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Hybrid PV/battery-storage unit for residential applications

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Abstract: Under their 'Gone Green' deployment scenario, National Grid forecast that energy generated from photovoltaics (PV) in the UK is expected to rise from 2 to 15 GW over the next 20 years. This is being driven by the UK's legal obligations around installing renewable energy sources and cutting greenhouse gases, the rising cost of energy and concerns around the security of supply. Power electronic converters are a key enabling technology for PV and other low-carbon technologies (LCTs). However, the use of LCTs can result in problems for the electrical distribution network such as supply voltage distortion and over-voltages, which threaten to limit or delay their uptake. The project described here is investigating the use of GaN-based converters in a hybrid PV/battery-storage unit for residential applications. The potential for MHz operation of GaN offers smaller, lighter, more efficient, and lower cost converters compared with existing silicon-based units and their deployment could lead to an increase in the installed LCT capacity on the network.

1 Introduction

The paper presents the results from an Innovate UK-funded Feasibility Study, which has investigated the requirements of GaN-based converters for hybrid PV/battery storage in terms of legislation regarding feed-in-tariffs (FIT), grid-codes, architectures, and circuit topologies. However, the results of this study are not restricted to GaN and equally apply to other high-speed semiconductor technologies such as CoolMOS™ Si MOSFETs and SiC.

Lowering capital costs of domestic PV as well as government financial incentives have resulted in an increased deployment of PV-based LCTs in the UK low-voltage network. The revenue that can be accrued from such an installation is dependent on the government set FIT, which is claimed from the energy supplier company (ESC) – also known as the FIT licensee. The benefits to the householder arise through three different mechanisms [1]:

- *Generation tariff (Feed Tariff)*: For every unit of electricity generated by a *renewable-energy* installation – for example a PV – the ESC pays for this energy regardless of whether it has been subsequently consumed, stored, or fed-back to the grid supply. This is measured by a Generation Meter. See Fig. 1, which shows a PV fed architecture with a grid in-feed and loads connected through a consumer unit.
- *Export tariff*: Electricity generated by the renewable-energy system but not consumed/stored in the home, is exported to the grid. This exported energy is paid for by the ESC and is usually measured by an Export Meter – shown by the Export/Import Meter in Fig. 1.
- *Saving*: Every unit of electricity generated by the PV and consumed in the home, means that it is not purchased from the ESC.

Present tariffs are such that the pay-back from exporting electricity to the grid is lower than the cost of importing electricity to supply loads within a house. This, therefore, encourages so-called self-consumption of the generated electricity [2–4]. Increasing the amount of self-consumed electricity also benefits the distribution network operator (DNO), in terms of reducing peak energy demand and hence minimising voltage regulation [5]. Self-consumption can be increased by installing a battery into the PV system [2]. Such a hybrid PV/battery system could also offer:

(1) A fast frequency response service to the grid through aggregation.
(2) Grid fault ride-through.
(3) The possibility of operating in islanded mode [6].

Both (2) and (3) give an improved security of supply but in order to respond to local faults they would require very high converter bandwidth in current mode, typically several tens of kHz. Combining the need for fast response with the attraction of smaller, light-weight converters for space/weight constrained locations within a house, has prompted the work in this project to investigate the use of new GaN transistors operating with MHz switching frequencies. However, operating a DC/AC inverter at these frequencies is very challenging in terms of the control hardware.

The work presented here starts with a review of the rules regarding FIT and how this impacts on the options for different system architectures and topologies. An averaged model of a candidate architecture is then used to obtain the ratings of the different power electronic converters within the system. This study takes a statistical approach to the calculation of residential loads and PV outputs, which is based on a validated load/PV use model that has been developed by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University [7]. Finally, preliminary results from a 3 kW GaN-based grid-tied converter, operating at 100 kHz/2 MHz switching frequency and using a DSP for sinusoidal PWM, are presented.

2 UK feed-in-tariffs

FIT was introduced in the UK in 1 April 2010 as a result of the government encouraging the uptake of LCTs by guaranteeing cash payments to households that produce electricity through renewable generation. This transaction was to be at a fixed price, index-linked, and tax free for the next 20 years. This gave the financial incentive to encourage the public to take up so-called 'clean energy' [1]. However, FIT pricing was subsequently changed in March 2012, making it less attractive for new installations.

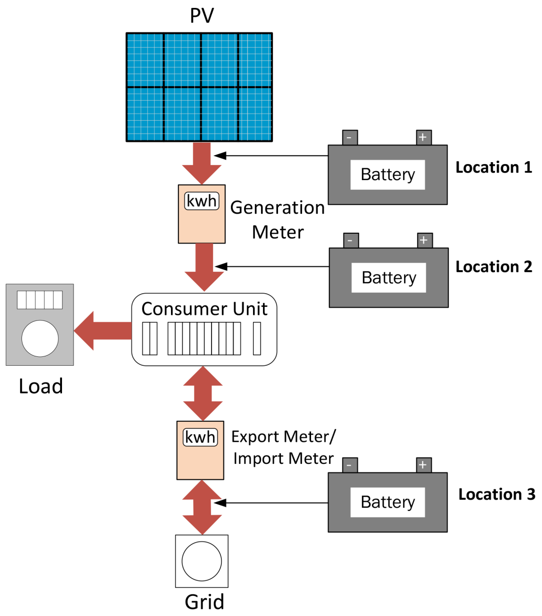

Fig. 1 *Generation and Export meter placement for UK FIT*

2.1 Metering

The UK FIT encompasses additional metering requirements for the distributed generation within domestic properties [1], in particular, the introduction of a Generation Meter to record renewable generation. Two points of metering are required in such a system: so-called Generation and Import/Export meters as shown in Fig. 1. The Export Meter can be combined with the existing Import Meter – shown as Export/Import meter in Fig. 1 – if the existing meter can discriminate between import and export. While this is true for modern 'Smart-Meters', problems can occur with traditional mechanic meters, which are still prolific within the UK. This is because some older mechanical disk type meters have no backstop constraint, meaning the meter runs backwards during export, rewinding the export measurement. These older meters cannot, therefore, function as pure import meters when generation is used within a property. A separate Generation Meter is required to measure the electricity generated within a property. In some cases, where an export meter is not available, the FIT export payment is estimated based on half the reading from the Generation meter. This is known as a 'deemed' payment. However, where consumption is higher than generation, which is the case for the majority of domestic households, the deemed payment will actually give a better financial return than that given by the Export Meter reading.

2.2 Battery location options

The meter arrangement shown in Fig. 1 offers the potential for placing a battery storage unit in three different locations. However, although all of these locations are allowed under FIT rules, there are additional points to be noted. For example, the architecture shown in Fig. 2 is based on battery location 1. FIT prohibits this arrangement because the battery could be charged from a non-renewable source and revenue then fraudulently claimed based on the generation meter reading – and the export meter if exporting. Note that the householder can opt-out of FIT and join a so-called aggregator scheme. In this case, the aggregator company installs their own equivalent of the export meter into the property and payment is made for export only. An aggregator scheme allows generation from both renewable and non-renewable sources including energy storage. However, this scheme has a variable tariff and so revenue may be reduced for renewable generation when compared with FIT. Another disadvantage of battery location 1 for an aggregator scheme is that most PV converters are unidirectional; therefore, the battery cannot charge from the grid and would, therefore, be underutilised.

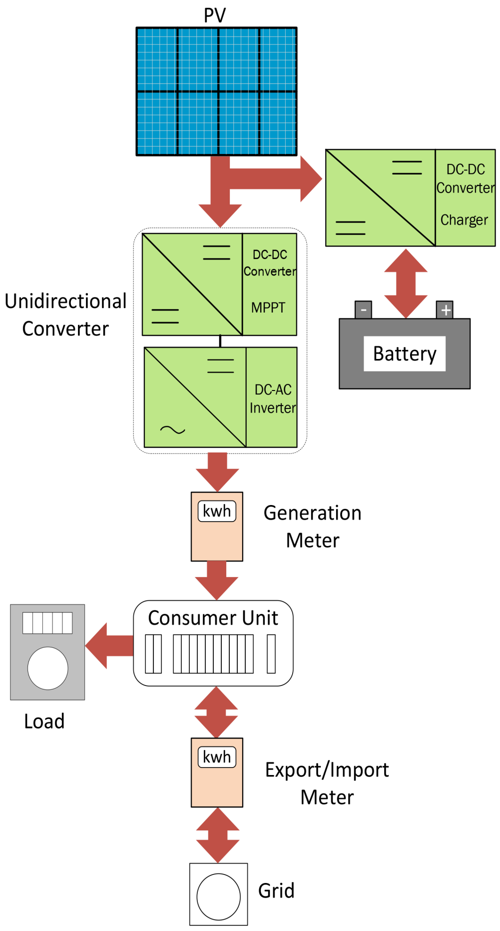

Fig. 2 *Example architecture for battery location*

Similarly, battery location 3 shown in Fig. 1 is also not allowed because this is an unmetered connection, which can be exploited for fraudulent use. This leaves battery location 2 as the best option for connection as shown in Fig. 3. Note the battery in this figure is shown connected to the consumer unit, as is the case for existing PV systems; however, this is electrically the same as Fig. 1.

Again, FIT rules for location 2 mean that the Export Meter cannot be used for FIT payments because the energy in the battery may have been obtained from a non-renewable source. In this case, export payment is deemed at 50% as specified under FIT.

2.3 Topology options

With the battery connected in location 2, it is possible to connect the PV and battery either through a common DC-link as shown in Fig. 4*a* or more traditionally through the existing AC link at the consumer unit as shown in Fig. 4*b*. However, again existing FIT rules make a DC connection an unattractive option as the Generation Meter – shown highlighted* – would have to be fitted into the DC bus. Whereas DC meters that have not been approved and certified by the ESCs at present [8].

The FIT requirements for the installation of meters also precludes a number of new proposed topologies. For example, the so-called multi-port DC topology [9], shown in Fig. 5 – figure taken from [9] – combines both the PV and battery converter into a single circuit to provide a DC output. An additional DC–AC inverter is needed to connect to the grid. Again, the problem with these types of converter is that under FIT requirements metering of the PV needs to be independent from the battery. In the case of [9], the Generation Meter would need to be inserted after or before the high-frequency transformer shown in Fig. 5. The meter design in this case would have to be radically different from existing technology and would be explicitly for this converter. Many other proposed topologies suffer from the same problem regarding the meter design [10]. For this reason, advanced converters have not

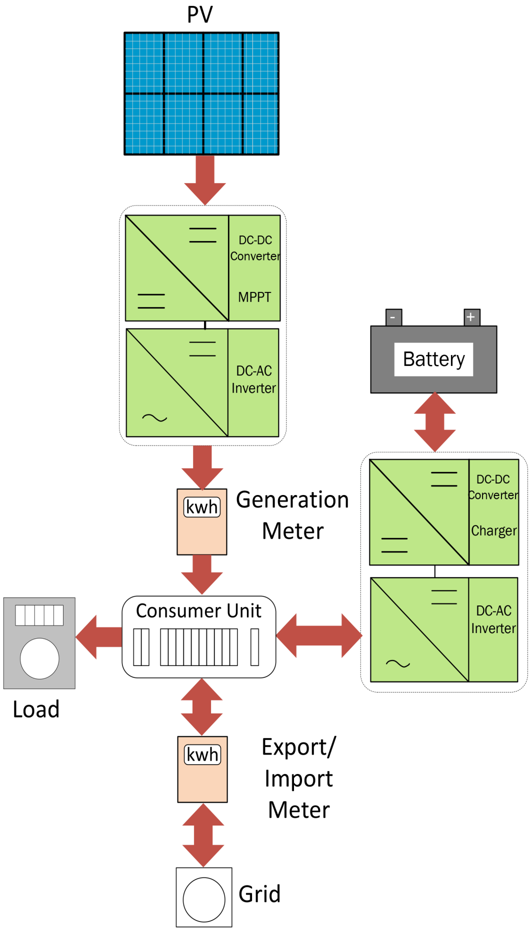

Fig. 3 *Example architecture for battery location 2*

been considered further in this project and the hardware has been based on tradition DC Boost and single-phase SPWM inverters.

3 Battery converter rating

While the rating of the PV converter is simply determined by the peak output of the PV array, the rating of the battery converter has been the focus of previously published work. In particular, the method proposed in [11] has been adopted here, which claims significant savings in battery converter rating can be obtained for a modest reduction in the annual energy despatched by the battery. This rating depends on a number of factors such as the profiles of PV generation/loading within a house, battery capacity and whichever tariff strategy optimises revenue for the customer – for FIT, this is self- consumption. The study described in [11] was based on electricity demand and solar irradiance data from Germany, whereas the data used in this project were derived from a UK load/irradiance model developed by CREST at Loughborough University [7]. A program was created in MATLAB that calculated the temporal power flows between the main components of the hybrid PV/battery system, a block diagram of this model is shown in Fig. 6:

The MATLAB model consists of:

- PV irradiance/electrical power from the CREST model at 1-min time resolution, for 1 year: P_{PV0}.
- CREST stochastic electrical load power for a typical four-person house at the same time resolution and duration as the PV irradiance: P_{load}
- Power loss from the PV converter: P_{PVloss}
- Power loss from the battery converter: P_{BATTloss}
- Any excess/deficit of power flows into/out of the grid supply: P_{grid}

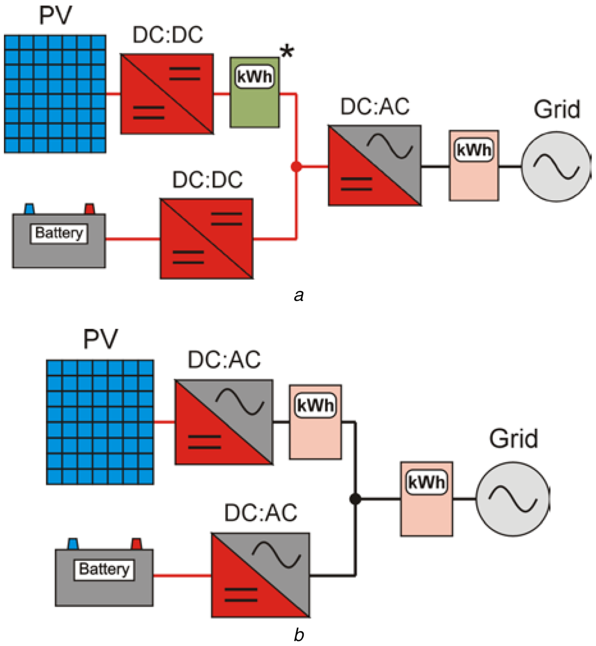

Fig. 4 *Architecture options for battery/PV connection*
(a) DC coupled, ***(b)*** AC coupled

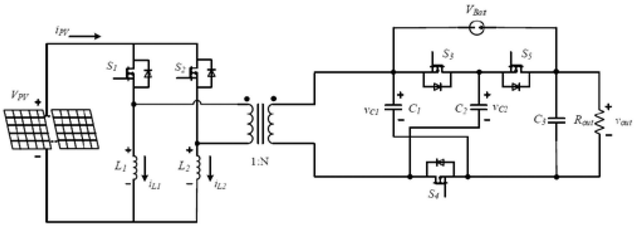

Fig. 5 *Multi-port DC-AC converter topology- figure taken from [9]*

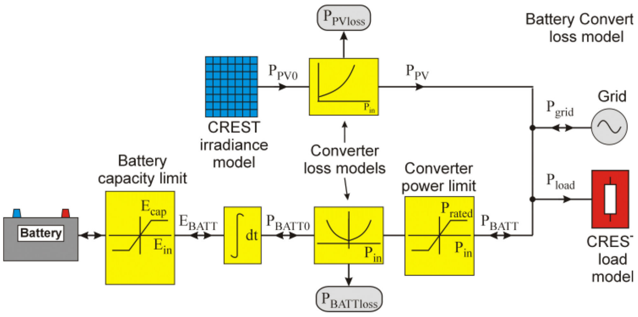

Fig. 6 *Block diagram of the MATAB model used to calculate battery converter rating*

The converter loss models are traditional second-order polynomials that take the converter output power P_{out}, as an argument.

The battery charging strategy is optimised for self-consumption such that if $P_{\mathrm{PV}} > P_{\mathrm{load}}$, power is diverted to the battery rather than the grid as long as the battery has unused capacity. A capacity and power limit is used for the battery and its converter, which corresponds to 0 to 100% of usable energy and battery converter maximum power rating. Fig. 7 shows the power flows calculated from the MATLAB model for a typical Spring-Summer day for a 5 kW peak PV array and a battery with a 5 kWh capacity and 5 kW converter rating. Note that positive and negative grid power flows Feed/Supply, are highlighted in different colours as are the battery power flows Charge/Discharge.

The optimum battery converter rating is based on maximising the annual battery charge/discharge energy versus charge/discharge power curves, whichever is the greater [11].

The model was, therefore, repeatedly run for different converter ratings and the cumulative battery charge/discharge energies calculated as shown in Fig. 8 for a 5 kW battery converter rating.

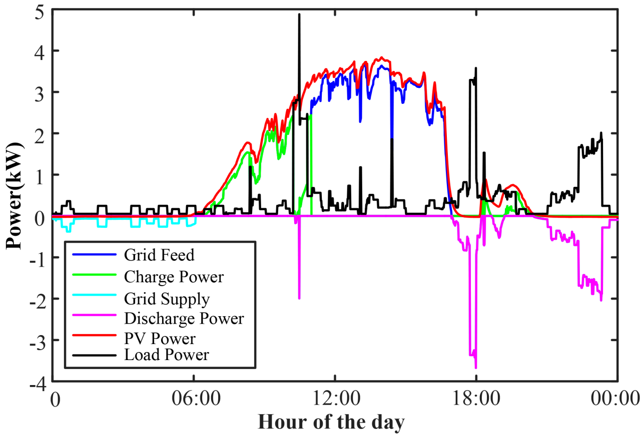

Fig. 7 *Example 24-hour, Spring-Summer power flows*

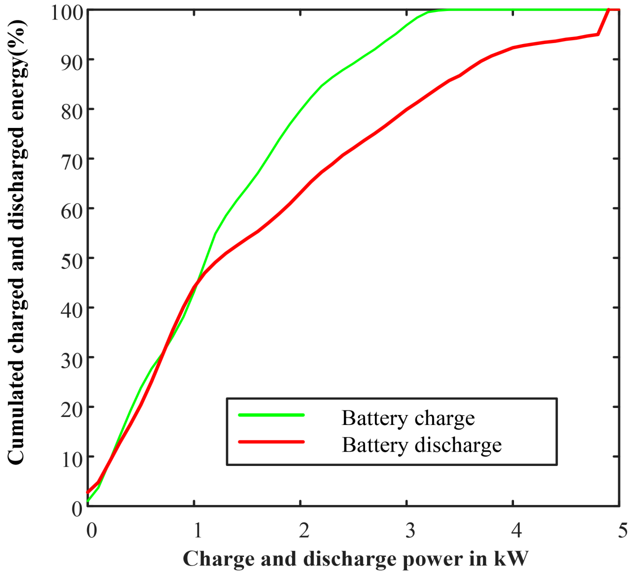

Fig. 8 *Percentage annual cumulative battery charge/discharge energy as a function of battery charge/discharge power (kW) for a 5 kW battery converter*

It can be seen from this figure that the energy is constrained by the *discharge* energy as it is significantly below the *charge* energy curve for most of the plot. In addition, >80% of the discharge energy occurs at powers <3 kW. The 5 kW battery rating is, therefore, significantly underutilised in this case. The results from calculating the maximum discharged energy for various battery converter ratings is shown in Fig. 9, where the energy has been normalised to the peak.

Fig. 9 shows that maximum battery utilisation is achieved at a battery power rating of ~4.2 kW. This would mean that the battery converter would be rated at 80% of the PV inverter. However, with a modest reduction in utilised discharge energy to around 95%, the battery rating is reduced to 1.5 kW as seen in Fig. 9. The battery converter is then 30% of the PV converter rating, which is a highly desirable cost saving for the system. These findings approximately align with those from [11], which were for domestic properties in Germany.

This process of analysis was repeated for a number of other battery capacities, where a 95% utilisation of the discharge energy was used in order to reduce the battery converter rating. These savings in battery ratings are shown in Fig. 10 as a percentage ratio of the 95% energy utilisation case compared with the 100% utilisation case.

It is difficult to identify any general trends in this figure other than to observe that in most cases a saving of >50% in battery rating can be gained by reducing the battery energy utilisation by 5%. In particular with a typical UK PV output power of around 5 kW, battery converter ratings are reduced by a factor of four.

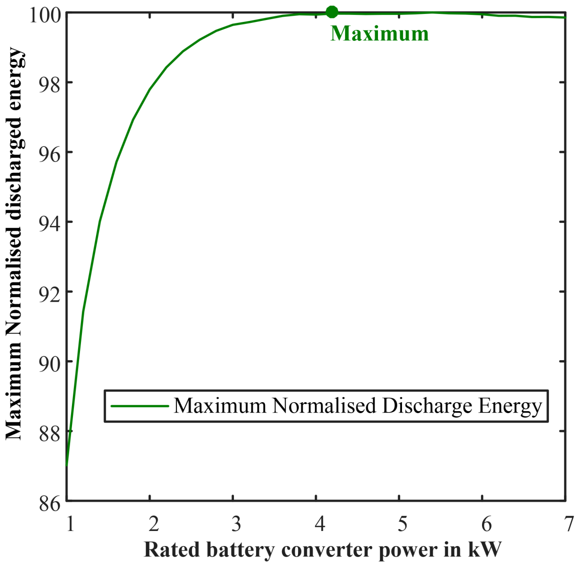

Fig. 9 *Maximum normalised discharged energy (%) against battery converter power rating (kW)*

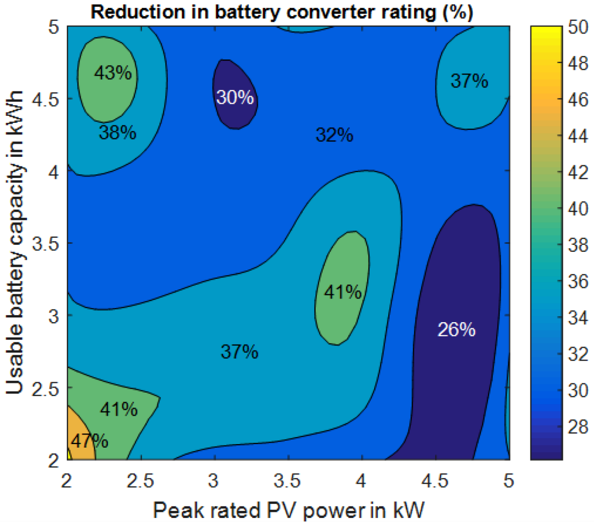

Fig. 10 *Reduction in battery converter rating in % for a range of PV converter ratings (kW) and battery capacities (kWh)*

4 GaN prototype hardware

Hardware was built in order to evaluate the performance of a GaN-based hybrid PV/battery system. This hardware consisted of a four-leg converter – two half-bridge legs for the PV and battery converters, respectively and a full-bridge for the single-phase grid-tie inverter. Each leg consisted of a GaN Systems GS66508T-EVBHB evaluation module and bespoke current sensors based on Sensitec CDK4025 evaluation boards. A picture of the hardware is shown in Fig. 11.

Designing the controller for the inverter provided a significant challenge, with a 2 MHz PWM switching frequency as this only gives 500 nS maximum for a controlled conduction period. The first decision to be made was the switching strategy, this required an examination of the waveform distortion requirements, fault responses, and control loop bandwidth. Using double-edged modulation on a full-bridge allows the PWM rate on a pole pair to be set at 1 µS, with the overlap of the pole pairs effectively doubling this to the required 2 MHz. The next question to be answered was the required resolution and what processor would meet this and give us the low distortion requirements. Simulation with PLECS and previous experience indicated that at least 10 bit resolution was called for, which corresponds to a PWM resolution of better than 480 pS. The Texas Instruments TMS320F2837xD Dual-Core Delfino Microcontroller range, with a clock speed of 200 MHz and its High-Resolution Pulse Width Modulator

Fig. 11 *GaN based hardware prototype*

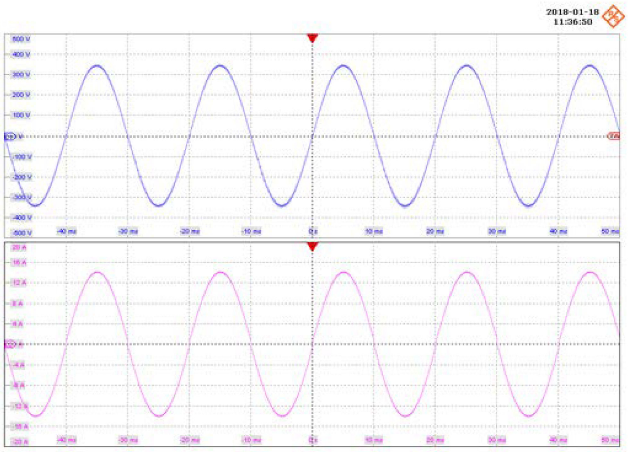

Fig. 12 *Inverter output voltage (V) and current (A) when supplying a 2 kW electronic load at 50 Hz and unity power factor*

(HRPWM) gives an effective maximum PWM resolution of 150 pS and this together with its low cost, high performance, and flexibility made it the controller of choice in this application. With the controller chosen, a set of typical control loop timing results were measured on the DSP to determine what could be considered to be a reasonable control loop update rate. The control loops times took ∼7 µS, and with a 35% utilisation, a reasonable interrupt time would be 20 µS or an update rate of 50 kHz. With these chosen, the other elements, such as response time, loop bandwidth, and values for hardware components were estimated. For example, the inverter output filter comprised two single 100 µH Molypermalloy Powder core inductors and a 12 µF polypropylene output capacitor. The inverter AC output 50 Hz, AC voltage, and current waveforms when connected to a 2 kW unity-power factor electronic load are shown in Fig. 12.

Note, due to the limited cooling provided by the heatsinks on the GaN evaluation module, these waveforms were measured with the converter running continuously at a switching frequency of 100 kHz. However, similar results were obtained with transient operation at 2 MHz switching frequency.

5 Conclusion

This paper has discussed the options for a residential, hybrid PV/battery system, in terms of architectures and converter topologies, which meet existing UK FIT requirements. This has shown that FIT effectively limits the choice to an AC-coupled architecture comprising separate, traditional DC–DC and DC–AC converter circuits. While the use of GaN has resulted in a reduction in the size and weight of the converter passive components, it was concluded that other anticipated benefits such as the ability to provide fast-frequency response or fault-ride-through would not benefit from the higher switching speeds offered by GaN when compared with traditional Si IGBT/MOSFET-based equipment. However, the higher current-loop bandwidth that GaN provides when switching at MHz frequencies could offer the possibility of islanded operation and hence improve security of supply.

A statistical study has been carried out, which shows that the battery converter can have a significantly lower rating than the PV converter. Results from a hardware prototype have demonstrated the operation of a GaN-based converter switching at both 100 kHz and 2 MHz under closed-loop control.

6 Acknowledgments

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