IMPLEMENTING A BATTERY ENERGY STORAGE SYSTEM WITH A CONVERTERLESS DIRECT CONNECTION TO AN LVDC DISTRIBUTION NETWORK

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ABSTRACT

This paper addresses the design and implementation of a battery energy storage system (BESS) for a low-voltage direct current (LVDC) distribution network. To improve the energy efficiency of an energy storage connected to a DC network, the target is to implement and demonstrate a BESS with a converterless direct connection to the LVDC network. The paper discusses (1) the requirements and technical properties of the grid interface and the BESS itself and (2) the operational functionalities, (3) control and management system, and (4) charging and discharging of the BESS. As the final step, the installation of the BESS system into a public LVDC network and the first experiences of the operation are discussed.

INTRODUCTION

A research site, presented in Fig. 1, was established in a public low-voltage distribution network to enable practical studies on different areas of the LVDC distribution, also outside laboratory conditions [1], [2], [3]. The system is continuously supplying actual customers, and it is developed towards an LVDC smart grid capable of, for instance, power flow regulation, island operation, and customer-end load control.

To enable some of these functionalities, a battery energy storage system (BESS) was introduced. First, the target of the BESS implementation is to improve the customer-end supply security and facilitate research on smart grids and energy market functionalities. Energy storage systems are generally connected to the network through power electronic converters, which are responsible for the charging and discharging of the storage. In AC networks, DC/AC converters are mandatory because of the power conversion. In some DC network structures, it might be possible to connect the storage directly to the DC network without an interface converter, and therefore, a converterless BESS structure was investigated [4].

LVDC NETWORK POWER ELECTRONICS

In this application, the LVDC distribution network feeds the customer-end inverters (CEIs) responsible for the end-user AC supply [1]. The DC network has a bipolar structure with ±750 V nominal voltage levels. To achieve longer transmission distances and/or a high power transmission capacity, more than a 20 % voltage drop in the DC network can be allowed [3]. As a result, the CEIs in this network are guaranteed to produce a nominal 400 VAC three-phase voltage from the 580–790 V input DC voltage. Hence, an active DC voltage control is not a necessarily required feature of the rectifier, which enables the use of simple and economical passive or active rectifier structures such as a diode bridge and a half-controlled thyristor bridge. These structures, however, allow only unidirectional power flow, and in the case of an energy storage, an interface converter is required between the storage and the DC network. Further, if there is generation connected to the DC network, an active rectifier with a bidirectional power flow is required.

The LVDC network is supplied directly from the 20 kV medium-voltage network through a 20/0.53/0.53 kV double-tier transformer. To enable bidirectional power transmission and DC voltage control, the previous half-controlled thyristor bridge rectifier was replaced by a commercial grid-tie rectifying converter [1]. With a 500 VAC input voltage, the output voltage of the rectifier can be adjusted between 707 V and 800 V. The minimum voltage is defined by the hardware; the diode bridge in the rectifier limits the minimum voltage to $\sqrt{2} \cdot 500V = 707V$. As a result, the DC voltage level can be easily adjusted in a wide range, and it has no effect on the customer-end voltage level and quality. Thus, could an energy storage with compatible voltage levels be directly connected to the DC network without an interface converter and use the rectifier to manage the charging and discharging of the storage?

DESIGN OF THE BESS

The power flow control of the BESS and the DC network relies on the grid-tie rectifying converter located at the rectifying substation shown in Fig. 1. With a bidirectional power transmission and an accurate DC voltage and power control, the target is to enable the charging and discharging of the BESS without any additional power electronics, because a rectifier is required for the normal operation of the LVDC system. Without an interface converter between the storage and the network, it is obvious that supercapacitors do not represent technology that could be adapted to this application. The main reason is that most of the energy cannot be used because of the 707 V minimum voltage of

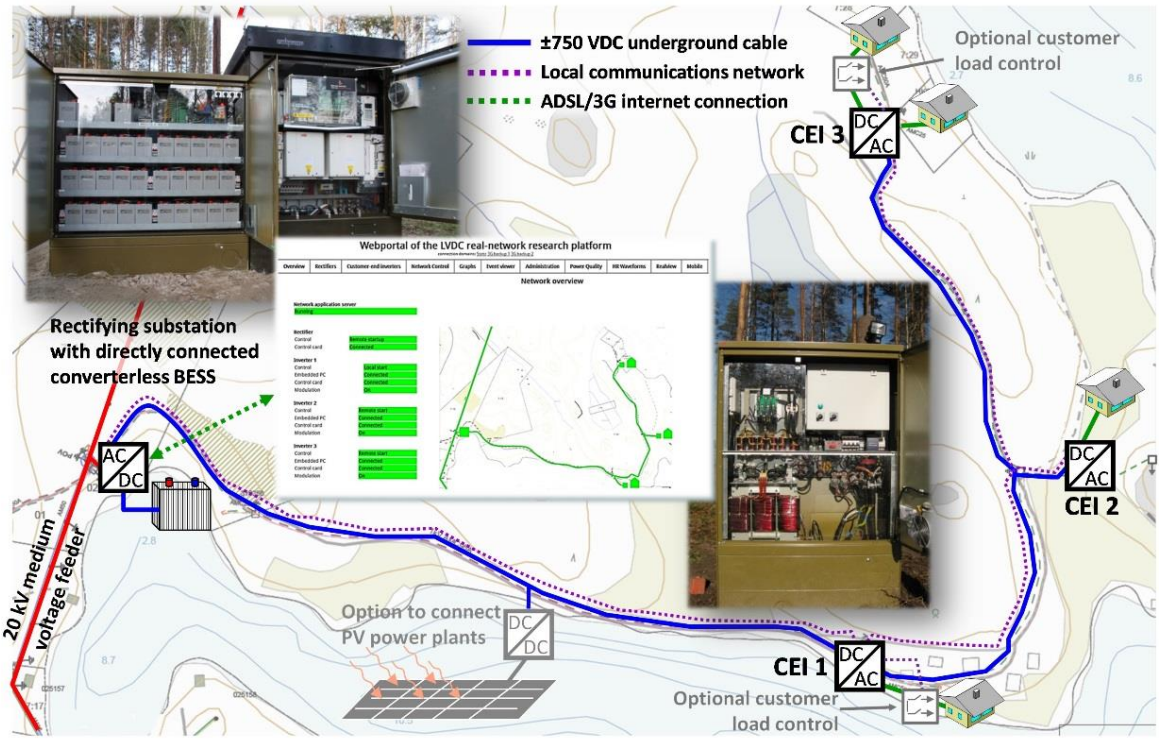


Fig. 1. LVDC distribution network research site and its components located on the map. The BESS is installed beside the rectifier substation, shown on the top left.

the rectifier. The situation is similar to lead-acid batteries: the difference between fully charged and fully discharged battery terminal voltages is quite high, and to meet the capacity requirements, noneconomical dimensioning is required [4]. Because of their suitable technical properties, price, and availability, lithium iron phosphate ($LiFePO_4$) batteries were selected. With the $LiFePO_4$ chemistry, the following requirements can be achieved:

- 30 kWh nominal capacity
- 1C discharge and charge current (≙30 kW)
- the minimum voltage of the rectifier is equivalent to the "fully discharged" voltage of the BESS
- the maximum voltage of the rectifier is equivalent to the "fully charged" voltage of the BESS

Batteries

The number of individual battery cells depends on the cell voltage. To ensure that the cells can be fully charged and discharged, the voltages corresponding to 0 Ah and 40 Ah charges have to be reached (Fig. 2). However, the battery cells are normally not fully discharged and charged, and therefore, the linear middle part of the curve is used. The calculations and the manufacturer recommendation resulted in the same 235 cell count. In Tab. 1, the properties of the battery cell and the BESS are shown. It can be seen that 710 V and 790 V BESS voltages correspond to 3.02 V and 3.36 V cell voltages, respectively. Fig. 2 shows that the BESS can be fully discharged if the current is less than 0.5 C. With the 1C current, the cell voltage has to reach 2.8 V, which corresponds to 658 V. A voltage this low cannot be reached because of the rectifier limitations, and therefore, the entire 40 Ah capacity cannot be exploited with the 1C current.

Because of the bipolar DC network, also the BESS has to be bipolar. Therefore, it consists of two 235 individual 40 Ah battery cells connected in series, resulting in a 750 V nominal voltage. Hence, the BESS consists of "BESS A" and "BESS B", both with control devices and measurements of their own. Two battery management systems are responsible for individual cell monitoring and balancing. As a result, A and B are not interdependent.

Mechanical Structure

The initial target was to use commercially available products in the design. Because of the outdoor installation, an IP rating of IP34 of the cabinet, at least, was required. Further, as small physical size as possible without compromising on the serviceability was desired. The CEIs were installed in a standard cable distribution cabinet, and therefore, the largest model of the same cabinet with the dimensions of 1200x1350x360 mm (HxWxD) was selected as a basis of the design. Because the total cell count is 470, consisting of two 235-cell strings, two cabinets were required. In addition to the batteries, the main circuit components, the battery management system (BMS), and the BESS control devices had to be installed in the same cabinets. Fig. 3 illustrates the BESS; the cabinets are installed back-

Tab. 1. Properties of the BESS and the battery cells.

BESS	
Nominal capacity	30 kWh
Fully charged voltage	790 V (3.36 V cell voltage)
Fully discharged voltage	710 V (3.02 V cell voltage)
Maximum charging power (current)	30 kW (1C)
Maximum discharging power (current)	30 kW (1C) (nominal) 60 kW (2C) (peak)
Battery cell number	235
Battery volume	0.23 m^3
Cabinet volume	0.58 m^3
Battery mass	329 kg
Battery cells	
Type	$LiFePO_4$
Capacity	40 Ah
Nominal voltage	3.2 V (752 V BESS voltage)
Upper limit voltage	3.65 V (858 V BESS voltage)
Discharge cut-off voltage	2.5 V (588 V BESS voltage)
Cycle life	2000 @ 80% DOD, 0.2C discharge

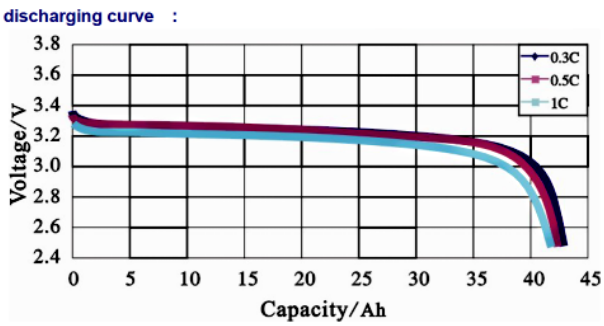


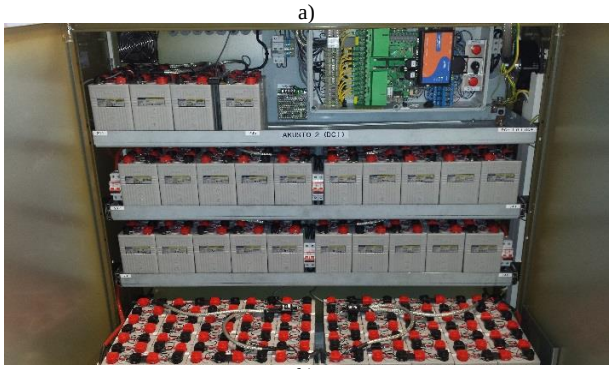
Fig. 2. Discharge curve of the $LiFePO_4$ battery cells [5].

to-back, and three battery shelves from the bottom can be pulled out to allow the replacement of the batteries and the BMS cell modules.

Main Circuit Components

To ensure electrical safety, only components with correct ratings can be used. When the DC voltage level is high enough, the availability of the control products is quite poor. For instance, 750 V rated DC contactors are usually available for high-current applications only. However, it is possible to use multipole AC contactors and connect the poles in series to achieve the required DC breaking capacity, but the datasheets do not always indicate DC breaking capacities. The growing adoption of solar power has enhanced the availability of circuit breakers and fuses rated for 1 kV DC. A circuit breaker can be equipped with a remote control, and therefore, a single device can be used for both protection and control. The operation lifetime of the circuit breaker is not a problem, because the BESS is normally connected to the network, and therefore, the circuit breaker is seldom operated. When there is a single device with a specified DC breaking capacity, other control devices in the main circuit can be AC rated components; they are only used to close the circuit, and they remain closed

a)



b)

Fig. 3. Battery cells installed on the pull-out shelves. The main circuit control components are installed in the "BESS A" cabinet (a) and the control electronics in the "BESS B" cabinet (b).

until the DC circuit breaker has operated first. Fig. 4 demonstrates the main circuit of the BESS. There are three control devices in the main circuit:

1) DC circuit breaker with a remote switching unit (F1+RSU). F1 is used for connecting and disconnecting the BESS from the network. This is the only device with a rated DC breaking capacity.
2) Resistor bypass contactor (C1). Before C1 is closed, the DC network voltage is controlled to match the BESS voltage to avoid high current peaks during the switching. This contactor is always opened in the zero current condition.
3) Resistor contactor (C2). C2 is always closed before F1 is closed, and it is opened when C1 is closed. If the voltage of the BESS is lower than the minimum voltage of the rectifier, R1 is used to charge the BESS slowly until its voltage exceeds the minimum voltage of the rectifier to avoid a high charging current. Further, if the target is to start up the DC network without the rectifier, the capacitances in the DC network are charged through the resistor. This contactor is always opened and closed in the zero current condition.

For the maintenance purposes, there are seven disconnector switches (S1…S7) that can be used to separate the 235-cell battery string to six 35-battery and one 25-battery banks. As a result, there exists no voltages higher than the extra low-voltage limit of 120 V.

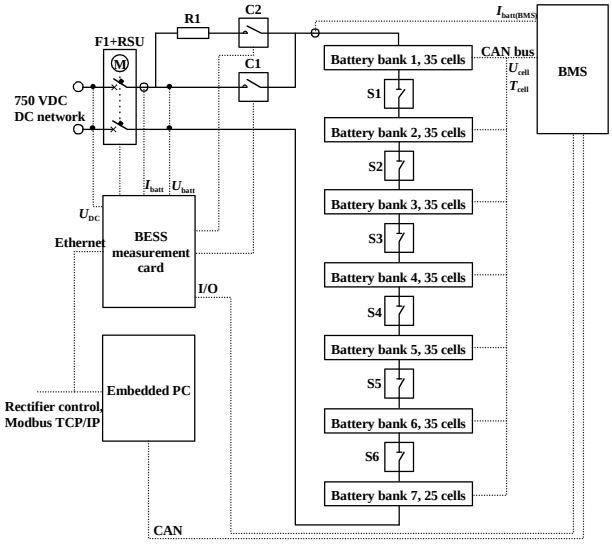


Fig. 4. Control electronics and main circuit of the BESS. The dashed lines represent the control and the measurement signals, and the solid lines the main circuit.

BESS CONTROL

The control of the BESS is discussed in [6], and therefore, this paper focuses on the main details of the control only. A DSP-processor-based measurement and control card [1] is responsible for the control of the contactors and the circuit breakers. It also includes protection functions such as overcurrent protection. The card measures voltages both on the BESS and DC network side of the circuit breaker, because the voltage on the DC network has to match the BESS voltage before closing the bypass contactor C1. In the case of a low BESS voltage, the BESS is charged through the resistor R1, until the BESS voltage reaches the minimum voltage of the rectifier. When C1 is closed, only the network voltage measurements are used for the voltage control, but both measurements are compared to detect possible faults in the measurements or the main circuit.

The control card has an Ethernet interface for communication with the BESS embedded PC. The voltage reference value for the rectifier is transmitted using the communications. The entire control system, including the BESS and the rectifier control, is shown in Fig. 5. The control card includes PI controllers for both the current and voltage control, and three control modes have been developed for the comprehensive BESS and rectifier power flow control:

1) BESS current control. Current measurements can be used, for instance, for a constant current (CC) stage during charging (Fig. 6) and discharging (Fig. 7).
2) Network voltage control. The DC network voltage can be matched with the BESS voltage before the connection. Furthermore, the voltage control is used for the constant voltage (CV) stage of the charge/discharge process of the storage, and during the top balancing of the individual cells (Fig. 8).

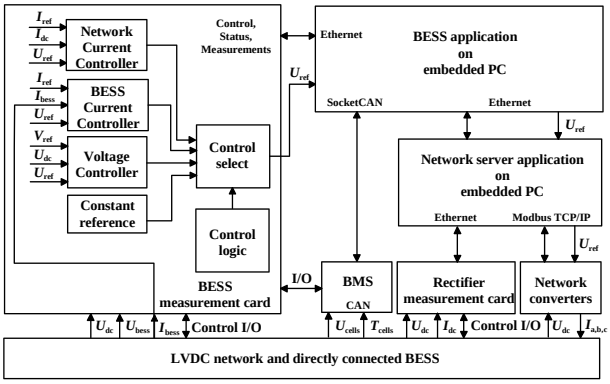


Fig. 5. Control system of the BESS and the rectifier [6].

3) Rectifier current control. By using the current measurements obtained from the rectifier measurement card, the rectifier current can be controlled. That is, the power taken from the medium-voltage network can be controlled (Fig. 9).

The measurement results shown in Fig. 6-Fig. 9 are gathered from the control and monitoring web portal [1]. When a new control command is given, measurements over a 10 s time frame are stored using 2 kHz sampling frequency.

Control Resolution

The DC reference voltage resolution is 1 V, limited by the communication interface of the rectifier. With the 1 V voltage resolution, the current control resolution is 1–2 A, depending on the current and voltage of the BESS. As can be seen in Fig. 6 and Fig. 7, this causes current ripple, even though the current reference is constant. The frequency of the ripple depends on the PI controller parameters and the dead zone in the current and voltage PI controllers. Currently, the voltage and current dead zones are 0.5 V and 0.5 A, respectively. However, the resolution is adequate for this purpose, and the charging and discharging of the BESS can be controlled with a sufficient accuracy.

CONCLUSIONS

In this paper, the design and implementation of a BESS with converterless direct connection to an LVDC distribution network were discussed. The paper considered the requirements for the interconnection to the existing LVDC distribution network and introduced the implemented energy storage. The storage has been operating since October 2014. By using the measurement results gathered from the integrated data acquisition system, the basic functionalities of the BESS were analyzed. The results show that the BESS operates as planned, and the charging and discharging can be accurately controlled using only the grid-tie rectifying converter. Experiences of the operation and measurement data are continuously collected, and after the implementation of the control hardware and software, the use of the BESS in an LVDC smart grid will be discussed in future publications.

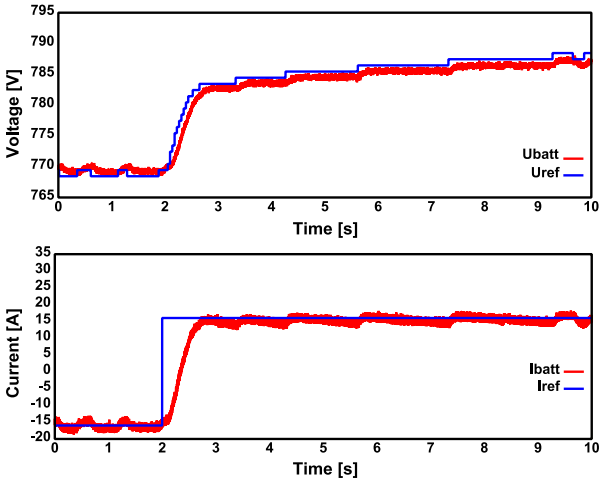


Fig. 6. BESS voltages (top) and currents (bottom) during the constant BESS current mode. At 2 s, current reference step from -15 A (discharge) to 15 A (charge) is made.

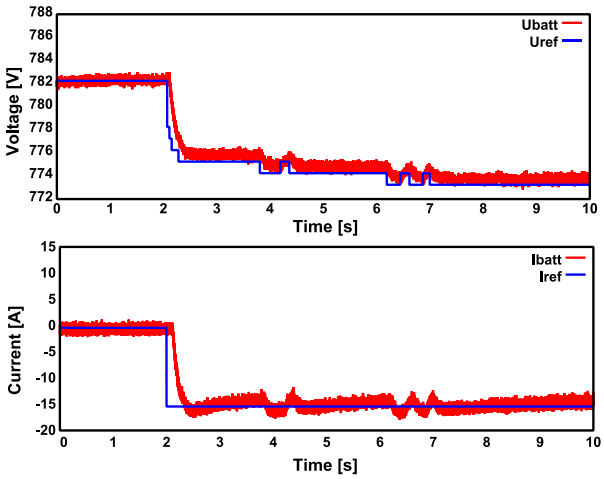


Fig. 7. BESS voltages (top) and currents (bottom) during the constant BESS current mode. At 2 s, current reference step from 0 A to -15 A (discharge) is made.

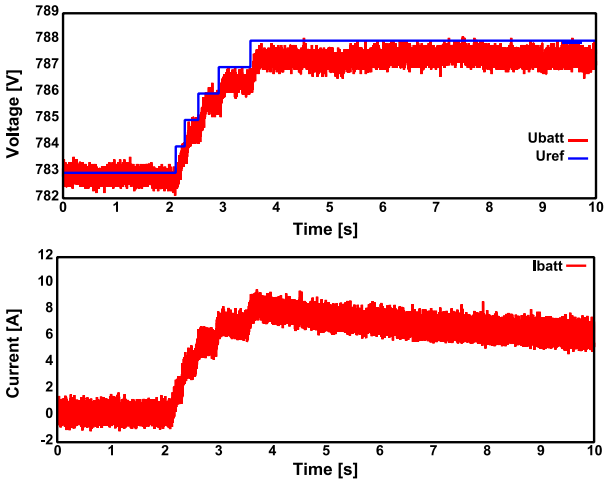


Fig. 8. BESS voltages (top) and current (bottom) during the constant voltage mode. At 2 s, the voltage reference is increased from 783 V to 788 V.

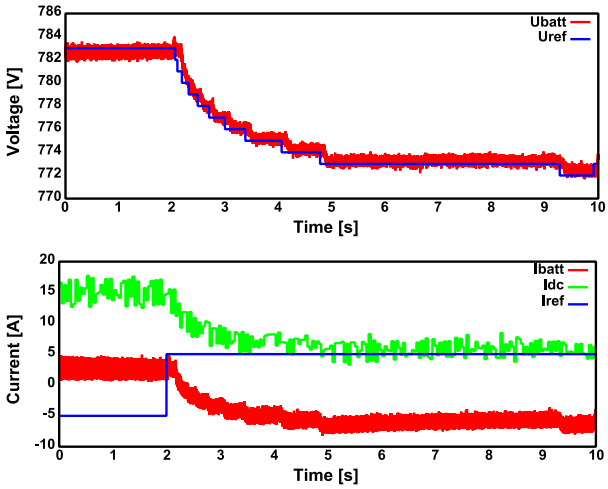


Fig. 9. BESS voltages (top) and currents (bottom). At 2 s, 783 V network voltage reference is changed to 5 A rectifier current reference and the power taken from the grid is limited. The BESS current increases while the rectifier current decreases.

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REFERENCES

[1] P. Nuutinen, T. Kaipia, P. Peltoniemi, A. Lana, A. Pinomaa, A. Mattsson, P. Silventoinen, J. Partanen, J. Lohjala, and M. Matikainen, 2014, “Research site for low-voltage direct current distribution in an utility network - structure, functions, and operation”, *IEEE Trans. Smart Grid*, vol. 5, 2574–2582

[2] P. Nuutinen, T. Kaipia, P. Peltoniemi, A. Lana, A. Pinomaa, P. Salonen, J. Partanen, J. Lohjala, and M. Matikainen, 2013, “Experiences from use of an LVDC system in public electricity distribution”, *Proceedings CIRED 2013*, 10–13 Jun. 2013, Stockholm, Sweden

[3] T. Kaipia, P. Nuutinen, A. Pinomaa, A. Lana, J. Partanen, J. Lohjala, and M. Matikainen, 2012, “Field test environment for LVDC distribution – implementation experiences”, *Proceedings CIRED Workshop 2012*, 29–30 May 2012, Lisbon, Portugal

[4] A. Lana, J. Karppanen, P. Nuutinen, T. Kaipia, J. Partanen, “Consideration on Battery Energy Storage System for an LVDC Distribution System”, 2014, *Proceedings NORDAC 2014*, 8-9 Sep. 2014, Stockholm, Sweden

[5] Calb CA40 battery datasheet. Available: http://en.calb.cn, 13 Jan. 2015

[6] A. Lana, P. Nuutinen, J. Karppanen, P. Peltoniemi, T. Kaipia, J. Partanen, 2014, “Control of directly connected energy storage in LVDC distribution network”, *Proceedings ACDC 2015*, 10–12 Feb. 2015, Birmingham, UK