PROGRAMMATIC SMART GRID TRIAL DESIGN DEVELOPMENT AND ANALYSIS METHODOLOGY

Pádraig LYONS
Durham University – UK
padraig.lyons@durham.ac.uk

Philip C. TAYLOR
Durham University – UK
p.c.taylor@durham.ac.uk

Rosie HETHERINGTON
Northern Powergrid - UK
rosie.hetherington@northernpowergrid.com

David MILLER
Northern Powergrid - UK
david.miller@northernpowergrid.com

Daniel HOLLINGWORTH
EA Technology – UK
dxh.hollingworth@eatechnology.com

David ROBERTS
EA Technology – UK
david.roberts@eatechnology.com

ABSTRACT

The Customer Led Network Revolution (CLNR) is the largest UK smart grid trial project thus far. A total of 87 smart grid interventions and a hierarchical control system will be trialled and evaluated as part of this project. Developing a trial programme which enables comprehensive evaluation of the interventions and all combinations thereof is a non-trivial task. In this work a pair of complementary trial design and trial analysis methodologies are proposed. The trial design methodology enables rationalisation of the number and the duration of the trials. The resultant trial programme results are systematically augmented and expanded by the application of the VEEEG (Validation, Extension, Extrapolation, Enhancement and Generalisation)trial analysis methodology.

INTRODUCTION

The UK government's aggressive CO_2 emissions targets, will require electrification of much of the country's infrastructure through low carbon technologies (LCTs) such as Photo-Voltaic cells (PV), Electric Vehicles (EVs) and Heat Pumps (HPs). The large scale proliferation of these technologies will necessitate major changes to the operation and planning of distribution networks. Smart grids are seen as an enabler for this paradigm shift and the Customer Led Network Revolution (CLNR), funded by the GB regulator (Ofgem), is the largest UK trial of smart grid systems.

This paper initially details the CLNR smart grid trials and surveys. An overview of the development of the smart grid trial design methodology is then presented. An example of one of the detailed trial designs is presented with reference to the literature and the methodology proposed. The post-trial analysis methodology that was concurrently developed is then detailed. Finally, conclusions are drawn on the final trial design and the post-trial analysis methodology.

CLNR TRIALS AND SURVEYS

As part of the project programme, a series of smart grid trials began in March 2012. 87 smart grid interventions are deployed across four geographically distributed test networks. These test networks have been deliberately chosen to minimise the possibility of serious network disruptions in the event of failure or mal-operation of a smart grid intervention(s). A hierarchical control system, known as the Grand Unified Scheme (GUS) is to be deployed enabling collaborative control. Two of these test networks represent those found in rural and urban areas and a further two remaining two test networks were selected to ensure they contained high concentrations of LCT. All the test networks have additional monitoring installed to enable evaluation of the performance of the smart grid network interventions and control system(s).

Six Electrical Energy Storage (EES) systems will be installed at various voltage levels and locations, with output power ratings ranging from 50kVA to 2.5MVA. Real-Time Thermal Ratings (RTTR) devices have been installed and commissioned on overhead lines, at voltages of 20kV and 66kV, with additional systems due for commissioning on primary and secondary transformers and cables at voltages from 400V to 33kV. Secondary transformers will also be upgraded with On Load Tap Changers (OLTCs) to enable voltage control on the LV system. Finally, the primary transformer tapchange systems will be upgraded to enable remote actuation by the control system.

In addition to the smart grid network intervention trials a complementary set of customer based trials began in May 2011. These consist of customer interviews and surveys, smart meter data capture and detailed monitoring of residential and commercial customers. Customer flexibility trials are also underway which incorporate new time-of-use tariffs and commercial and residential Demand Side Response (DSR) programmes. These trials include customers who have LCTs installed. Results from both the customer and smart grid trials will be combined to enable reliable modelling and evaluation of future smart grid enabled distribution networks with large scale proliferation of LCTs.

SMART GRID TRIAL DESIGN

Smart Grid Trial Review

The trial network interventions implemented as part of the

AuRA-NMS project are similar to those proposed as part of CLNR including voltage control and EES however collaborative operation was not investigated to the extent required by CLNR [1]. In the SuperTapp N+ trials an existing commercial product was tested and trialled [2]. This project however investigated only a single voltage control component. This is similar to the GenAVC trials with additional work used to validate the operation of the state estimator [3].

The Skegness/Boston registered power zone is (RPZ) an ongoing project which includes an overhead line RTTR device and a capability to curtail generation if required [4]. The Orkney RPZ has a system that regularly responds to thermal overload through generation curtailment where and also integrates RTTR [5, 6]. The Scottish Power Energy Networks project includes an RTTR system and a capability to curtail generation if required [7].

It can be seen from the review presented above that the scope and of interventions and collaborative operation has not investigated previously on GB distribution networks.

Field Trial Design Methodology

Objectives

Previous work has identified voltage control and thermal overload as the primary technical obstacles to the large scale proliferation of LCTs in distribution networks [8]. Therefore, the primary objectives of smart grid systems are the control of voltage and the management of powerflows within operational limits under high penetrations of LCT.

In addition to the requirement to evaluate new network interventions, the trial programme requires evaluation of the collaborative operation of the network interventions under multiple control system architectures. This can vary from highly distributed, passive co-ordination between the network interventions, to a semi-centralised/hierarchical approach under the control system. Furthermore, the design of the trial programme must also facilitate the post-trial analysis methodology proposed later in this work which systematically augments the results from the field trials.

The trials also need to be designed to minimise disruption to the network where possible and be cognisant of the operational and safety requirements of the Distribution Network Operator (DNO). Finally, the trial programme also needs to consider the commissioning programme for the interventions and control system(s).

Design

Due to the objectives outlined previously, the trial programme has been subdivided into the following basic phases: baseline, voltage control, power flow control and integrated system trials as illustrated diagrammatically in Figure 1.

Baseline

These trials are required in order to analyse the existing operation of the network. This will enable quantification of the impact from deployment of the smart grid interventions and associated control systems.

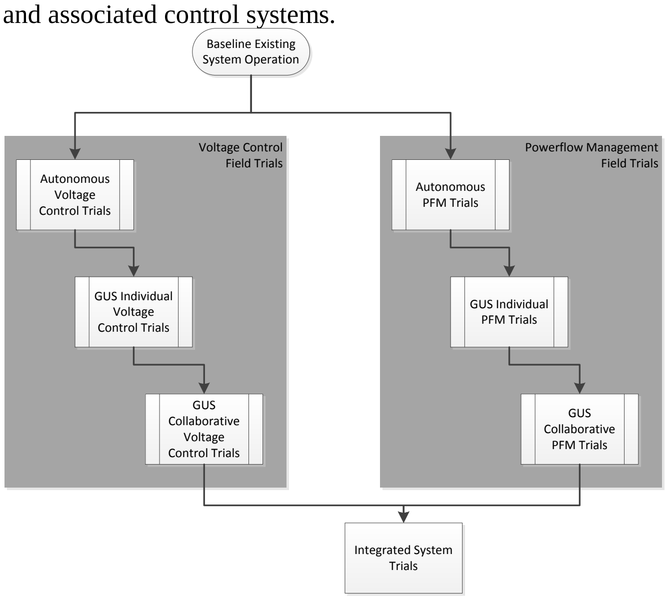

Figure 1: CLNR Field trial design

Voltage Control Trials

Since the networks under investigation have been chosen to be robust, the voltage variations that are likely to be observed in the trial networks will be relatively small. Therefore, the operational limits and set points need to be examined to ensure that the smart grid systems are invoked regularly in reaction to voltage events during the trial period to enable comprehensive evaluation of their characteristics and performance. A number of approaches have been identified to enable this [2]. Proxy voltage limits are to be used, within these trials, as this limits the possibility of customers' power quality being adversely affected.

Voltage control trials are broken down into three sub stages:

- *Autonomous* - In this stage each individual smart grid intervention utilises local measurements to determine a control action. Where network interventions exist in loosely electrically coupled network locations, trials will be carried out in parallel.
- *GUS Individual* - In this stage each individual smart grid intervention utilises global measurements to determine a control action. Where network interventions exist in loosely electrically coupled network locations, trials will be carried out in parallel. In this case global is defined as encompassing the control system monitoring area. In all cases open loop control will be trialled and evaluated prior to closing the loop [1]. Lower voltage network interventions will be carried out first, where the lowest numbers of customers are involved, with higher voltage network interventions involving the largest numbers of customers carried out later in the programme.

- *GUS Collaborative* - Lower voltage network interventions will be integrated earlier in the trial programme, where the lowest numbers of customers are involved, with higher voltage network interventions involving the largest numbers of customers integrated later in the trial programme.

Power Flow Management Trials

The test networks under investigation are unlikely to be thermally overloaded during the trials as they have been selected for robustness. Therefore, a number of approaches were considered to ensure that the smart grid systems are invoked regularly by thermal events during the trial period to enable comprehensive evaluation of their characteristics and performance. A number of approaches have been identified: -

1. Network element models held in smart grid intervention/control system are lower rated than reality
2. Scale thermal/current ratings
3. Reconfiguration of the network (N-1, N-2 conditions)
4. Scaling of results from monitoring systems prior to their submission to control system/GUS.

A combination of the options 1 and 2 was generally used in the trial design process. In addition, option 3 was also used when it did not materially impact customer supply.

Similarly to voltage control trials, the power flow management trials are also broken down into the same three sub stages:

- *Autonomous*;
- *GUS Individual;*
- *GUS Collaborative.*

In the final trial programme, where possible, trials are run in parallel. In particular, RTTR device trials will continue for the duration of the programme. This is particularly important as the ratings of network elements are impacted by seasonal factors.

Integrated system trials

The integrated trials investigate the multiple objectives of voltage and powerflow control. These may conflict and require the arbitration of intervention actions. In addition, the trials will seek to evaluate a number of secondary system objectives:

- Reduction of distribution network losses
- Conservation Voltage Reduction (CVR)
- Asset management (tapchange-operation reduction)

Exemplar Trial

To illustrate the application of the methodology to generate the trial design programme the development of an exemplar trial titled *Closed loop GUS voltage control system at Wooler Ramsey EES2, DSR (Wooler Ramsey), Hedgeley Moor capacitor bank and Glanton HV regulator* is presented. This is a voltage control trial and tightened voltage limits, as per the methodology, are implemented in this trial. This is a *GUS collaborative* trial, thus the primary objective of this trial is to evaluate the collaborative operation of the network interventions (EES unit (EES2); demand side response (DSR); capacitor bank and a 20kV in-line regulator under the control of a hierarchical control system. Earlier trials investigate the operation of fewer interventions operating collaboratively and later trials in the programme include more interventions in collaborative operation as per the methodology. *Autonomous* and *GUS Individual* trials, investigating the operation of each of these interventions, with and without GUS control, are included earlier in the trial programme which facilitates commissioning and post-trial analysis.

POST TRIAL ANALYSIS METHODOLOGY

Following the completion of individual trials, the post-trial analysis methodology known as VEEEG (Validation, Extension, Extrapolation, Enhancement, Generalisation) is used. This methodology ensures that the results from the smart grid trials are systematically analysed to provide robust findings regarding smart grid interventions and control system architectures. This methodology is illustrated in Figure 2. The methodology requires that the trial results are firstly used to validate the network and network component models. The results from the trials are then expanded and augmented to fully explore the capability of smart grid network interventions to enable LCT proliferation in future distribution networks.

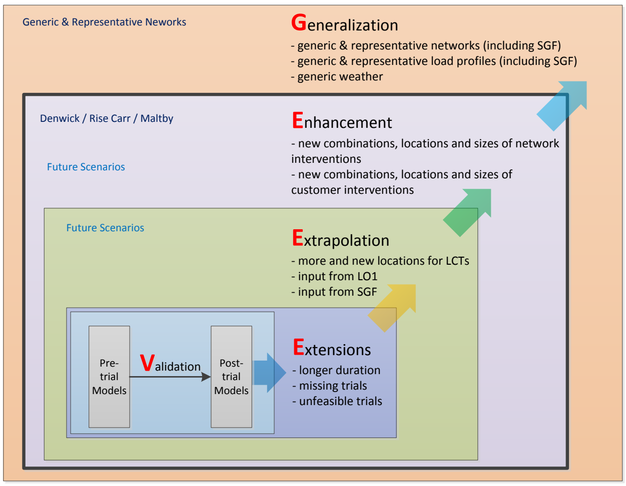

Figure 2: Post-trial methodology

Validation

Validate distribution network and smart grid intervention models with results from field trials. This enables development of the network and model library for the later phases of the VEEEG methodology.

Extension

Field trials that will be carried out during the CLNR network flexibility field trial programme will be of limited duration. These trials will need to be extended to evaluate the operation of the field trial over a full year. In this phase, the trials are extended by simulating longer durations of trials, simulating any trials which could not be completed for unforeseen reasons, and simulating the trials which are not feasible.

Extrapolation

In this phase, trial results are extrapolated by modelling both relocation and increased penetrations of LCTs, to evaluate future LCT scenarios of the trial networks. The profiles used within the future predicted scenarios are informed by results from analysis of smart meter data, detailed monitoring surveys and relevant literature. Evolving load and generation patterns and LCT penetration growth will impact on the capability of distribution networks to accept LCTs and determines the optimal choices of smart grid network combinations.

Enhancement

The enhancement phase enables evaluation of the introduction of new locations and larger numbers of smart grid interventions. The actual trials are limited in terms of the location and number of interventions available. Network simulation is used to overcome this. In addition, the enhancement phase enables evaluation of mixtures of smart grid interventions and customer flexibility interventions (DSR and tariffs).

Generalization

As the test networks have been selected to represent rural and urban networks, generalisation is already implicit in the trial design. This is reinforced by ensuring commonality between trials carried out on both the rural and urban test networks, achieved by deployment of similar smart grid interventions and combinations. In addition, generic and representative networks, derived from literature, in combination with the elements from the previous phases can be used to expand the work beyond the test networks [9]. Furthermore, to further generalise results, generic load, generation and weather data will be implemented through simulation.

CONCLUSIONS

It can be seen that the development of the field trial programme for the CLNR, is a non-trivial task due to the complexity and scale of the smart grid networks. The number of possible network configurations and combinations of equipment make it unfeasible to run every possible trial. The trial design methodology proposed provides a system to rationalise the number of trials carried out as part of the programme and ensure that the trials are as comprehensive as possible within the limited timescales of the CLNR project programme. The VEEEG methodology systematically augments and expands the results from the trial programme in order to provide robust findings regarding smart grid interventions and control system architectures, in future distribution networks with large quantities of embedded LCT.

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