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Vehicle-to-grid response to a frequency contingency in a national grid

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Vehicle-to-grid technology enables electric vehicles to contribute their large, high-power batteries to power systems reserves. Here we report the first demonstration of a fleet of vehicles discharging to support system security after a frequency contingency in a national grid. Our results highlight the potential of vehicle-to-grid, with vehicles discharging within 6 s of the contingency event, and shortcomings, with vehicles recommencing charging before the power system had fully recovered.

Vehicle-to-Grid (V2G) technology enables Electric Vehicles (EVs) to discharge power from their batteries into electricity grids. Since its conception in 1997, V2G has been motivated by three sustainability goals, as a way of (1) providing the energy storage capacity required to "facilitate large-scale integration of intermittent-renewable energy resources"[1], (2) reducing material consumption by "using electric vehicles when they are parked and underutilized"[2], and (3) by "foster[ing] EV adoption … add[ing] a revenue stream for EV owners"[3].

Of the many ways in which V2G can be used in service of these goals, we here focus on V2G supporting power system security. This use is defined by the need for very rapid (dis)charging responses, on the timescale of seconds, in contrast to longer duration V2G energy storage applications, such as balancing the availability of renewable energy[4], energy market arbitrage[5] and electricity bill management[6]. Power system security relies on two components: control systems for constant regulation of voltage and frequency, and reserves that can be dispatched to respond to unforeseen contingencies (as illustrated in Fig. 1). These services have been popular with V2G developers because they do not consume large amounts of battery energy. The provision of backup reserves doesn't draw any energy from vehicles except during rare contingencies. The provision of frequency support has been included in at least 57 demonstration projects[7]. These projects have generated substantial data on the performance of V2G for regulation services, where vehicle (dis)charging levels are updated every few seconds based on a control signal[2,8]. In contrast, the provision of V2G contingency frequency support has been demonstrated in laboratory tests[9] and is enabled in multiple trials, but it has not, to the best of our knowledge, not been observed in response to a real-world grid contingency.

This paper reports on the response of 16 V2G EVs to a contingency that occurred in the Australian national grid on the 13th of February 2024 which caused 90,000 customers in Melbourne to lose electricity supply[10]. The EVs are part of a fleet of 51 Nissan LEAF vehicles that deployed as part of the Realising Electric Vehicle-to-Grid Services (REVS) project, together with 51 bidirectional chargers[11] and charge control systems designed to provide frequency support services[9].

At the time of the contingency the 16 EVs were plugged in to chargers at six properties across Canberra, about 500 km from the location of the downed transmission lines that caused the contingency. Fig. 2 presents the power system frequency and power imports recorded on high-speed power metres at the six properties (25 ms time resolution, frequency data is averaged across the properties while power is summed). It shows that the contingency underfrequency trigger of 49.85 Hz was crossed at 13:09:43, at which point the power imports of the properties quickly began to decline from an average of 799.9 kW in the minute before the event to 699.0 kW at 13:09:57 and 662.9 kW 13:11:18. Such a decrease in power demand is precisely what is needed to correct the power supply-demand imbalance evidenced by an underfrequency (see Fig. 1).

This decrease in import power exceeds the combined discharging capacity of the 16 chargers, which is limited to 80.0 kW due to a 5.0 kW export limit being imposed on each charger to meet the phase balancing requirements specified by the distribution network operator[11]. Fig. 3 shows the charging powers of the 16 EVs, as recorded by the chargers. These data have a lower temporal resolution of 30 s but extend for a longer period than the high-speed data that are only recorded for 10 min after a contingency event (due to data storage limits). This reveals that an additional 27.1 kW of the observed decrease in property import power can be attributed to the termination of charging by four V2G vehicles as their first step in responding to the contingency. This data furthermore confirms that all 16 vehicles discharged at their (constrained) maximum of 5 kW within 60 s of the frequency trigger and remained at this power level for ten-minutes, as specified by the Australian National Electricity Market rules for contingency frequency services[12]. This modest power ramping is due

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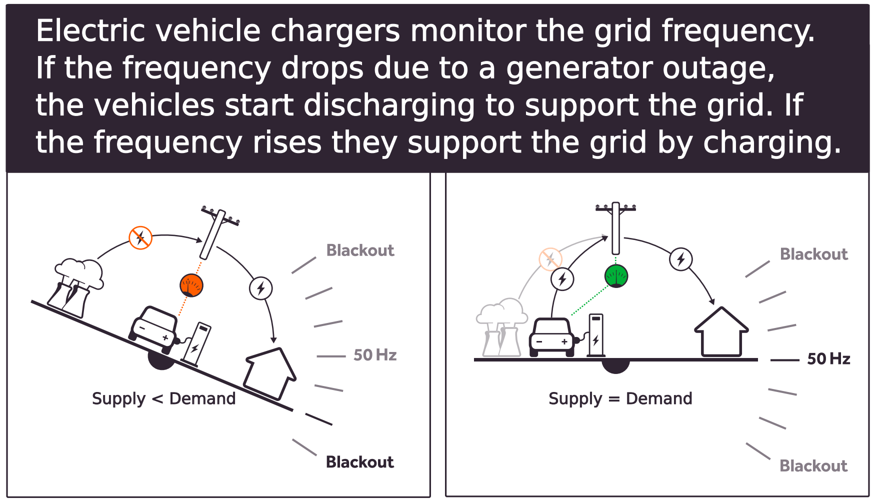

Fig. 1 | Infographic of vehicle-to-grid contingency frequency response. Illustration of how power supply-demand imbalance during a contingency event where a generator trips offline (as occurred on the 13th of February 2024 near Melbourne, Australia) impacts grid frequency and how V2G can contribute to restoring balance and frequency.

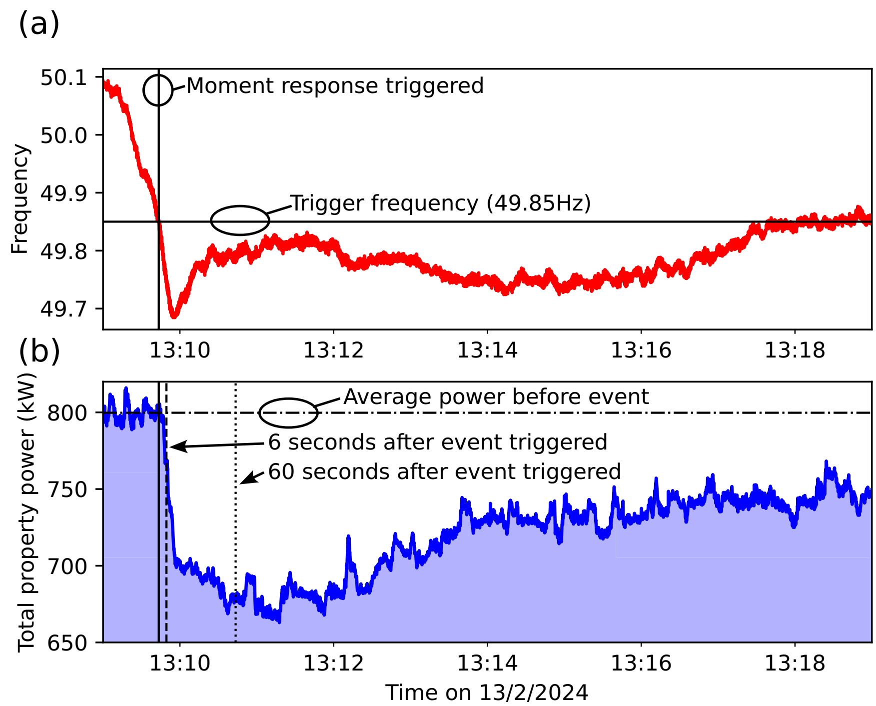

Fig. 2 | Grid frequency and total property power consumption. a Frequency of the Australian power system as recorded by high-speed power metres at six properties in Canberra for the ten-minute period from 13:09 (trace shown is their average). **b** Total power imported across the six properties.

to a constraint applied by the charger manufacturer's implementation of Australian Standard 4777.2:2020[13]. In laboratory testing we recorded chargers reaching their full rated discharge of 5.5 kW within 4.5 s[9]. The total impact on the V2G response was therefore 107.1 kW, which is consistent with Fig. 2 – accounting for the variability in the properties' other loads.

Taken together, these results represent the first known demonstration of V2G contingency frequency response in a real-world grid. They demonstrate the success of V2G in providing a high quantity of high-speed, high-quality frequency response services, and doing so from assets (EVs and chargers) that were otherwise idle (or were making the contingency supply-demand misbalance worse by charging).

However, the data also reveal shortcomings of the current V2G implementation (and the market driven approach to frequency control that they are designed to). This can be seen in the chargers' behaviour immediately after the ten minutes of specified discharging, when nine chargers began to charge at their maximum power of 6.3 kW. This led to a power swing of 129.1 kW in 2 min from 13:19 (from −80.04 kW to 49.07 kW), of which 99.3 kW occurs in the minute from 13:20 (from −49.6 kW to 49.07 kW). These results would be worse were it not for a software bug that led two chargers to continue to discharge (for two and ten minutes).

While the root cause of this behaviour is the specifications of the frequency services market, the addition of load to the power system—particularly so rapidly—is antithetical to the recovery of the power system from a contingency. In this case, the EVs added load before the power system frequency had fully recovered to 50 Hz (at 1:23[14]), with the frequency having only just exceeded the lower operating threshold of 49.85 Hz at 13:18. This highlights the need for improving the integration of EV charging with the systems and standards for power system security.

This point is further emphasised by data we collected from the rest of the ACT Government EV fleet in the garages of the 6 properties (that were not part of our project and are not enabled with V2G). This revealed that 23 EVs were charging throughout the event

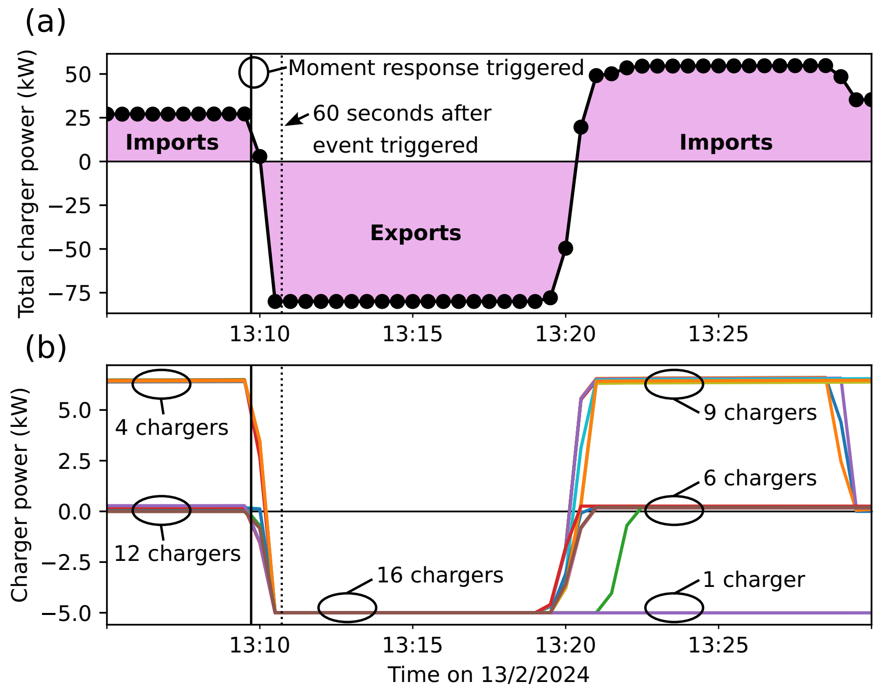

Fig. 3 | (Dis)charging profiles of individual electric vehicles. EV charging and discharging power as recorded by the bidirectional chargers. **a** Total power for 16 chargers combined. **b** Power of each charger individually.

with an average power draw of 30.8 kW. Stopping this charging, together with the charging of the four V2G EVs that were charging at the outset of the contingency, would have created a contribution of 57.9 kW to power system frequency restoration without the use of V2G. While this is less than the 80.0 kW contribution from V2G discharging, it illustrates the potential to make very substantial contributions to power system security from well managed uni-directional (non-V2G) EV charging. To put this in perspective, the load shedding of 90,000 customers would be equivalent to stopping 60,000 EV's charging at 5 kW. Stopping this amount of EV charging demand will quickly become a practical opportunity, even factoring in the uncertainties in vehicle availability and charging profiles, for 60,000 vehicles is less than 1.2% of the vehicles registered in the State of Victoria (in which Melbourne is located).

Coupled with the evidence of high-quality V2G provision of contingency frequency response, this analysis makes a strong case for the importance of enlisting EVs to support the power system (on which they ultimately depend also). This is particularly the case given the low impacts of pausing EV charging and/or discharging small portions of vehicles' battery capacities using V2G compared to the potentially severe impacts of disconnecting customers, as well as the substantial financial and carbon costs of procuring power reserves from generators.

The adoption of such EV grid services requires two major investments. Firstly, into the development of control systems that account for the mass adoption of EVs and, consequentially, the significant impacts that EV (dis) charging actions can have on the power system dynamics to avoid introducing system shocks. These will likely be similar to the droop algorithms used for voltage control—which in Australia is only required of bidirectional chargers, again missing the major opportunity for unidirectional charging to support the grid – and are in development in multiple jurisdictions (for example National Grid in the UK[15]). Secondly, a parallel investment must be made into social research to direct the evolution of these technologies towards socially acceptable models[16,17].In conclusion, our results demonstrate the successful provision of frequency support from V2G in response to a contingency in a real-world power system. This builds confidence that V2G can truly delivery system security services in real-world conditions. The data from the V2G response indicates aspects that could be improved for our particular V2G implementation and frequency control market settings. Additionally, we identified significant opportunities for all EVs (including non-V2G enabled EVs/chargers) to contribute to a more secure and sustainable power system by responding to grid conditions by pausing their charging.

Data Availability

All presented data, from vehicle chargers and grid connections, have been deposited in the Zenodo repository with doi: 10.5281/zenodo.11195210.

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Author contributions

B.C.P.S. wrote the manuscript and prepared the figures. L.H. collated the presented data. All authors contributed to the project that designed and deployed the vehicle-to-grid system and reviewed the manuscript.

Competing interests

The authors declare the following competing interests: L.H. is an employee of energy retailer ActewAGL, J.B. is an employee of electric vehicle charging systems company JetCharge.

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