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Design and analysis of electrical energy storage demonstration projects on UK distribution networks ☆

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HIGHLIGHTS

- Results of an EES system demonstration project carried out in the UK.
- Approaches to the design of trials for EES and observation on their application.
- A formalised methodology for analysis of smart grids trials.
- Validated models of energy storage.
- Capability of EES to connect larger quantities of heat pumps and PV is evaluated.

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ABSTRACT

The UK government's CO_2 emissions targets will require electrification of much of the country's infrastructure with low carbon technologies such as photovoltaic panels, electric vehicles and heat pumps. The large scale proliferation of these technologies will necessitate major changes to the planning and operation of distribution networks. Distribution network operators are trialling electrical energy storage (EES) across their networks to increase their understanding of the contribution that it can make to enable the expected paradigm shift in generation and consumption of electricity.

In order to evaluate a range of applications for EES, including voltage control and power flow management, installations have taken place at various distribution network locations and voltage levels. This article reports on trial design approaches and their application to a UK trial of an EES system to ensure broad applicability of the results. Results from these trials of an EES system, low carbon technologies and trial distribution networks are used to develop validated power system models. These models are used to evaluate, using a formalised methodology, the impact that EES could have on the design and operation of future distribution networks.

1. Introduction

The forecast electrification of key UK infrastructure such as heat and transport required by the UK government's aggressive CO_2 targets will result in major changes to the planning, design and operation of the UK's electrical infrastructure. This paper describes research undertaken by projects funded by the UK energy regulator's (Ofgem) Low Carbon Network Fund (LCNF) and the Engineering and Physical Sciences Research Council (EPSRC). A trial of electrical energy storage (EES) has been carried out by UK Power Networks (UKPN), ABB, Durham University and Newcastle University to evaluate the use of EES on distribution networks. This project was originally part of the AuRA-NMS Strategic Partnership between the EPSRC, Scottish Power Energy Networks, ABB and UKPN (formerly EDF Energy Networks) [1,2]. Subsequent work, focussing on the deployment of the EES system, was the first project to register in the LCNF as a First Tier project [3,4]. The validated network and LCT models described in this work come from the Customer Led Network Revolution (CLNR) project programme [5] again funded by Ofgem's LCNF. This is the UK's largest smart

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Nomenclature

ASHP	air-source heatpump
AVC	automatic voltage controller
CO_2	carbon dioxide
CLNR	Customer Led Network Revolution
DG	distributed generation
DNO	distribution network operator
EES	electrical energy storage
EOL	end of life
EPSRC	Engineering and Physical Sciences Research Council
EV	electrical vehicle
LCT	low carbon technology
LCNF	Low Carbon Network Fund
NOP	normally open point
OLTC	on-load tap changer
PCC	point of common coupling
PV	photo-voltaic
SOC	State-of-Charge
SOH	State-of-Health
UKPN	United Kingdom Power Networks
UK	United Kingdom
VEEEG	Validation, Extension, Extrapolation, Enhancement, Generalisation
VSC	voltage source converter

grid project thus far with metering data from over 20,000 industrial, commercial and residential customers as well a smart grid trial programme of over 87 smart grid interventions.

In this work the resultant realistic load, generation, network and EES models are used collaboratively to evaluate, using a formalised methodology, the impact that EES could have on future distribution networks. This formalised methodology can be used to evaluate the capability of these networks, equipped with EES or other advanced interventions, to connect the anticipated large scale proliferation of LCTs. This approach will enable DNOs to make more informed network planning, design and operational decisions based on a combination of realistic models based on trial results.

2. Background

The projected increase in customer demand, due to the proliferation of EVs and heat pumps, and much higher levels of zero-carbon intermittent renewables based generation to distribution networks will present major challenges to DNOs in terms of voltage control and powerflow management [6,7]. Grid connected energy storage can provide a variety of network services, including voltage control and powerflow management, in future electrical power systems [3,7–24]. These can be summarised as follows:

- *Voltage control:* Support heavily loaded feeders, power factor correction, reduce generator curtailment, minimise on-load tap changer (OLTC) operations, mitigate flicker, sags and swells [3,16–18,25];
- *Power flow management:* Defer network reinforcement, reduce reverse power flows, reduce generator curtailment, reduce losses [3];
- *System Restoration:* Voltage control and power flow management in a post-fault network [9];
- *Energy/ancillary markets:* Energy arbitrage, balancing market participation, reduce intermittent generation variability, increase intermittent generation yield from non-firm connections [3], provide ancillary services (frequency response/operating reserves) [26];
- *Commercial/regulatory:* Assist in compliance with energy security standard (ER P2/6) [27], reduce customer minutes lost, reduce generator curtailment [3,9];
- *Network management:* Facilitate islanded networks, support black starts, switch EES between alternative feeders at a normally open point (NOP) [3].

However, the adoption of grid-connected energy storage within electrical power systems has been hampered by technology costs, limited deployment experience, existing electricity market and regulatory structures and complex value chains which increase investment risk [24]. To mitigate against these issues a number of assessment techniques have been developed.

Comparative, techno-economic analytic assessments of the capability of energy storage to participate in energy arbitrage, frequency regulation, managing short–term fluctuations, and standing reserve are described in [20,22,28–30]. Economic assessments of the use of energy storage to increase the energy yield of and reduce the generation uncertainty associated with stochastic energy sources, by using it as an energy buffer, have been extensively evaluated [31–33]. Sophisticated modelling of economic or financial scenarios for energy storage is required to understand and determine the economic benefits of energy storage in electrical power systems. However, it should be noted that these analytic methods do not require accurate modelling of the dynamic operation of an energy storage system.

More detailed, dynamic models of energy storage, in electrical power systems, have been used extensively to evaluate the increase in energy yield and reduction in generation uncertainty associated with stochastic energy sources, by using it as an energy buffer [25,34–40]. A filtering time constant is used to model the impact of energy storage on the input wind power data in [34]. A year round evaluation of wind and energy storage system operation, using an hourly wind and demand time series and a simple energy storage model is used to evaluate the value of energy storage in [41]. In [25], a model which accounts for efficiency of energy storage is used to evaluate the capability of energy storage with reactive power control to minimise energy loss and enhance voltage stability of an islanded system. In [40], a dynamic model of a wind turbine and flywheel energy storage system model is used to evaluate its capability of wind power smoothing.

For voltage control, powerflow management, system restoration and network management, models that reflect the dynamic behaviour of an actual system are necessary to ensure that the resultant network design is not only economically feasible but is also technically acceptable. Steady-state load flow analysis of an electrical network model loaded with values from historical operational data sampled at 30-minute intervals is used to evaluate the capability of energy storage to regulate voltage and manage powerflows in [3,17,18]. In this case the energy storage was modelled as an electrical load when charging and a generator while discharging. A similar modelling approach is applied to evaluate a strategy which integrates sophisticated control of an automatic voltage controller (AVC) with EES systems, to regulate voltage across a representative future distribution network, with large numbers of EVs, heat pumps, PV installations and a windfarm [16]. Optimised combinations of real and reactive power for voltage support and loss reduction were assessed using detailed dynamic models of the