{1}$$

This quantity is further normalized to the battery capacity so that state of charge lies between 0 and 100%. This part of the calculation can be represented by the first section of the circuit in the figure 1. The battery state of charge is limited within 20-95% for simulations to avoid damage of the battery and to preserve battery life. In the V2G application, the battery management protection system takes over the priority from the V2G regulation service on reaching the above limits. By adopting a typical non-linear relationship between the battery voltage and charge status as shown in figure 3 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 as represented in equation 2.

$$V_{bat} = V_{oc}(SOC) + V_{transient} + V_{series} \tag{2}$$

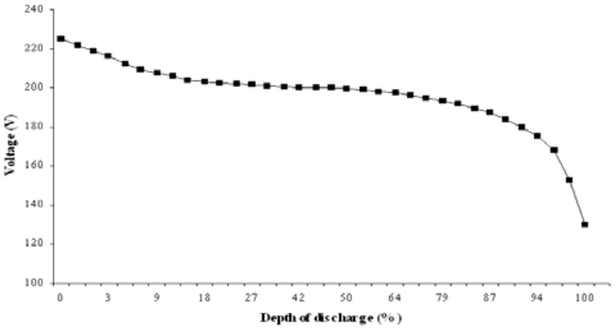

Fig. 3 Typical discharge characteristics of generic battery storage

The electrical parameters for the MW range aggregated battery are adopted from reference [13] where an existing 10MW, 40MWh battery power plant unit is used for frequency regulation. The parameters of the battery model used for simulations in this paper are based from 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 figure 1, as longer periods of battery characteristics are not taken into account. Also the temperature effects are not accounted as it is assumed that the battery operates at the nominal temperature conditions.

IV. VEHICLE TO GRID FOR POWER SYSTEM REGULATION

Table 1 shows the main power system capacity figures of West Denmark [14]. The larger power plants are either coal or gas based thermal units. More than 50 % of the installed power capacities for electricity generation are from the land based wind turbines and decentralized CHP units. The capacity of the offshore wind farm Horns Rev A is 160MW which is connected to the 150kV HV transmission system. On an average, the wind power supplies more than 20% of electricity consumption in West Denmark. The West Denmark transmission system is interconnected to the UCTE synchronous area in the south through Germany. The system is AC connected with Germany which it is dominated by thermal and nuclear power plants and fast growing wind power. To the north, West Denmark is connected to Nordel synchronous area through HVDC links to Norway and Sweden dominated by hydro power plants.

TABLE I WEST DENMARK POWER SYSTEM CAPACITY FIGURES IN MW FOR 2007

Centralized power plant units	3400
Decentralized CHP units	1750
Wind turbines	2400
Offshore Wind - Horns Rev A	160
Maximum demand	3767
Minimum demand	2669
Transmission capacity from Germany to W. Denmark	950
Transmission capacity from W. Denmark to Germany	1500
Transmission capacity with Norway	1040
Transmission capacity with Sweden	740

Today in Denmark, the regulating power to balance the planned generation and unpredictable load are provided by the central and local power plants and from external connections from abroad. The variable 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 they are not dependable. The "visionary Danish energy policy 2025" plans to double the present wind power capacity in Denmark to 6500MW. However, this aims for an expedited change of replacing the central power stations in the whole of Denmark to about 40% of the present capacity to 4100MW [1]. This future scenario is highly challenging for a reliable operation of the power system as it demands for alternate means of faster and larger regulating reserve power capacity. Table 2 gives the reserve power types in West Denmark.

The primary control is used as 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 30seconds. The secondary control is a slow process which will replace the primary reserves to restore the nominal frequency and minimise the power exchange deviations. Secondary control makes use of a centralised automatic load frequency control which will be activated fully within 15 minutes. The manual or tertiary reserves are slowest of all the control reserves used in order to restore the secondary reserves.

TABLE II DETAILS OF RESERVE POWER IN WEST DENMARK [15]

Regulation reserves	**Primary**	**Automatic**	**Manual**
Capacity (MW)	+/- 24	+/- 90	+290/- 310
Activation time	0 - 30sec	30sec - 15min	15min
Contracting approach	Voluntary tender	Voluntary tender	Regulating power market
Payments	Negotiated capacity and energy prices	Negotiated capacity and energy prices	Regulating power market
Activation mode	Automatic	Load frequency control	Manual

Alternate methods to provide future reserve power have been proposed in the form of wind power regulation, increased grid transmission capacities, heat pumps and boilers, electric vehicle storages etc [1]. This paper mainly focuses on the use of electric vehicle based storages (V2G) which is considered to be one of the feasible future regulation reserves in Denmark. The feasibility projects for implementing the same have been initiated in Denmark as mentioned in section II. To analyse how V2G system storage could participate as an automatic regulation reserve in West Denmark, a typical day with large wind production is considered. Figure 4 shows the electricity consumption and production, wind power, load frequency control (LFC) signal (regulation power requirement) and power deviation with UCTE at the German border for a weekday in January 2009.

This time series data of five minutes resolution from the West Denmark SCADA system is obtained from the Energinet.dk, the transmission system operator in Denmark. A positive LFC signal indicates regulation up and negative signal gives regulation down values. Similarly a positive power exchange deviation with Germany indicates less planned power being transferred and negative value gives surplus power exchanged. From the data available, the wind power meets an average of 45 % of the total daily electricity consumption, where the total production exceeds the demand. The need for more down regulation during the day is also indicative of high proportion of wind power.

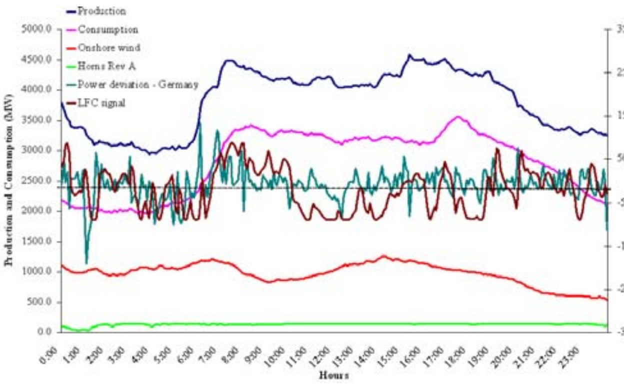

Fig. 4 Power generation, consumption, regulation requirement and exchanged power deviation profile of West Denmark for a typical day in January 2009

To test the aggregated EV battery model representing V2G system in Section III, the LFC signal data is applied as the input signal. The EV battery is modelled using Matlab-SIMULINK blocks. The aggregated battery is assumed to have an initial state of charge of 50%. The aggregated battery capacity is normalized to current secondary regulation capacity of West Denmark which is 90MW as given in table II. A battery storage capacity for four hours (360MWh) and a V2G power line connection of 10kW is considered. The above storage capacity hours of V2G system is based on the "Tesla Roadster" electric vehicle which has approximately 40kWh after the daily driving requirements (Ref Section II). A total of 9000 electrical vehicles are required and it is assumed as 50% of the vehicles are available all the time. The remaining 50% storage is accountable for the uncertainties related to the vehicle availability and management. So, a total of 18,000 electric vehicles must be contracted for V2G regulation which is approximately equivalent to less than 2% of total fleet of vehicles in West Denmark. In Denmark, the total number of cars available is 2 million and the total population is 5.5 million. Approximately one in three persons possess a car in Denmark which accounts to roughly more than 1 million cars in West Denmark, where the population is 3 million [16].

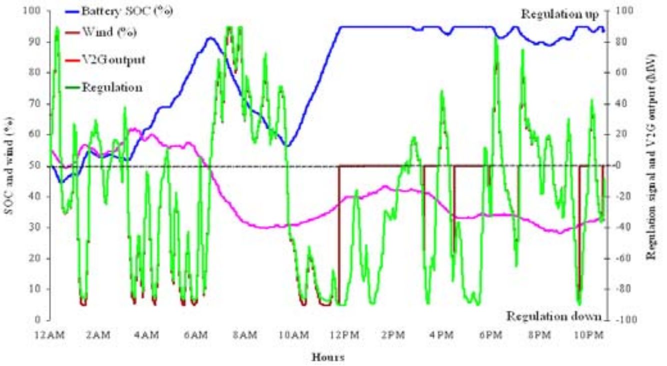

Fig. 5 Simulation results showing the battery state of charge and V2G system output

Figure 5 shows the simulation results of the power output and the state of charge of the 90MW aggregated battery storage. The V2G responds and tracks the regulation signal very closely. But, the battery is fully charged at many instants like as seen during (12-3 pm) and (4-6 pm) where the V2G could not provide any regulation service. The battery capacity during those periods is not sufficient enough to meet the overall regulation power, mostly needed to charge the regulation down power. Other regulation alternatives of sinking the surplus power are desired. Typically, the regulation requirement fluctuates more frequently between positive and negative values so a large deviation from zero is avoided. Under such situations, the net energy balance of the storage tends to be zero over time and battery service could provide the regulation services indefinitely. However, there will be cases similar to the simulated case where the regulation power requires extended periods which could exhaust the V2G regulation capabilities. The solution could be to utilise more V2G capacity by optimal selection and allocation of EV storage by the aggregator. Another alternative is to limit the total energy supplied over a specific time and filter out those longer periods of regulation requirement. In actual practice, it would not only be the V2G system alone to supply the whole of regulation requirement as analysed here. The V2G services will be contracted to provide the regulation services along with other sources of reserve power through the load frequency control model as used in West Denmark. The next section of this paper examines how V2G could provide regulation power through LFC operation simulated for the same typical day in West Denmark.

V. VEHICLE TO GRID IN LOAD FREQUENCY CONTROL

Figure 6 shows the block diagram of a Load frequency control model for West Denmark integrating aggregated models of power plant units and the EV battery storage. The power capacities of generation units use the figures from table I. The LFC models and simulations are performed using DIgSILENT Powerfactory software. The models of generator units used in the simulations are those recommended by IEEE and are available in the global library of the Powerfactory. The centralized power plant is modelled based on the steam turbine units and that for the decentralised CHP plant is modelled based on gas turbine units ([17], [18]). The wind power units and external connections are modelled as negative loads. The power system model is based on a single bus bar model of the West Denmark system connected with system load, Nordel connections, aggregated model of generation units and the UCTE connection as a slack bus. The transmission line capacities and constraints are neglected in this study as it primarily focuses on the collective performance and regulation capabilities of the generators in the system.

For a large variable wind power integrated power system, more power imbalance and power deviations could result. Larger power deviations result in congestions which causes the electricity market and balancing prices to deviate largely from the system prices. If a V2G regulation service is available in the grid, the appropriate charging and discharging of the aggregated battery storage could minimize the wind variations and power congestions thus regulating the price variations. Similar to section IV, a V2G system storage of 90MW, 360MWh is considered here as the V2G base capacity. The secondary control operation using the load frequency control model with V2G in West Denmark is shown in figure 6. The area control error of an interconnected system due to power imbalance is given by $ACE = B.\Delta f + \Delta P_t$, where B is the frequency bias factor, Δf is the frequency deviation and ΔP_t total power deviation with the interconnected system. As the West Denmark power system is interconnected to a larger synchronous UCTE system which could be considered as an infinite bus, the frequency deviations are assumed to be negligible. The LFC operation is accomplished through a tie-line control where the inter-tie power must be maintained at the scheduled values. The difference between the planned and actual exchange power gives the power deviations between the two areas. The deviation is passed through a first order filter to eliminate noise. The signal is then integrated with a PI controller to generate the LFC order or signal which is the average power to be distributed among regulation units participating in regulation.

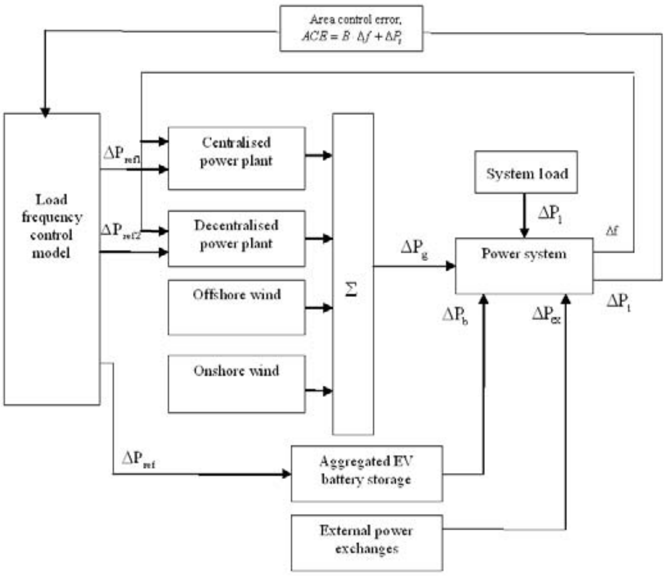

Fig. 6 Load frequency control block diagram including aggregated EV battery storage

The V2G system in the load frequency control model are constrained by the state of charge limits as explained in Section III. Apart from the activation and communication delay of 4 seconds as mentioned in the previous section, V2G regulation is considered to be free from any ramp rate limitations [12] compared to that of conventional generators. The faster up and down regulation possibilities of V2G could relieve or minimize 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 by subtracting the insufficiency of the EV battery storage in meeting the regulation power. The generator units are allocated their regulation shares through economic dispatch functions, like the simple participation factor method, $pf_1 \ldots pf_n$, where the $\sum pf = 1$[19]. The LFC parameters for the generation units used in simulation are given in Table III.

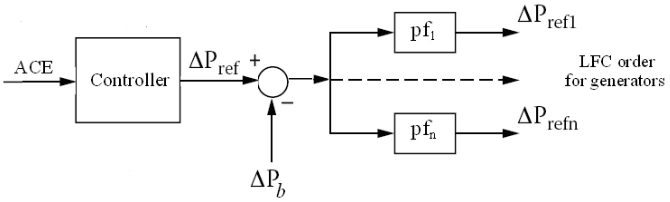

Fig. 7 Load frequency control

The LFC simulations are performed for the typical winter day for West Denmark where time series data given in figure 4 are used. The key battery and LFC parameters used in the simulations are given in table IV. A proportional gain of 0.5 and integration time constant of 150sec are used as parameters for the PI controller in the simulations. The higher time constant is considered to ensure a smooth LFC operation and to avoid any interference with the normal primary regulation [20].

TABLE III UNITS PARTICIPATION FACTORS AND RAMP RATES

Unit	Participation factor	Ramp rate (% per minute)
Centralised power plant	0.8	4%
Decentralised power plant	0.2	10%

TABLE IV KEY BATTERY AND LFC MODEL PARAMETERS

Battery gain (kA/LFC signal)	10
Converter time delay (sec)	0.5
V2G Activation delay (sec)	4
Filter time constant (sec)	1
Series resistance (Ω)	0.013
Transient capacitance (F)	1F
Transient resistance (Ω)	0.001
LFC proportional gain	0.5
LFC integrator time constant (sec)	150

Figure 8 shows the simulated power deviation without V2G obtained from the LFC simulations and the measured available data. The simulated deviations without V2G are considered as the reference case where only the thermal generators participate in the load frequency control. The responses are reasonable in comparison except the sharp and peak values in actual data. This is because the simplified LFC model may not replicate many shorter events that could happen within a highly dynamic power system operation. Most of peaks are related to the hourly power shifts for updating the planned generation. Figure 9 depicts the actual available LFC signal and the simulated response. The deviations visible in the responses could be due to the differences in the simulation system parameters of the simplified LFC and generators model from the real data. Nevertheless, similar to the simulated deviation, the LFC simulated signal provides a reasonable agreement with the real time data. This is sufficient enough to analyse the LFC model with V2G system for regulation services in the West Denmark power system.

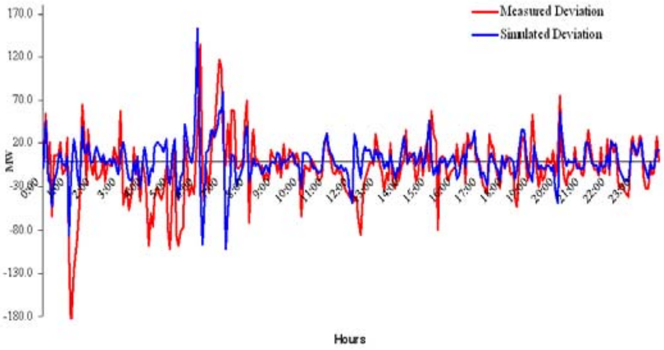

Fig. 8 Measured (red colour) and LFC simulated (blue colour) power deviations with Germany for a typical windy day in West Denmark

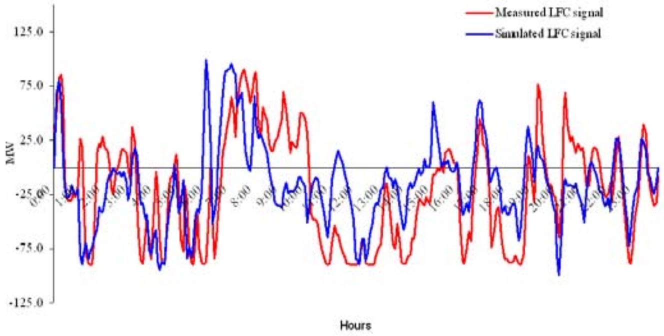

Fig. 9 Measured (red colour) and LFC simulated (blue colour) regulation requirement for a typical windy day in West Denmark

As it has been observed from Figure 5, an aggregated EV storage of 90MW, 360MWh was unable to provide complete regulation for the typical day considered. To validate the same through LFC simulations, two configurations of battery storages are analysed. First the V2G base case of 90MW, 360MWh and a second case, a five times larger battery storage (450MW, 1.8GWh) is considered which is termed here as V2G+.

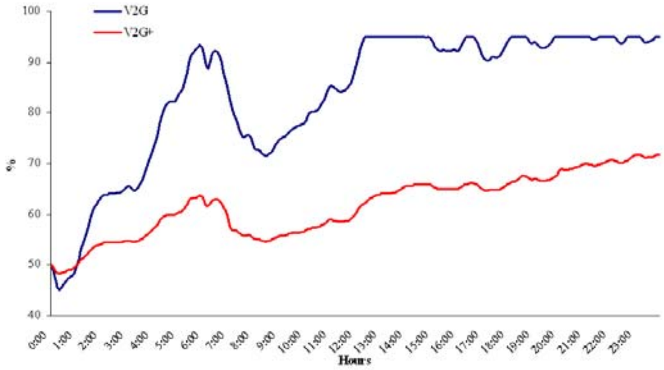

Fig. 10 Battery state of charge from V2G base and V2G +simulation cases

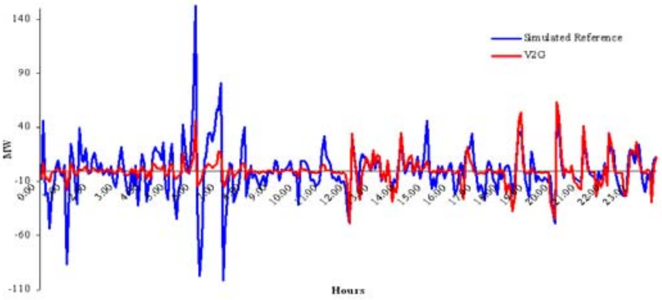

Fig. 11 Power deviations with Germany from the LFC simulations (reference case) without V2G and with V2G base case

Figure 10 shows the simulation results of battery state of charge for the two configurations of the V2G system participating in the LFC regulation. The initial battery state of charge was assumed to be 50%. The base case V2G is fully charged at many instants, such that the regulation capability is lost. The V2G+ provides a better regulation and maintains an acceptable state of charge limits. The power deviations are minimised by the faster V2G regulation compared to the reference case during the instants where the battery storage capacity is available which is shown in Figure 11. Figure 12 shows the minimised power deviations obtained from V2G+ case. The deviations are significantly lesser than the V2G base case as it has larger battery storage than the former. The V2G+ battery size is indeed realistic with less than 10% of total V2G contract electric cars in West Denmark. This percentage could be further reduced with future higher energy storage electric vehicle batteries.

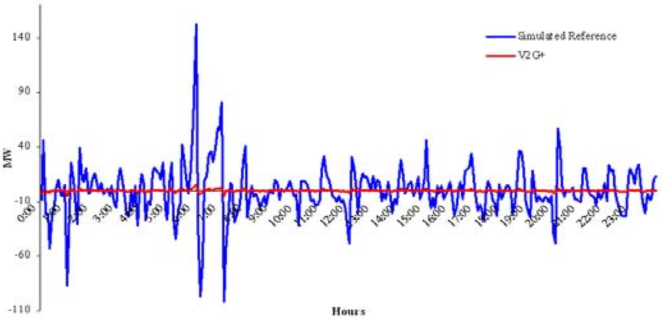

Fig. 12 Power deviations with Germany from the LFC simulations (reference case) without V2G and with V2G+ case

VI. CONCLUSIONS

The vehicle to grid can provide faster reserves unlike conventional generators, by charging and discharging the stored energy during the regulation service. This unique property is well suited and essential to support the integration of large amounts of fluctuating wind power in future Danish power system. The V2G is a feasible solution for a large future reserve power requirement which could substitute the traditional generation resources. The investigation is carried out with a simplified load frequency control model with aggregated V2G system model for the West Denmark power system. The simulated power deviations and regulation requirement using the simplified LFC model could fairly match the actual data.

The grid related constraints were neglected in the model. It was observed that, less than 10% of V2G based electric vehicles could provide sufficient regulation services for a typical day with 45% wind power production. The power deviations are observed to be significantly reduced by faster V2G regulation. This could benefit the power system operation in minimising congestions and deviations of electricity balancing and market prices against the system price. The unpredictable regulation signal may at times fully charge or discharge the V2G system storage. As a simplified solution using aggregated model, a larger storage capacity was used in the study to overcome this limitation. Optimal solutions are possible by better vehicle management system at the vehicle aggregator levels. The V2G system concept is still in its investigation stages. The distinctive features of electric vehicles like cost benefits from power regulation to the vehicle owner, environmental friendly vehicles, renewable energy support, improved versions of high capacity efficient batteries, and initiation of pilot V2G projects gives an added advantage to the promotion of V2G regulation services. Taking into account a large proportion of wind power generation in the power system, the LFC model with V2G system combined with wind power regulation and sensitivity analysis of relevant LFC parameters are planned as part of further work.

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