

Whole System Modelling of V2G Power Network Control, Communications and Management

J. Donoghue¹, A. J. Cruden¹

James.Donoghue@soton.ac.uk A.J.Cruden@soton.ac.uk

*¹Electro-Mechanical Engineering Group, Faculty of Engineering and the Environment,
University of Southampton, UK*

Abstract

This paper presents an investigation into the potential benefits of the provision of V2G (Vehicle to Grid) ancillary services, from the aggregated utilisation of a number of grid connected electric vehicles (EV) batteries, through the use of a bi-directional converter between the EV and the electricity grid. Further, the V2G charger must be capable of remote control from a central V2G management centre facilitated by an on-board GPRS enabled communications interface. The authors have developed, and will discuss, the design, integration, simulation and operation of a whole system V2G model through exploration of 4 key areas of research: Power system integration, covering the development of an on-board bi-directional charger; V2G Communications, focusing on streamlining the network communications needed by a truly mobile charging unit; System management, the software and control techniques to manage a large number of V2G enabled vehicles enabling automation of service provision to be investigated; Power network simulation, discussing development of a software simulation package designed to provide realistic grid data to the management software to facilitate more accurate development of control algorithms within the management suite.

1 Introduction

There is a clear need for increasing amounts of electrical energy storage to be available for use within future power systems, particularly where large renewable energy penetrations are forecast [1,2] in order to tackle some of the key problems that could potentially arise if the load on the network was to increase by predicted amounts over the next decade [3]. Utilising the large aggregate battery storage capacity of many EVs being plugged into the grid at one time to provide ancillary services such as frequency regulation and load balancing is one possible solution currently attracting attention. It promises end users monetary incentives to allow electricity

suppliers to buy, at premium, small quantities of energy from their vehicle batteries during peak load times. This is known as Vehicle-to-Grid (V2G) technology and is briefly outlined in Fig 1.

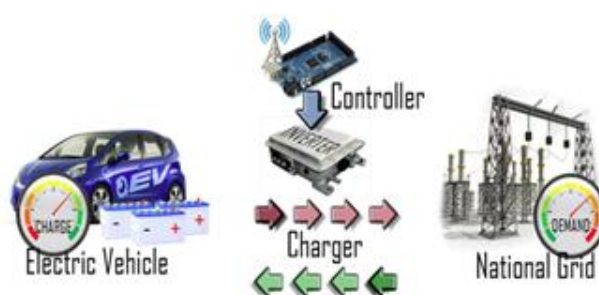


Fig 1: Simple V2G Concept Overview

1.1 Load Balancing

In 2011 the UK harvested over 12,000 MW of renewable power, with over 4,000 MW coming from onshore wind generation [2], and this number is set to steadily increase as more distributed generation sources are connected to the grid. The main problem with renewable sources is their unpredictability and the difficulties involved with regulating their generation. In order to prevent potential power going to waste during times of low demand it must be stored for later use. The UK's current dominant source of energy storage lies in its meagre 2,788 MW capacity pump storage hydroelectric stations [4]. V2G Aims to provide the network with a large aggregate distributed capacity of highly efficient battery storage that can be used to bolster the reserve capacity of the grid, allowing for reduced dependency on non-renewable sources.

1.2 Frequency Regulation

Throughout a standard day electricity demand constantly fluctuates. Load Serving Entities (LSE) attempt to predict in advances how much power they will need throughout the course of each day and buy this capacity in advance from Generators. On the day, however, if demand rises higher than predicted the energy providers must start buying extra capacity at premium through the balancing markets. In order to be able to provide this extra generation the grid keeps a 'reserve' generation capacity on standby. This reserve generation can come from large coal and combines-cycle gas turbine (CCGTs) which the grid pays to run below full capacity, an inefficient process burning more fuel for every unit of energy generated. This reserve generation can also be supplemented by the pump storage stations. For larger, more infrequent imbalances the grid contracts a capacity of open cycle gas turbines (OCGTs) and diesel generators as 'standing reserve', as they are only run when necessary due to their much higher running costs [5]. V2G aims to reduce LSE dependency on such sources by providing a fast acting reserve of clean energy.

In order to properly facilitate the communications required to effectively manage such a V2G supported power system a robust foundation network protocol must be defined that is both efficient and compliant with modern standards, as

well as being secure. Other work in this field includes that done in 2011 by Yang et al. [6] which describes the basic architecture for a secure network protocol for V2G which incorporated identity-based public key cryptography, simplifying the certificate management as in traditional public key infrastructure (PKI), and restrictive partially blind signatures to protect the identity of the EV. This protocol was based upon a business model providing monetary incentives for customers partaking in the V2G scheme. This protocol was adopted and progressed by Tseng [7] who introduced a certificateless restrictive partially blind signature scheme based on work done by Wang and Lu [8] in 2008. This paper presents a simplified PKI solution, shown in Fig 2 that is uniquely targeted and optimised for the GPRS cellular network allowing a secure system to be established without the need for external key generation centres and pre-existing secure channels. This protocol will provide security while also requiring a minimal amount of computational power allowing the low power microcontrollers in each EV to effectively manage communications.

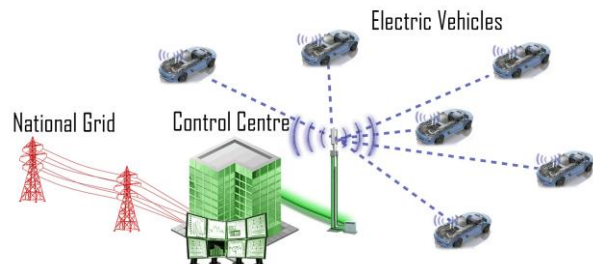


Fig 2: Communications network structure

In order to fully implement a V2G scheme a scalable, automatable, system management software suite must also be developed to maintain control of all EV's connected to the grid and to manage which vehicles are providing which services in their current location of charge. It must also be able to be expanded to meet the specific challenges presented by a growing and evolving V2G enabled dynamic power network. The author's management software solution presented here has the added ability of being able to simulate various grid demand situations through the use of a bespoke V2G power network simulation tool allowing system level scenarios of complex V2G operating algorithms to be tested and demonstrated through the software's integrated virtual testing environment.

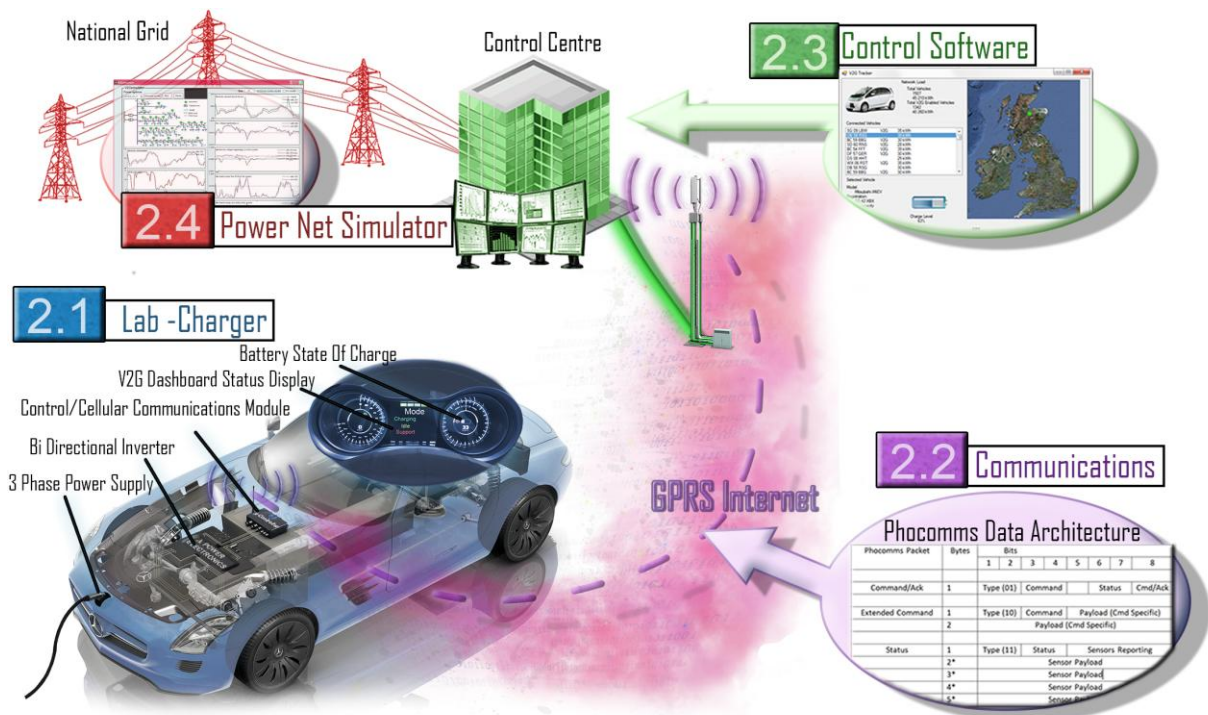


Fig 3: High level overview of a V2G enabled power system

2 V2G System Hierarchy

Fig 3 shows a high level overview of a V2G system, highlighting the four key areas of development by the authors within such a system. These specific areas will now be discussed in more detail.

2.1 Laboratory based EV Charger

The authors have developed a lab based single phase, 230V, 50Hz, battery charger, shown in Fig 4, as a basic demonstration model representing the 3 phase charging system normally found in an EV, this has been designed to demonstrate remote V2G control and communication, utilising a single low power microcontroller (MCU) to manage all the vehicle's computational needs. The chosen MCU is a Texas Instruments MSP430 based 16 bit mixed signal controller[9] with a von Neumann architecture designed specifically to suit low power and low cost applications while still providing a high level of performance and an array of common useful peripherals for integrated embedded systems[10]. This MCU interfaces with a simple H-Bridge inverter and feedback sensors. Internally it implements a software based look-up table styled algorithm to produce PWM control signals that allow the H-Bridge inverter to operate as a bi-directional charger. The MCU is also interfaced with a GPRS modem and GPS device through use of its embedded peripheral communications ports allowing data to be sent and received over the mobile cellular data packet network, thus allowing it to effectively communicate status updates including current

location, State of Charge (SoC) and mode of operation to the Control Centre (CC). Conversely this also allows the CC to send commands to the vehicle and set the mode and rate of charge/discharge that the vehicle should provide in order to effectively deliver V2G services.

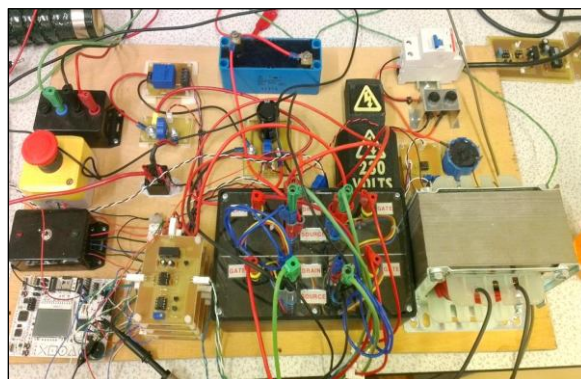


Fig 4: Lab based single phase inverter

The system aims to demonstrate some novelty through the integration of all computationally controlled aspects of the system from inverter drive control to communications onto a single, low powered, low cost MCU. This reduces the quantity of external circuitry components required and reduces the complexity of the system while increasing its robustness.

2.1.1 Preliminary results

Preliminary testing of the single phase MCU controlled demonstration equipment has proved promising with the target MCU comfortably operating at speeds of up to 40MHz. Running the

MCU at this speed has allowed communications infrastructure to be programmed into the firmware along with the controlling algorithms at no cost to signal generation performance. The MCU seems well capable of controlling the single phase inverter while also simultaneously being able to handle communications with the GPRS modem. Fig 5 shows a simple test circuit set up for preliminary testing. In this basic circuit the MCU is set up to control the simple H-Bridge and generate an AC waveform across a single 50mH load.

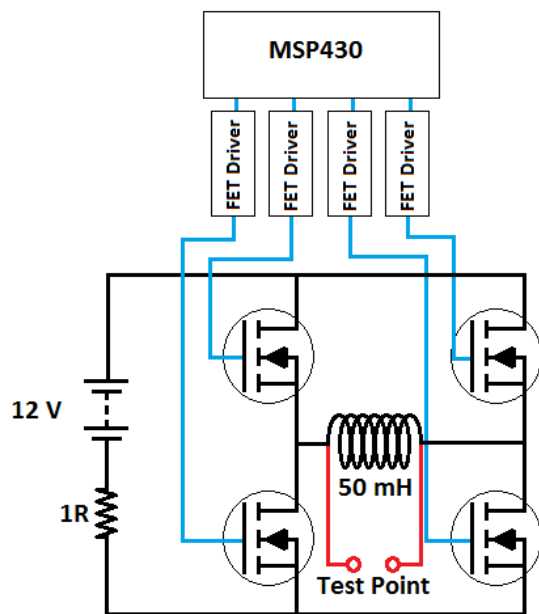


Fig 5: Simple test bed for H-Bridge control testing

Fig 6 shows the resultant signal generated at the load with the MCU set to a maximum switching frequency of around 2kHz. The dark blue trace shows the current through the inductor peaking at near to 12 Amps as the MCU attempts to match the frequency and phase of the light blue reference trace.

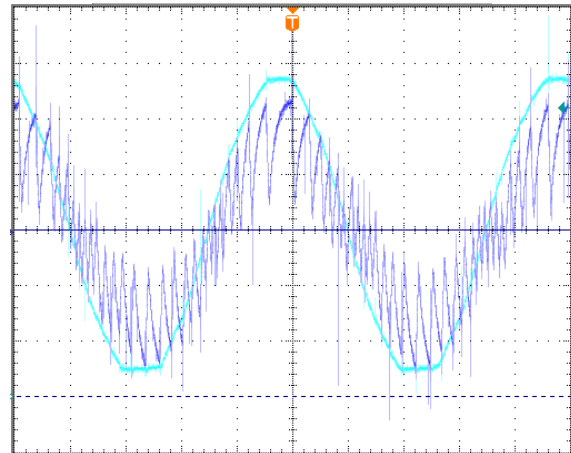


Fig 6: The darker trace representing current through the inductor at 2kHz maximum switching frequency

2.2 Communications

In order to effectively manage an integrated bi-directional charging system on an EV, the on-board control unit must be able to communicate with the national V2G CC securely and from anywhere in the country. As an EV could effectively be plugged in to the grid from any location it is important that each EV is not geographically locked within the management software. In order to address these challenges the author proposes a bespoke V2G communication protocol, Phocomms. This protocol is optimised for wireless GPRS communication of V2G related information including geographical location-based data and on board system status data in a secure stream and is based upon current IP standards for compatibility and currently relies on a simple PKI for standard levels of security while keeping computational costs to a minimum.

2.2.1 Optimisation

The mobile cellular network is an inherently lossy network suffering from large regions of poor signal quality and black spots all over the country. As each EV is able to freely roam through this network the communications protocol must be well equipped to handle operations in areas of low data signal quality and bandwidth provisioning. By optimising the quantity of data that needs to be sent and received over this network the systems reliability can be improved.

The Author's proposed protocol uses dynamically sized data packet structures to ensure that no more data is sent than required. This works by including a simple 2 bit packet type field as an identifier to the receiving system. This allows 4 types of packets to be defined. These packet types are:

- **Acknowledgement Packet:**
This is a fixed size packet that contains acknowledgement of receipt of data or commands and thus is the smallest of the packet types.
- **Command Packet:**
This fixed size packet contains only information related to direct commands such as setting mode or rate of charge/discharge. This packet type is also very small.
- **Simple Status Packet:**
Another fixed size packet that contains minimal information sent frequently to the CC such as current SoC. Also a very small sized packet.
- **Extended Status Packet:**
Dynamically sized packet dependant on what data is being sent. This type of packet has a second field that informs the receiver of exactly what sensors or information is included, or not included in the packet allowing the size of the sent packet to change depending on what has been requested, or the type of vehicle sending the data. This type of data packet has the potential of being very large to the order of many IP packets dependant on whether information being sent includes any kind of power quality monitoring data or waveforms.

2.2.2 Security

Data security is an issue that has been receiving a lot of attention in the press recently with rising concerns over privacy within public networks such as the internet.

Security within the Phocomms protocol is still under development but is currently handled by a simple PKI to keep computational costs to a minimum. The initialisation process, detailed in Fig 7, works as follows.

- The EV requests communications with the CC by making a request for comms over an unencrypted channel.
- The CC responds to the EV request providing its public encryption key to the vehicle to allow it to open a secure channel.
- The EV then transmits its unique identification to the CC. If the CC does not recognise the vehicle it requests a public key from the EV.
- The EV sends its public key to the CC which stores the public key along with its

unique identification for future authentication of signatures the next time the vehicle logs in to the server.

- The CC then requests specific user ID related login data using the vehicles own encryption key, If the vehicle responds with the correct details then the CC will go on to request a full status announcement and update the CC software interface with the new vehicle data.

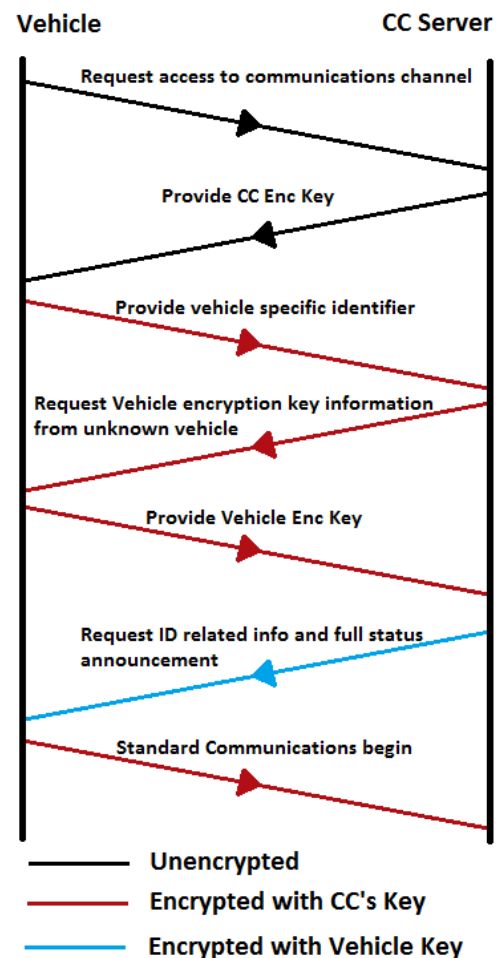


Fig 7: Infographic showing the standard communications procedure followed when an unknown vehicle connects to the network for the first time.

2.2.3 Preliminary results

The Phocomms protocol is still under development with initial tests proving promising. Command packets and status data is currently being sent and received by the author's lab based equipment, however, the efficiency of the optimisations and overall system security has yet to be fully determined.

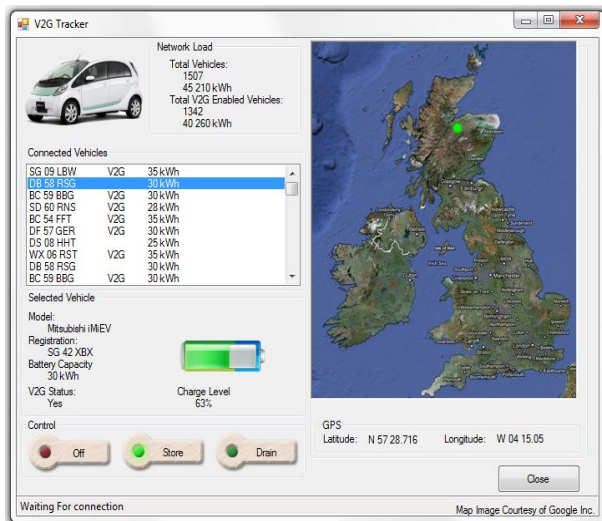


Fig 8: Basic V2G Management Software

2.3 System Control Software

An ideal V2G network, potentially comprising of thousands of connected vehicles, requires an intelligent software package to allow successful management of the system. This software must allow for communications with all connected vehicles and allow relevant data to be easily accessed by operators and system monitors. The software should also feature a degree of smart automation, and be able to intelligently make decisions based on current grid conditions about how best to utilise the fleet of connected EVs. The author's first basic demonstration system, presented in Fig 8, illustrates a graphical user environment where an operator can oversee a list of vehicles currently connected to the grid, and their geographical locations. Each vehicle displays location, SoC, battery capacity, charge/discharge rate limits and the V2G services enabled on the vehicle. The operator can also press buttons on the interface to send commands to the selected vehicle ordering it to enter charge, idle or V2G modes of operation.

This simple interface was designed purely as a demonstration of the types of data that would be useful to obtain for a V2G system and the type of basic control that would be possible.

2.3.1 V2G Management Suite

A new version of the Management suite is currently under development. Targeted at the Windows OS and based in C++ the new system allows a much more flexible and robust level of control over all areas of the application from the way it handles communications with each connected EV to the way it manages and segregates the pool of EVs available for use. Proposed features include the segregation of connected vehicles into regions, making it easier for the end user to navigate the potentially large list of connected vehicles. New visual outputs indicate which parts of the country have a 'healthy' V2G availability by colour coding each region depending on the number and availability of EV's in that area. Searches for specific EVs can be done by specifying any one of their attributes including registration and location. Search results can also be displayed in customisable orders such as listings by battery capacity, current SoC or even by time connected to the system.

The Management control suite will also host an embedded software link to a bespoke V2G simulator package written in Matlab. This software link will allow the simulator to be run directly within the software suite, and will allow simulated data to be fed into the control algorithm allowing thorough testing of different control strategies to be carried out using a wide variety of virtual grid demand profiles, connecting the simulator through the control suite to the physical elements of the whole system model in a 'Hardware-in-loop' fashion.

2.4 Power Net Simulator

The author's whole systems modelling environment also includes an embedded V2G power system simulator.

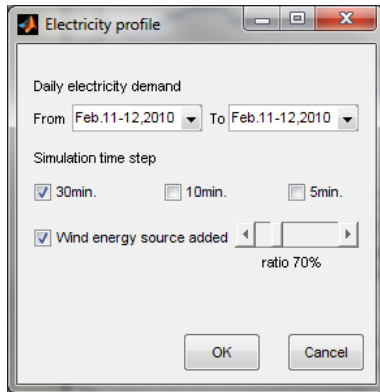


Fig 9: V2G Simulator Electricity Profile Setup

This simulation package, developed in Matlab, allows a customised power network to be modelled in software and realistic network demand loads to be fed into the control software package. The simulator holds a set of realistic Electricity load profile data from which the user selects a time period to simulate over. (Fig 9) The user can also choose to include a local wind energy source for the selected time period and the simulator allows this data to be scaled to the user's needs for the simulated time frame. A time step can also be selected ranging from 30 minutes down to 5 minutes allowing a higher resolution simulated output to be achieved at the

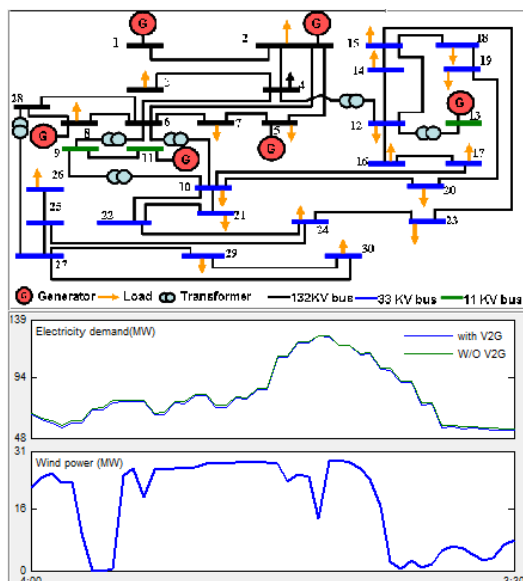


Fig 10: Generated demand and renewable energy generation in the simulation

cost of higher computational workload and, consequently, an increase in simulation runtime.

Once set, the simulator presents a graphical output showing the generated demand profile that will be applied during the simulation process. (Fig 10) The user can then input some final options including the percentage of total vehicles that will provide V2G services, the percentage of buses assigned to accept V2G services and whether or not peak time charging and non-peak time V2G services will be allowed in the simulation. Once set the simulation is then started by the user. Once complete the Interface provides two graphical output pages containing simulated data relating to two separate categories on a bus by bus basis.

The first page (Fig 11) shows power system related information. This information includes electricity demand at the bus, bus voltage magnitude, maximum/minimum voltage magnitude of the system, maximum branch power flow of the system and maximum branch energy loss of the system.

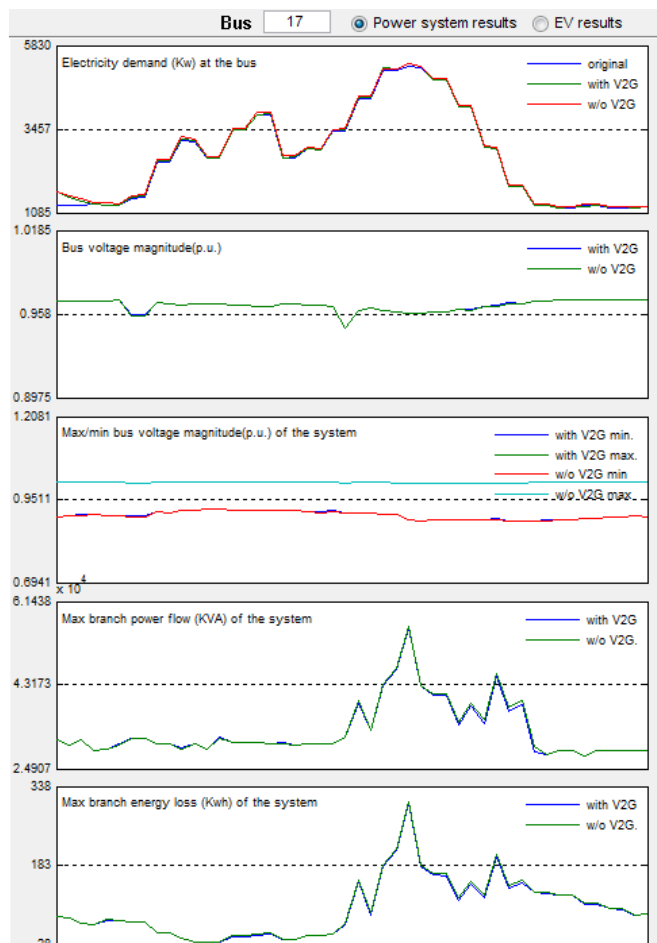


Fig 11: Sample simulation output, power system results.

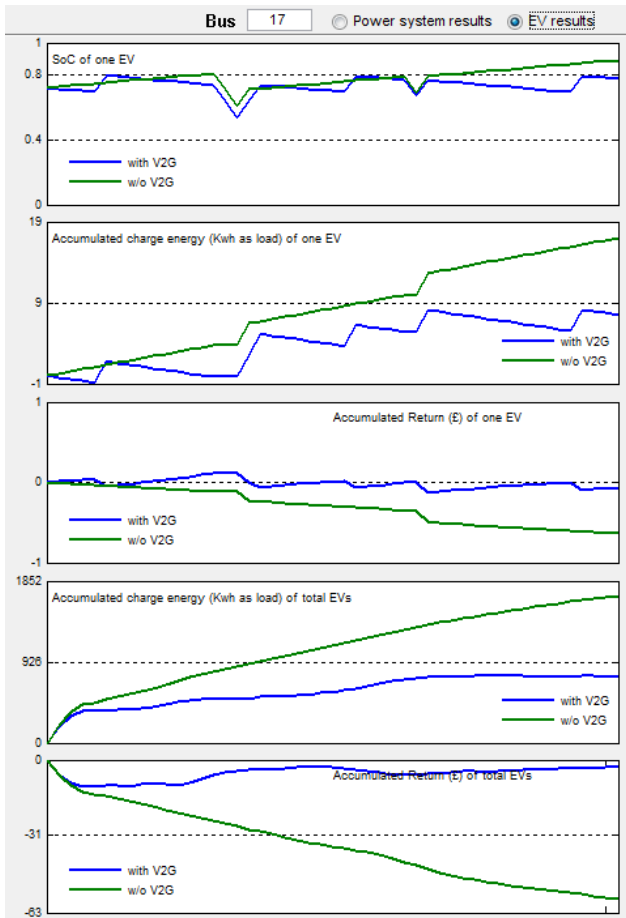


Fig 12: Sample simulation output, EV results.

The second page (Fig 12) shows data pertaining to the EVs including SoC of a single EV, Accumulated charge energy of a single EV, Accumulated monetary return of a single EV, Accumulated charge energy of all EVs and accumulated monetary return of all connected EVs.

As it was intended that the simulation package form an integral part of the V2G management suite package it is currently being developed to include an internal link based on the Matlab Engine. This engine allows external code to communicate with a separate Matlab process via pipes in UNIX based platforms, and through ActiveX in Windows based platforms. This will allow simulation data to be sent directly from the simulator to the controlling software allowing it to make informed decisions based on user defined scenarios aimed at testing the systems capability to respond correctly to any grid demand profiles that can be provided by the simulator.

3 Conclusions

This paper describes the author's whole system V2G modelling environment, including bidirectional converter, communications interface, control software and power system simulator. By combining each of these four elements the author aims to develop a fully operable, low cost, scalable V2G model capable of providing a foundation for the further development and integration of V2G systems and control algorithms. This model not only allows the user the ability to simulate a wide variety of network demand profiles enabling testing and development of V2G control and command strategies but also boasts the added advantage of direct testing and development of the communications technology and topology by providing a 'hardware-in-loop' physical charge system with integrated cellular data modem to more realistically reproduce the difficulties associated with attaining a data link with consistent quality of service while roaming throughout the dynamic cellular network. The whole V2G model therefore aims to provide a testbed capable of challenging the full range of technological difficulties that have yet to be overcome in the field of Vehicle to Grid technology.

Acknowledgements

The authors would like to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) for supporting the Vehicle Electrical Systems Integration (VESI) project (EP/I038543/1).

References

- [1] *UK Renewable Energy Roadmap*, URN 11D/698, UK, Department of Energy & Climate Change, www.decc.gov.uk, 2011
- [2] Iain MacLeay et. al., *Digest of United Kingdom Energy Statistics 2012*, ISBN 9780115155284, UK, Department of Energy & Climate Change, 2012
- [3] A. De los Ríos et. al., *Building a business case for corporate fleets to adopt vehicle-to-grid technology (V2G) and participate in the regulation service market*, Thesis for M. Eng. in Logistics, Massachusetts Institute of Technology. Engineering Systems Division, 2011
- [4] *British Hydropower Association Website*, http://www.british-hydro.org/hydro_facts.html, accessed February 2013

- [5] Parliamentary Office of Science and Technology, 'postnote' number 306, <http://www.parliament.uk/documents/post/postpn306.pdf>, accessed December 2012
- [6] Zhenyu Yang et. Al., *P²: Privacy-preserving Communication and Precise Reward Architecture for V2G Networks in Smart Grid*, IEEE Transactions on Smart Grid, DOI 10.1109/TSG.2011.2140343, Dec 2011, 697-706
- [7] Huei-Ru Tseng, *A secure and privacy-preserving communication protocol for V2G networks*, 2012 IEEE Wireless Communications and Networking Conference (WCNC), DOI 10.1109/WCNC.2012.6214259
- [8] C. Wang and R. Lu, *A certificateless restrictive partially blind signature scheme*, The 1st IEEE International Conference on Intelligent Information Hiding and Multimedia Signal Processing (IIHMSP), 2008
- [9] Texas Instruments, *MSP430 Ultra-Low-Power Microcontroller*, <http://www.s.ti.com/sc/techlit/slab034.pdf>, Accessed June 2013.
- [10] D. Peters, D. Raskovic, and D. Thorsen, *An Energy Efficient Parallel Embedded System for Small Satellite Applications*, ISAST Transactions on Computers and Intelligent Systems, vol. 1(2), 2009

Authors

James Donoghue received a BEng (Hons) degree in Electronic and Electrical Engineering from the University of Strathclyde, UK, in 2012. He is currently working towards the Ph.D. degree in the Electro-Mechanical Research Group at the University of Southampton, UK. His research interests include vehicular electrical systems integration, vehicle-to-grid technologies and embedded system/software design for energy management.



Andrew Cruden is Professor of Energy Technology within the Faculty of Engineering and Environment at the University of Southampton. Previously he was a Reader within the Renewable Technology Group at Strathclyde. His current research interests are: vehicle-to-grid energy storage of aggregated electric vehicles; wind turbine condition monitoring; continuously variable transmissions for electric vehicles using magnetic gears.

