# Frequency response from electric vehicales

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*Abstract*—**The contribution of plug-in Electric Vehicles (EV) for frequency response was investigated. 24-hour EV load profiles obtained from a probabilistic approach was used. Three time dependent charging modes were considered. A single bus model of Great Britten power system was used for simulations. Simulations were carried out for a day with low demand. The simulation results shows that shedding EVs that are charging can reduce the frequency excursion significantly.**

***Keywords - Frequency response, Electrical vehicles, Smart meter, Virtual power plant, Power system inertia***

## I. INTRODUCTION

A number of countries have taken specific policy initiatives to encourage renewable power generation and for introducing electric vehicles as they contribute to decarbonise their electrical energy and transport sectors. For example, in the UK, 15% of all energy is to be supplied by renewable energy by 2020. This translates into 30 - 40% of electrical energy being generated from renewable sources. It is anticipated that a large proportion of this power will come from wind power. Perhaps up to 40 GW of wind turbine generation on a Great Britain (GB) system with a total of around 100 GW of generating plant. The UK government also has plans to cut emissions from domestic transport by 14% on 2008 levels by 2020.

The uncertainty brought by variability of renewable energy generation will introduce a number of concerns over operation of the power system. A very high penetration of renewable energy sources demands considerable increase in frequency response and reserve that the system operator should maintain to ensure frequency performance within the control limits [1][2].

In this paper, the flexibility offered by plug-in electric vehicles (EV) by removing their charging load immediately after a frequency event is investigated. It is anticipated that this will enable operation of the future power system with current level of reserve margins.

The paper is organized as follows: initially the frequency control in the GB system is discussed; secondly integrating EVs for frequency studies is discussed; then modeling of the GB system with EV for frequency studies are discussed and finally results are presented.

## II. FREQUENCY CONTROL IN THE GB SYSTEM

Frequency is determined and controlled by balancing system demand and total generation. The nominal frequency of the GB system is 50Hz. If the demand is greater than the generation, the frequency falls below 50Hz. Conversely, if the generation is greater than the demand, the frequency rises above 50Hz. In practice, the frequency varies around 50Hz by a small amount as the system demand continuously changes. When there is a significant power imbalance of the system, the frequency will show a large deviation.

The Electricity Supply Regulations require the system frequency to be maintained at 50Hz ±1% [1]. The Transmission License places an obligation on the National Grid Company (NGC) to plan and operate the system to ensure compliance with the Electricity Supply Regulations [2]. To meet these obligations the system is designed to accept the largest credible loss of 1320MW of generation (two of the largest generators, 2×660MW, on the system) and is operated to the following frequency containment policies:

- System frequency under normal operating conditions will be maintained within the operational limits of 50±0.2 Hz (NGC's current practice),
- For a sudden loss of generation or demand up to 300MW, the maximum frequency change will be limited to ±0.2Hz,
- For a sudden loss of generation or demand greater than 300MW and less than or equal to 1000MW, the maximum frequency change will be limited to ±0.5Hz,
- For a sudden loss of generation greater than 1000MW and less than or equal to 1320MW, the frequency change will be limited to –0.8Hz with frequency restored to 49.5Hz within 1 minute.

Any loss of generation greater than 1320MW will be treated as an emergency condition as it may cause the system frequency to fall below 49Hz. Automatic low frequency load shedding arrangements usually commence at 48.8Hz. In the event that the frequency is above 52Hz or below 47Hz, the independent protective actions are permitted to protect generators against danger to plant and/or for personnel safety.

A typical frequency transient for a generation loss of 1320MW is shown in Figure 1 [3][4].

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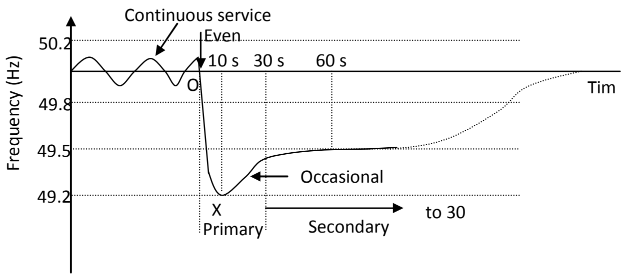


Figure 1. Typical frequency deviation following a loss of 1320MW generation [3]

Even though EVs are considered as an ideal choice for providing primary and secondary response, they have a negative effect during phase OX (see Figure 1). As modern wind turbine generators and EVs are connected to the grid through a power electronic interface, they will not contribute to the system inertia. This reduction in the overall system inertia and the increase of demand will lead to rapid change in frequency during phase OX.

## III. INTEGRATING EVS FOR FREQUENCY SERVICES

An EV could participate in low frequency response services mainly in two ways. Easiest approach would be to switch off all EVs that are charging. This will introduce a proportional reduction in load, thus reducing the frequency excursion. In an event of a high frequency event all the plug-in EVs that are in stand-by mode with the state of charge of battery is less than 100% could be charged thus adding an additional load to the grid. EVs could also support the grid by acting as an energy store. For example during a low frequency event, EVs could discharge its stored energy thus acting as a distributed energy source. This paper concentrates on former aspect that is disconnecting a charging fleet of EVs during a frequency event.

The way EVs could participate for frequency services depends on the grid operator. For example, in the UK the frequency response services such as *Firm Frequency Response* (FFR) and *Frequency Control Demand Management* (FCDM) allow demand side participation in primary frequency control. The large-scale consumers are contracted in advance to switch OFF their loads (more than 10 MW and 3 MW in FFR and FCDM respectively) during a frequency excursion. In FFR and FCDM schemes, the contracted consumer should reduce load within 30 sec and 2 sec and maintain 10min and 30 min respectively.

### A. Individual EV on a frequency-responsive switch

The demand side support for frequency reserve by controlling loads was proposed as early as in 1980 [5]. The paper proposed a frequency-responsive switch which controls significant energy consuming industrial or domestic loads. A similar switch could be utilized at each EV to switch them off when a frequency excursion occurs.

Recently, Smart Meter (SM) has drawn wide attention as a device which can help to save energy and to improve the efficiency of a power system. A number of initiatives that deploy smart meters are reported in [6]. The SM has a two-way communication between the supplier and also with domestic appliances including EVs connected to home area network (HAN). On the receipt of a signal from suppliers, the SMs could send signals to the control units to shed the EV immediately.

### B. EV as a virtual power plant (VPP)

Several studies have identified the potential of EVs to participate in the electricity markets [7][8]. As power capabilities of an individual EV is rather small, their participation in the electricity markets will require a new entity: the EV Supplier/Aggregator (EVS/A). The EVS/A will serve as an intermediary between a large number of EVs and market players and/or system operators [9]. The role of the EVS/A is to cluster geographically dispersed EVs, and manage their generation and demand portfolios as a single entity.

The Virtual Power Plant (VPP) concept is an aggregation model which aims to overcome the challenges of Distributed Energy Resources' (DER) integration and enable their market participation. The VPP concept is considered as an ideal candidate for EVS/A. Figure 2 shows how the VPP interacts with the system operators (DSO and TSO). Upon recognizing a frequency excursion, the system operator could instruct the VPP to shed some or all of the charging EVs.

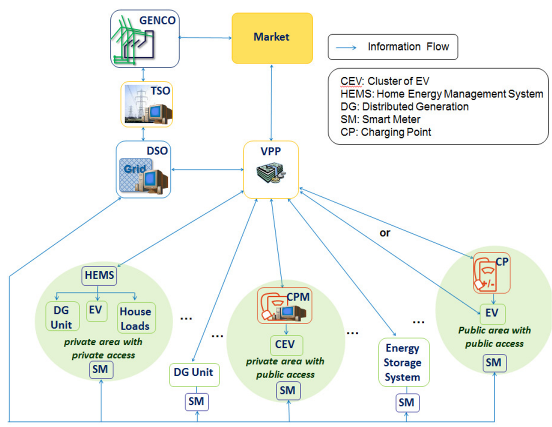


Figure 2. Integration between the VPP and grid operators [10]

## IV. MODELLING OF POWER SYSTEM AND EVS FOR FREQUENCY STUDIES

### A. Power system representation

Assuming a coherent response of all generators in the system to changes in the load, the power system can be represented by an equivalent generator [11]. The equivalent generator has an inertia constant $H_{eq}$ and calculated using the following equation:

$$H_{eq} = \sum_{i=coal,gas,.....} H_i * \frac{S_i}{S_{sys}} \qquad (1)$$

where $H_i$ and $S_i$ are the inertia constant and MVA rating of the individual power plant.

A simple model representing the inertia and damping of the GB system without the contribution due to governor action of synchronous generation is shown in Figure 3. In the model ΔPm refers to change in mechanical power of all the generators on the GB system and ΔPL is any change in total load. The damping providing by rotating loads is lumped into a single damping constant *D*.

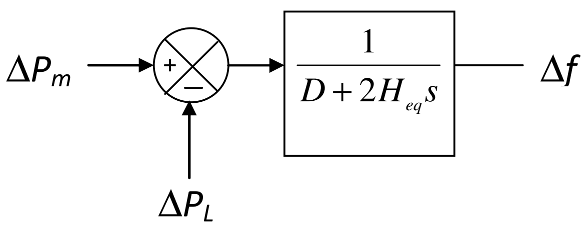


Figure 3. The system equivalent for frequency control analysis

### B. Turbine-governor model

The composite power/frequency characteristic of the power system depends on the combined effect of the droops ($R_1, R_2$, ---, $R_n$) of all generator speed governors. It also depends on the frequency characteristics of all the loads in the system. For a system with the n generators and a composite load-damping constant of D, the steady-state frequency deviation $\Delta f_{ss}$ following a load change $\Delta P_L$ is given by equation (2).

$$\Delta f_{ss} = \frac{-\Delta \boldsymbol{P_L}}{(1/\boldsymbol{R_1} + 1/\boldsymbol{R_2} + \cdots + 1/\boldsymbol{R_n}) + \boldsymbol{D}} = \frac{-\Delta \boldsymbol{P_L}}{1/\boldsymbol{R_{eq}} + \boldsymbol{D}} \qquad (2)$$

where, the composite governor speed droop can be written as equation (3):

$$\boldsymbol{R_{eq}} = \frac{1}{1/\boldsymbol{R_1} + 1/\boldsymbol{R_2} + \cdots 1/\boldsymbol{R_n}} \qquad (3)$$

The typical speed droop setting for both thermal and hydro generator governors is around 5% in per unit value. Thus, a system (as above) with a number of machines, each with a droop of 5%, will have a total system speed droop $R_{eq}$ of 5%. However, the actual speed droop may range from 2% to 12%, depending on the different types of unit [11].

Taking account of the characteristics of steam and hydro turbines in the system, a system turbine-governor model shown in Figure 4 can be derived. The speed control of the turbine is provided by a droop governor with an equivalent gain value, $R_{eq}$. It operates on an input of the speed deviation formed between the reference speed and the actual speed. This changes the governor valve (steam turbine) or gate (hydro turbine) position. The typical governor actuator time constant, $T_G$, is 0.2 second. For a stable performance of the speed control, a transient-droop-compensation, which is a lead-lag transfer function with time constants $T_1$ and $T_2$, is introduced between governor and turbine. The turbine relates the response of mechanical power output following the governor action and is characterized by a time constant $T_T$ which varies between 0.3 and 0.5 second.

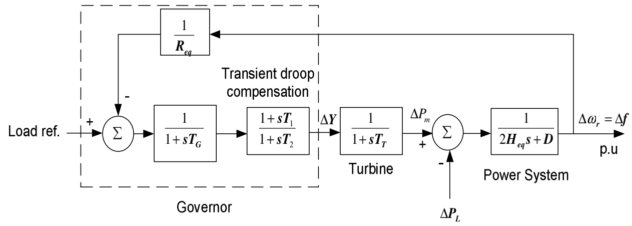


Figure 4. Block diagram of a system turbine-governor model

The parameter values of the single generator model shown in Figure 3, were obtained through parameter identification and model validation. A severe frequency event shown in Figure 5 which occurred in the UK on 27th May 2008 was used for validation.

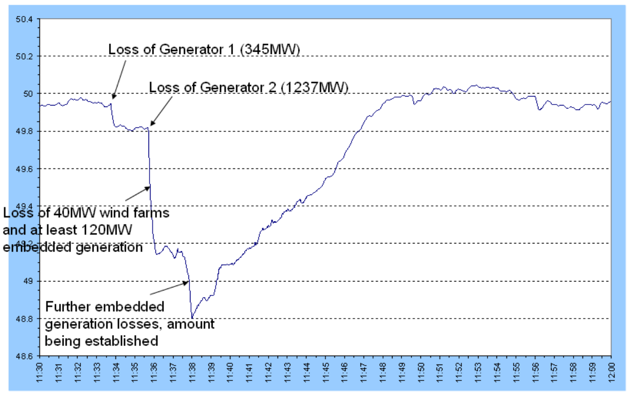


Figure 5. Frequency response on 27th May 2008 (http://www.nationalgrid.com/NR/rdonlyres/D680C70A-F73D-4484-BA54-95656534B52D/26917/PublicReportIssue1.pdf)

### C. EV representation

To investigate the impact of the EV participation, a vital step is how to obtain realistic 24-hour EV load profiles. Different from conventional load forecasting, there is no historical EV use data available for reference. A feasible way is to generate the profiles via reasonable predictions and assumptions of EV market penetration, technical specifications, and use patterns (especially charging patterns), etc.

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To determine regular EV charging profile a probabilistic approach was used. More details of this approach could be found in [12]. In this study three time dependent charging modes, namely, after-work charging, on-work and after-work charging and delayed night charging were considered. The EV power demand profiles for 2020 were obtained for three charging modes and shown in Figure 6. The information used in this study in mainly from reference [6].

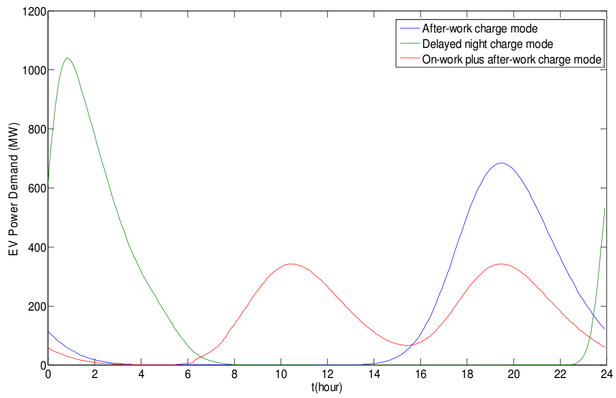


Figure 6. EV power demand profile for three charging modes considered

### D. The GB system model

The model shown in Figure 4 was used to investigate the contribution of EV for the frequency response. $H_{eq}$ was calculated for 2020 system assuming the generation schedule and inertia constants shown in Table 1.

TABLE I. OVERALL INERTIA CONSTANT OF THE GB SYSTEM

| Generator type | Assumed Capacity GW | $H_i$ | $H_{eq}$ |
|---|---|---|---|
| New Coal | 2.41 | 6.0 | 0.23 |
| Coal | 9.30 | 6.0 | 0.88 |
| Gas | 15.02 | 9.0 | 2.13 |
| Nuclear | 6.00 | 4.5 | 0.43 |
| Interconnector | 3.30 | 0.0 | 0.00 |
| Other | 4.76 | 6.0 | 0.45 |
| Onshore wind | 5.72 | 0.0 | 0.00 |
| Offshore wind | 13.68 | 0.0 | 0.00 |
| Other renewables | 3.36 | 6.0 | 0.32 |
| Total | 63.54 | | 4.44 |

Figure 7 shows the model used to investigate the EV frequency response for the 2020 GB system. It was assumed that immediately after a frequency event is detected, EVs which are charging on the power system are disconnected using a frequency sensitive switch. This model was implemented in MATLAB/Simulink.

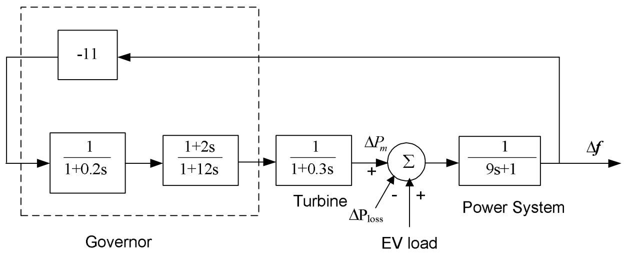


Figure 7. GB system model to investigate EV frequency response

## V. RESULTS

Based on the obtained EV power demand profiles and the developed GB system model, the contribution from EVs for frequency response was studied. Figure 8 shows the EV contribution to the primary frequency response under different EV loads and low total demand condition. It is assumed that demand in 2020 is as same as in 2008 due to electricity network efficiency improvement activities in GB. The demand used in the simulations is the minimum summer GB demand in 2008 plus the three EV load profiles shown in Figure 6. It is assumed that the EV loads will be disconnected as soon as frequency starts to drop.

## VI. CONCLUSIONS

The importance of frequency response from EV in a regime where there is a high penetration of renewable energy generation is demonstrated in this paper using computer simulations. A single bus GB system was used for simulations. The system inertia was determined to reflect the high penetration of renewable energy sources.

EVs were modeled using its demand curve over a day. Three charging modes namely, after-work, on-work and after-work, and delayed-night charging were used to construct the EV demand curves. During a low frequency event, the charging load was shed to provide frequency support. Simulations show that EV load has a significant contribution to reduce the frequency excursion. Highest effect was obtained with delayed nigh charging mode, if a frequency event occurs at mid night. At this time frequency drop can be reduced from 1.2% to 0.2%.

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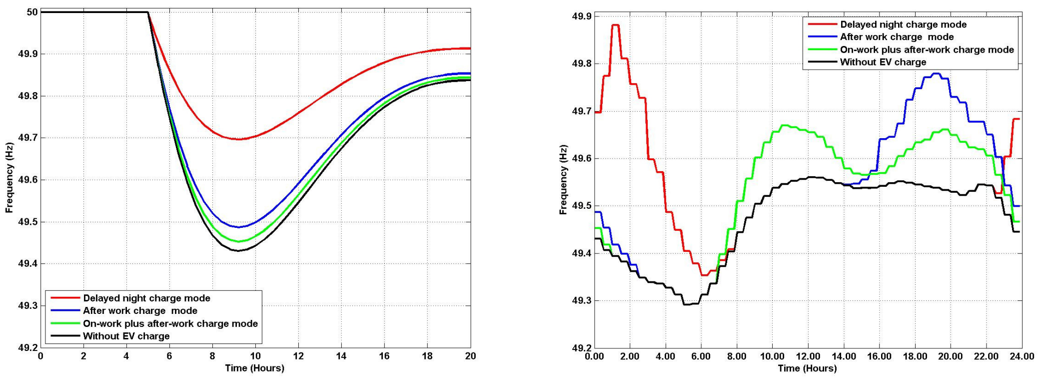


(a) Frequency drops at 00.00 hrs

(b) Maximum frequency drops at every 10 min during a day

Figure 8. The graphs when 1320 MW generation is lost in 2020 GB system (with minimum demand).