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SMART HUBS – DC INTERCONNECTION AND MANAGEMENT OF PV, EV AND ESS

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ABSTRACT

Distributed Energy Resources (DER), including photovoltaics (PV), energy storage systems (ESS) and electric vehicle (EV) charging infrastructure are increasingly prevalent in distribution networks. They are typically connected independently of each other, both in terms of the electrical integration and operational management. This paper reports on the Innovate UK funded Smart Hubs project which is addressing the inefficiency and missed opportunities that result from uncoordinated installation of DER. A description of the system structure, centred on a central DC-bus and the connected subsystems is given. The emulation of subsystems for testing purposes is described along with interfacing and safety considerations. A rationale for energy management strategies is presented. Modelling of the energy flows in the Smart Hub is used to illustrate possible operational scenarios. Next steps in developing the Smart Hub are outlined.

INTRODUCTION

Changes are underway in the energy system that lead to a need for flexibility wherever it can be found [1]. An increased and increasing proportion of inflexible low-carbon generation along with moves to electrification of transport and heat necessitate a joining up of previously uncoordinated domains in the energy system. Solutions that integrate more than one part of the energy system are increasingly important to enable a reduction in the carbon intensity of our day-to-day activities at acceptable cost [2]. The Smart Hub concept integrates electricity production and electrical vehicle charging while enabling advanced energy management through the inclusion of a stationary energy storage system. Flexibility provided by the energy management functions can be used by the site operator to minimise their electricity connection capacity costs and energy bill, or to provide revenue from service delivery to the Transmission System Operator (TSO), Distribution Network Operator (DNO) and/or aggregators.

This paper describes the arrangement of the system and explains the novelty and benefits that follow. Each of the subsystems are detailed. Equipment and procedures for laboratory testing the Smart Hub are presented. A modelling process to illustrate the use-cases for the operation of the Smart Hub is explained and results from this are provided and discussed. Finally, the paper concludes with closing remarks and next steps.

SMART HUB SYSTEM STRUCTURE

The Smart Hub is centred on a power electronics platform developed by Turbo Power Systems for UK Power Networks' Flexible Urban Networks (FUN-LV) project [3]. The platform connects two sections of LV (400V 3-phase) network via a pair of inverter/rectifier stages, arranged in a back-to-back, or soft-open-point (SOP) configuration. The DC-bus at the centre of the SOP is the Smart Hub DC-bus (SH-DC-bus) through which power is exchanged with other energy resources. In this instance the other energy resources are a photo-voltaic (PV) array, an electric vehicle (EV) charge station and a stationary energy storage system (ESS). A control system is used to dictate the power exchange that takes place with the grid, using flexibility from the ESS and EV charge station. Bi-directional operation in the EV charge station provides vehicle-to-grid (V2G) functionality [4].

Subsystems

The key features of each subsystem are now described.

AC front-end

For the first stage in the development of the Smart Hub concept, only one half of the SOP has been used. This constitutes an AC front-end that converts 3‐phase 400Vac LV power to the 785Vdc (nominal) SH-DC-bus. This simplifies the initial testing programme as only one connection to the distribution network is required. If a particular installation can benefit from SOP functionality the second inverter/rectifier can be reconnected to the system to provide SOP distribution network services, in which power flows are redirected between feeders to manage constraints.

The single AC-DC converter has a 240 kW power transfer capability. Plans are in place to increase this to a 400 kW unit in future projects.

The control scheme in the AC front-end manages the power balance on the hub by monitoring the SH-DC- bus voltage. When there is excess power coming onto the bus the voltage rises and the controller responds by transferring power to the AC grid. Conversely a shortage

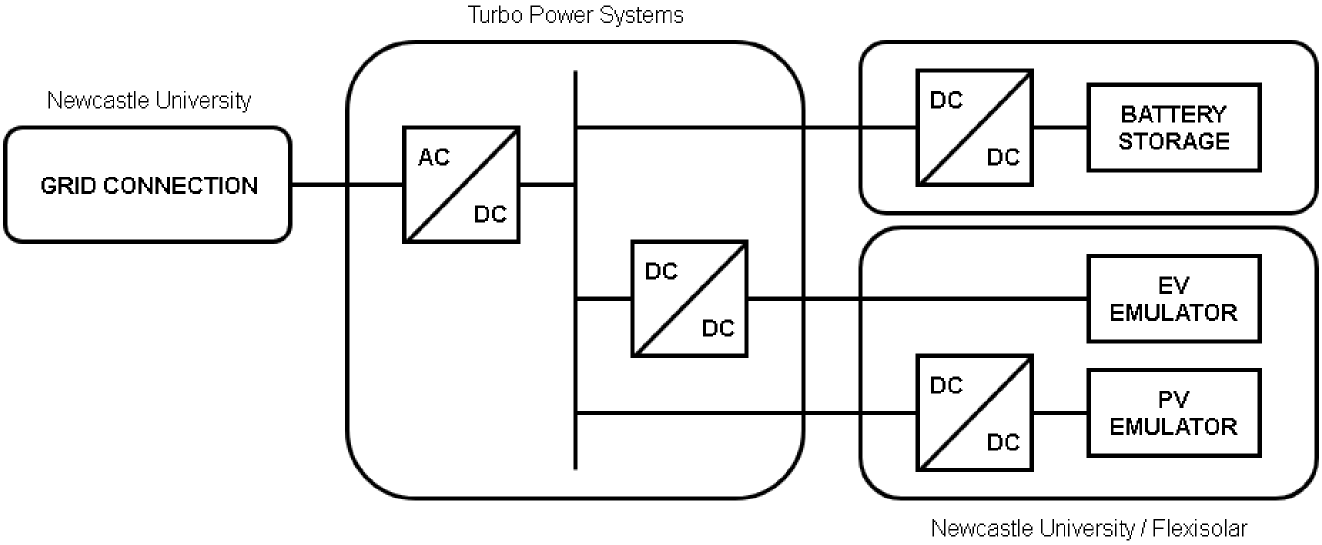

Figure 1. Single line diagram of the Smart Hub subsystems, showing the responsible partners in the demonstration phase.

of power on the bus results in a voltage drop and power is drawn from the AC grid to satisfy the overall SH-DC-bus demand.

Photo-voltaics

Energy generation is included from a solar photo-voltaic (PV) array. There is a particular synergy with vehicle charging and PV production since charging infrastructure can be combined with car parking using a canopy structure to hold the PV array. The use of a solar carport places generation at the location of demand and reduces the total land area needed. EV charging demand at commercial car parking frequently coincides with daylight hours which reduces reliance on the local distribution network infrastructure.

The voltage and current characteristics of a PV panel vary according to the panel type, configuration and the prevailing solar isolation [5]. A power electronic converter with maximum power point tracking is required to connect the PV array to the SH-DC-bus [6]. Under all generating conditions the converter must provide voltage regulation at the SH-DC-bus that maximises power production while presenting the optimal impedance to the PV array.

Vehicle to grid charger

Turbo Power Systems have designed and built a new DC-DC converter to interface a vehicle to the SH-DC-bus. A key innovation with this device is the use of Silicon-Carbide (Si-C) switching devices. Si-C devices switch at considerably higher frequency that conventional silicon devices which enables the use of much smaller reactive components, which is of most benefit in the case of the inductors. These magnetic components are usually large, heavy and relatively expensive, so size reductions are a major advantage.

High frequency operation also means that switching occurs above the audible range for humans where the cut-off is at most 20 kHz. Si based converters are not usually switched above about ~16 kHz, whereas Si-C can be switched up to 100 kHz. One limitation for the switching speed that can be attained is the time needed to compute the pulse-width-modulation (PWM) signals to drive the Si-C devices. This must be completed within a switching period (10 µs if operating at 100 kHz), thus needing a fast processor and efficient control code. In the Smart Hub the converter switches at 20 kHz.

The size reduction that is possible increases the challenge for cooling the devices. Air circulation in a compact system is more difficult, so careful design and testing of this aspect is critical. High efficiency helps to reduce the cooling burden. This is a 100 kW converter which has a design efficiency of 97% so that at full power 3% of loss requires 3 kW of heat energy to be extracted.

Stationary energy storage

The target performance of integrated energy systems can only be realised if the Smart Hub includes an energy storage system. Both power capacity and energy availability are variable and unpredictable in the short-term. Energy buffering between the PV generation, EV charging and grid service provision is provided by the ESS. The size of energy storage is specified in terms of power rating (kW) and the amount of energy (kWh) that can be stored.

In the demonstration system, the ESS is a lithium-ion (Li- ion) battery with a modest 25 kWh storage capacity and 50 kW power rating. As described in the next section, emulation of the ESS enables the Smart Hub to be tested at higher power and energy ratings.

Subsystem emulation

For laboratory demonstration of the Smart Hub system, hardware emulation is used in place of a photo-voltaic (PV) array and associated power conversion system. This means that any systems size and insolation conditions can be included in the testing process, within the capabilities of the equipment.

To simplify and thus de-risk the initial testing stage, the electric vehicle (EV) and stationary energy storage system (ESS) are emulated.

Emulation is provided from seven Regatron GSS 32 kW bi-directional DC sources. Each unit can provide up to 500 V and 80 A, units can be combined in series and parallel to increase either voltage or current capabilities, or both.

Since the PV subsystem connects directly to the DC-bus of the TPS AC front-end, operating at 785Vdc_{nom}, two units must be placed in series to provide a 1000 V, 80 A emulator that can deliver up to around 60 kW. The ESS is also connected directly to the SH-DC-bus and thus required the same configuration.

The EV is connected via a bidirectional 100 kW DC-DC converter to the SH-DC-bus which has a maximum voltage of 500 V so three emulators can be connected in parallel to provide a 500 V, 240 A, 96 kW capability.

Subsystem interfacing

When the system is powered up from the AC-grid, the SH-DC-bus is energised without the PV, V2G or ESS subsystems connected. A soft-start process is followed to connect each subsystem using the following steps:

1. use voltage set-point control to match the subsystem point-of-common-coupling (PCC) voltage to that of the SH-DC-bus
2. close a contactor with a soft-start resistance between the SH-DC-bus and the subsystem to prevent high currents in the case of a voltage difference
3. switch to current set-point control and reduce the current to zero
4. close a second contactor to short circuit the soft-start resistance
5. open the soft-start contactor
6. operate according to subsystem control scheme.

In the demonstration installation, communication is coordinated by a central controller operating under real-time Matlab Simulink.

Safety considerations

With several systems operating together on a single DC-bus, each of which can inject or extract current to/from that bus, coordination of control and protection needs particular consideration. Over-current is protected against by a combination of contactors, fuses and breakers. The first line of protection against over-voltage is the control loop on the AC front-end that is monitoring the DC-bus. Individual subsystems also carry out local monitoring and disconnect if fault conditions are detected.

ENERGY MANAGEMENT

The uncertainty around the EV charging demand and PV generation can be offset to some degree by the ESS. To do so requires an energy management strategy that takes the greatest advantage of the ESS in meeting the installation's objectives. A non-exhaustive list of objectives is given next.

Objectives

Objectives can relate to only the Smart Hub internal subsystems, provide benefits to the site in which it is connected (behind the meter) or deliver services to third parties in the energy supply chain, including DNO, TSO or aggregators.

Internal objectives

1. Maximise local consumption of PV generated energy.
2. Maintain ESS SoC at a level that minimises battery degradation.

Behind the meter objectives

3. Avoid peak hours for half-hourly billed customer.
4. Minimise peak power to avoid capacity charges.

System services

5. Join TSO frequency response programme by providing short term adjustments to demand (or consumption).
6. Participate in DNO active network management scheme.

Scenarios

Table 1 shows the energy management decision matrix used to illustrate Smart Hub operation. These are by no means the most sophisticated possible, but are designed to provide an indication of the variability, trade-offs and impact of alternative operating conditions. The first two columns show if the PV is generating and if there is an EV connected. The third column indicates the difference in PV generation and EV demand. If EV demand is less than PV generation then the category is 'deficit' and conversely if PV generation is greater than EV demand the category is 'surplus'. In row 2 where only PV is generating and there

Table 1.Modelling system decision matrix.

PV Generation	EV Connected	PV and EV diff.	ESS SOC	Decision
×	×	~	~	do nothing
×	✓	~ (deficit)	min	EV demand from grid
			partial	EV demand from ESS
			max	EV demand from ESS
✓	×	~ (surplus)	min	Charge ESS
			partial	Charge ESS
			max	Export to grid
✓	✓	deficit	min	EV demand from grid
			partial	EV demand from ESS
			max	EV demand from ESS
		surplus	min	Charge ESS
			partial	Charge ESS
			max	Export to grid

isn’t an EV connected the PV and EV difference is always in surplus, therefore it is a ‘don’t care’ input (represented by ~). Similarly for row 3, the hub is always in ‘deficit’. For row 4 the difference can be ‘deficit’ or ‘surplus’. The ESS states are minimum, meaning ‘empty’; ‘partial’, meaning that charge is available and ‘full’ meaning that the ESS cannot accept any more charge.

This decision matrix is configured so that EV charging by ESS is prioritised over grid. Any surplus PV generation is first used to charge the ESS and only exported to grid when the ESS is fully charged.

PV data has been taken from a PV installation at Newcastle University. The EV charging profile corresponds to a constant power charge from 10 to 80% SoC followed by a constant voltage charge from 80 to 100% (during which the power demand gradually decreases). The EV battery is 80 kWh, corresponding to a high performance EV. Two sets of EV arrival times are used, ‘EV1’ is spread out and ‘EV2’ is more tightly spaced. The ESS has a 100 kWh energy rating. The ESS is allowed to charge from the grid between the hours of 00:00 and 04:00.

Results

Plots have been produced for one day of operation under the operation matrix given in Table 1. These are described in turn.

High PV / EV1

The scenario in Figure 2 is for the highest PV production day considered and the spread out EV arrival pattern. All EV energy needs are met by the local PV production and the previously stored energy. A peak of 80 kW is exported to the grid when the ESS is full and PV production peaks.

Med PV / EV1

For Figure 3, the situation is the same except the PV production is for a medium output day. All EV charging energy requirements are met, but grid export is much less, only taking place at 15:00 when the ESS is full and the PV production of almost 20 kW is exported.

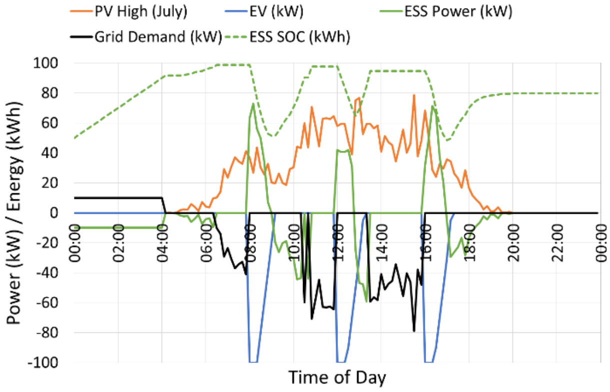

Figure 2. One day scenario with high PV insolation and spread out EV charging schedule.

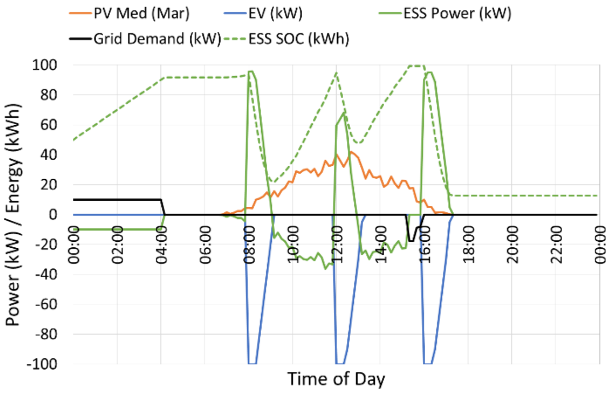

Figure 3. One day scenario with medium PV insolation and spread out EV charging schedule.

Low PV / EV1

PV production is very low in winter months and provides only a small input to the EV charging energy requirement as seen in Figure 4. The overnight stored energy covers the first vehicle’s energy requirements and a fraction of the second charging event. This suggests an alternative management strategy could be used to reduce the peak grid power demand. The storage energy could be shared across the three events and grid ESS charging could be used throughout the day.

High PV / EV2

When the EV arrivals are closer together the overall effect on the power flows is not significantly different in the high PV generation scenario in Figure 5. It can been seen that the depth of discharge on the ESS is greater, which would entail greater degradation to the battery.

Med PV / EV 2

In Figure 6 the medium PV generation case is now unable to fulfil the EV energy charging requirements. Peak grid power demand is reduced on account of the PV production taking place during the EV charging events, even with a depleted ESS.

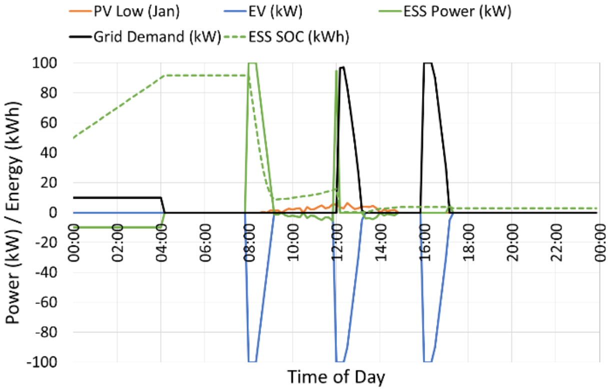

Figure 4. One day scenario with low PV insolation and spread out EV charging schedule.

Low PV / EV2
Finally, Figure 7 shows the worst case PV generation and short intervals between charging events. After the first EV charging event, almost all energy is covered by the grid.

DISCUSSION

This illustration demonstrates the significant impact of the energy management strategy on the power demand that is placed on the grid when the PV production and EV arrival times vary. Increasingly sophisticated management strategies can achieve more complex and conflicting objectives.

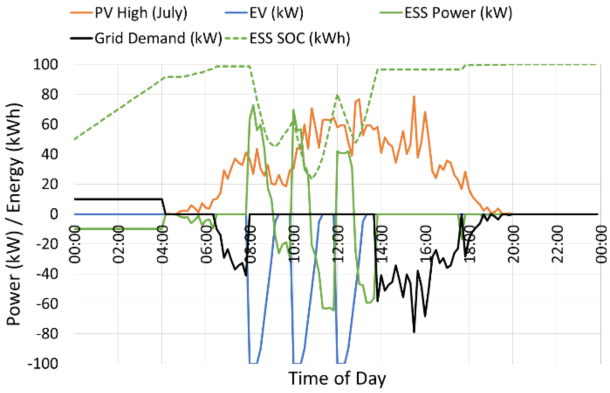

Figure 5. One day scenario with high PV insolation and tight EV charging schedule.

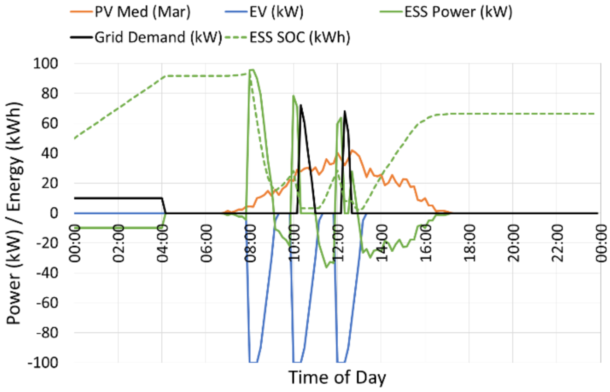

Figure 6. One day scenario with medium PV insolation and tight EV charging schedule.

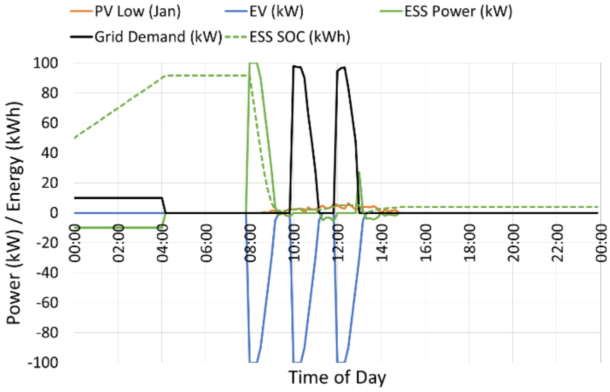

Figure 7. One day scenario with low PV insolation and tight EV charging schedule.

NEXT STEPS

The Smart Hubs project is ongoing and will go through the next steps as the development continues:

1. System integration and testing at Newcastle University
2. Further development of energy management algorithms to meet multiple objectives
3. Deployment of Smart Hub demonstrators at several customer sites across the UK

CONCLUSIONS

Integrated infrastructure systems enable new energy management functions that can bring benefits to the asset owners and operators. These benefits are seen both directly on the site of installation and in the broader energy system.

Acknowledgments

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