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Development and Deployment of Generic Models for Grid Code Compliance Studies

Stephen Sommerville
Department of Electronic & Electrical Engineering
Brunel University London, Uxbridge, UK
stephen.sommerville@brunel.ac.uk

Professor Gareth A Taylor
Department of Electronic & Electrical Engineering
Brunel University London, Uxbridge, UK
gareth.taylor@brunel.ac.uk

Professor Maysam Abbod
Department of Electronic & Electrical Engineering
Brunel University London, Uxbridge, UK
maysam.abbod@brunel.ac.uk

***Abstract*—A challenge faced by many Transmission System Operators (TSO) is how to adequately represent Inverter Based Resources (IBR) within TSO network models. At present most TSOs require a series of Grid Code compliance studies to be provided as part of the connection process, which use detailed vendor models. These are often encrypted, very detailed and contain multiple instances of the same controller for each sub-unit within a plant. This can be challenging to implement into existing TSO network models, and thus becomes a significant time and cost constraint. This paper demonstrates that the majority of IBR plant and the associated performance requirements, can be adequately represented using generic open source aggregated WECC models. A 50 MW, Battery Energy Storage System (BESS) plant connected to the UK network, following the UK Grid Code / RfG requirements, is studied by developing and deploying a aggregated Western Electricity Coordinating Council (WECC) model in DIgSILENT Powerfactory and is presented as a benchmark system.**

Keywords—BESS, Grid Code, IBR, Power Park Controller, Plant Controller, RfG, TSO, WECC.

I. INTRODUCTION

A. Introduction

All Transmission System Operators (TSO) require developers to provide a series of compliance studies, prior to connection, to demonstrate that the proposed generation meets the required grid code standards. Conventional synchronous generators have well established governor and excitation system models available in literature and standards, such as IEEE 421.5. Inverter Based Resources (IBR) however, pose a significant challenge to TSOs as their models are usually based on specific vendors designs, and are often encrypted. Integrating accurate models of IBRs into existing TSO network models, has therefore become complex and a significant time and cost constraint.

This paper shows how a correctly configured generic open source aggregated Western Electricity Coordinating Council (WECC) model can adequately represent IBR systems for the studies most TSOs routinely carry out. A 50 MW, Type D, Battery Energy Storage System (BESS), for the U.K. is used as an example demonstrating compliance with the general requirements of the U.K. Grid Code [1] and the European Requirements for Generators (RfG) [2].

B. Motivation & Contribution to Knowledge

The contribution of this paper is to demonstrate that a correctly configured WECC model can represent a IBR system and be easily scaled to work within a large TSO network, to carry out dynamic power system analysis studies. The motivation for the paper is due to the recognition that TSO networks are coming under increasing pressure to add IBR to their network; and high level of IBR integration creates design and operational challenges [3].

The use of large Root Mean Square (RMS) / positive phase sequence models is accepted to be satisfactory for many large-scale studies, and slow transients, although several concerns have been raised in relation to the accuracy of fast transients, such as Fault Ride Through (FRT) events [4]. For increased accuracy the use of more detailed Electromagnetic Transient (EMT) models is preferred, however, it is recognised that creating large scale detailed EMT models for a whole transmission system contains several significant challenges and is computationally intensive and time consuming [4]. For this reason many TSOs prefer to still run large scale RMS models for day-to-day analysis and planning.

A further problem faced by large EMT models is that most EMT modelling packages, have limitations for handling multiple network configurations, operational scenarios and contain only limited tools to facilitate, loadflow, short circuit, harmonics, and eigenvalue analysis. Therefore, whilst many TSO may aspire to have a detailed EMT model of the system, they will also need to run a parallel RMS model. For this reason, it is considered that robust RMS models, that accurately represent IBR systems will be needed for many years.

II. GENERIC MODELS

A few generic models are available for IBR systems, the most well-known being the IEC 61400-27-1 series [5] for Wind Turbine Generators (WTG) and the WECC models. The WECC models are primarily aimed at the North American area, and many have been approved for use by NERC [6]. The use of WECC models is less common within the U.K. / European context, which follows the RfG standard, and most developers use bespoke PPCs, with customised control designs. Some general work has been carried out on the use of WECC models within the European context, but their use is still not widespread [3], [7], [8] & [9].

A. IBR System Configuration

IBR networks are formed of many distinct individual converters controlled by an overall Plant Controllers (PC) / Power Park Controller (PPC), which in turn controls a large number of individual converters.

The PPC is essential in all large renewable energy power plants, as they provide control and dispatch of active and reactive power setpoints to the generators as well as providing power-frequency response and voltage-MVAr response. These control systems are typically operated with a response time of up to a few seconds. Standard models of PPCs have been available for several years, from WECC, and are generally considered robust PPC operation.

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Individual inverter control systems have also been developed by WECC [10] and are also well established, however as inverter control systems are necessarily more complex, and faster acting, the number of differences between a vendor model and a WECC generic model is expected to be higher. Inverter control systems are much faster than the PPC response and are operated with a response time in the range of microseconds to milliseconds.

Several different WECC models have been developed over the last 10 years and are commonly used within industry, and have been validated through a number of external bodies [11], [12] & [13]. The WECC models can be used for WTGs, Solar PV and BESS. The WTG models are generally the most complicated as they have several sub-models to represent the turbine mechanical dynamics, with the Solar PV / BESS being simpler. For Solar PV and BESS units, the required WECC models can be split into three main areas, summarised below.

B. *WECC Generator Interface (REGC)*

The REGC model represents the generator interface with the grid. It takes the input and output signals from the plant and processes them to interface to the generator controls. Signals include voltage measurement, real and reactive current command, and real and reactive current injections. The REGC model implements a Phase Locked Loop (PLL) for the generator, however as noted earlier, the reliability of the PLL during FRT events, is the subject of further investigation [4].

C. *WECC Electrical Control (REEC)*

The REEC model represents the inverter electrical controls to provide local P and Q control and current limiting controls and implements local voltage control and frequency control functions. The model takes P and Q set command signals from the Plant Controller (REPC), and feedback real and reactive current commands from the REGC module as well as a voltage reference signal from the plant.

Within the UK Grid Code / RfG requirements for Type C / D plants, the frequency control mode and voltage control modes within the generator local control are disabled and are implemented in the PPC instead (REPC). The REEC module is responsible for providing correct action during FRT events.

D. *WECC Plant Controller (REPC)*

The REPC model represents the PPC and is used to interface the overall control system to the inverters. The REPC is not necessary for smaller plants (such as RfG Type A or B plants) and is used for larger Type C or D systems. The model takes several P, Q, voltage and frequency measurements from the plant and provides and P & Q setpoints to the REGC module.

Within the UK Grid Code / RfG requirements for Type C / D plants, the REPC module is responsible for providing the power-frequency response and voltage control responses modes. During FRT events, the REPC module is ‘frozen’ and implementation of the response occurs at the inverter level (REEC). It is therefore important to note that the majority of the compliance studies required for UK Grid Code / RfG focuses on the performance of the PPC (REPC) model.

E. *Protection Functions*

WECC models do not include standard implementation of protection functions. This has been done deliberately as a wide number of different implementations are possible. WECC specifically note that, although an implementation is not provided, it is essential to incorporate a model, to ensure that the generator protection functions are represented correctly. This has been implemented directly by the DIgSILENT technical team within Powerfactory as part of one of the templates [14], and contains elements for over/under frequency, over/under voltage and RoCoF.

F. *Implementation in DIgSILENT Powerfactory*

Several ‘templates’ have already been setup within DIgSILENT Powerfactory [14], to facilitate use within the software. These templates were used as a starting point and implemented together to form an overall system as shown below in Fig. 1 & Fig 2, and a summary of the different WECC modules used is shown in Table I.

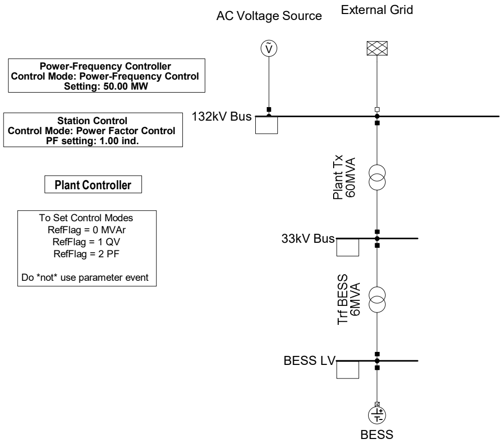

Fig. 1. DIgSILENT Powerfactory Model

TABLE I. MODEL CONFIGURATION

Control Element	WECC Model
Plant Control	REPC_C
Electrical Control	REEC_C
Generator Interface Control	REGC_C
Protection	DigSILENT Template

The Powerfactory model contains a single upstream busbar rated at 132 kV, a 133/33 kV 60 MVA transformer, 33 kV busbar and then an aggregated model of a series of smaller BESS units. The aggregated model consists of 13x 5.5 MVA 33/0.69 kV transformers, 13x 4.6 MVA BESS units. The base WECC PPC model is set to a nominal power of 50 MW.

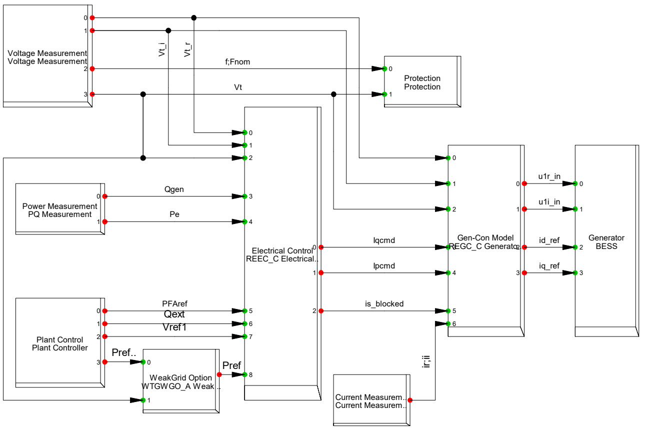

Fig. 2. DIgSILENT Powerfactory Model

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G. Model Aggregation

The majority of IBR installations are formed of a series of smaller, modular inverters and generation units. Detailed models of the installation are often developed during the compliance process, but the use of aggregated models is also possible, where the individual transformers, cables and IBR are represented by a single equivalent model [10], [15] & [16].

Model aggregation allows a more complex system to be represented by a much smaller equivalent model, and therefore simplifies computation times and modelling within a large-scale system, however it should be recognized that there is potential for certain reductions in accuracy.

III. UK / RFG GRID CODE REQUIREMENTS

A. General

The UK Grid Code follows the general requirements detailed in the European RfG. There are several specific differences within the UK and additional specific requirements for BESS units, such as repetition of the compliance studies in import mode and implementation of Low Frequency Demand Disconnection (LFDD). For the paper, the focus will be on the similarities and generalities of the requirements, to demonstrate the suitability of the WECC models.

B. Reactive Power Across the Voltage Range

Reactive power capability assessments in the UK Grid Code and RfG are defined in terms of a P-Q or V-Q capability diagram(s). To demonstrate compliance, a series of steady state loadflow studies are carried out to indicate the plant reactive power capability at different voltage levels. As the studies are static loadflows the operation of the WECC control modules is not directly relevant to the outputs and are therefore not discussed further.

C. Fault Ride Through (FRT)

Fault Ride Through (FRT) studies are one of the key challenges of IBR plant, and several concerns have already been raised about the suitability and accuracy of RMS simulation to correctly represent an FRT case in an RMS environment, and many TSOs require a more detailed EMT study to be carried out. As noted in part I-E, the REEC module is responsible for providing the FRT response, and during the disturbance the PPC (REPC) is frozen. Therefore, for the purpose of this paper, FRT studies are not explored in detail.

D. Limited Frequency Sensitive Mode (LFSM)

Limited Frequency Sensitive Mode (LFSM) is widely used within the UK and the European mainland, as a simple method of managing power output in case of rising or falling frequency and is defined as LFSM-O and LFSM-U for over-frequency and under frequency respectively. The required droop slope is between 2% and 10%. Within a Type C/D installation the implementation is carried out within the PPC (REPC) control module.

E. Frequency Sensitive Mode (FSM)

Frequency Sensitive Mode (FSM) is very similar to LFSM operation, but with the deadband between 49.5Hz to 50.4 Hz removed and with the droop slope restricted to a range of 3% to 5%. As with the LFSM mode, the FSM mode is implemented in the PPC (REPC). For implementation in the WECC models the parameters of the droop curve and deadband must be change from the LFSM settings.

F. Voltage Control Mode

The ability for the plant to operate in Voltage Control mode is generally required within the Grid Code / RfG, where the plant reactive power output changes on a voltage-MVAr droop slope. Within a Type C/D installation the implementation is carried out within the PPC (REPC) control module.

IV. VALIDATION SIMULATIONS

A. General Requirements

Within the UK Grid Code, the requirements for the compliance studies to be performed are detailed in Section ECP, Appendix A.3; and within the RfG code the equivalent requirements are generally detailed in Article 43 and specific requirements for Type C / D are detailed in Article 55 and 56 respectively. The list of specific study cases and scenarios for compliance is extensive, and producing all necessary study cases would be beyond the limits of the paper, however representative studies for each scenario are shown, in the following subsections, to provide proof of concept.

B. Configuration, Parameterisation and Setpoints

To obtain a satisfactory response from the system it is necessary to parameterise and tune the various control elements within the model. This is done through a combination of suggested settings from WECC, calculation of specific values, and tuning to find the most suitable values for the plant. The PPC control base MVA is set within the DIgSILENT Powerfactory model as 50 MVA. The model is analysed as a balanced RMS simulation with a time step of 10 ms. The gain values for the various controllers were tuned, using a simple trial and error basis.

TABLE II. MODEL CONFIGURATION

WECC Model	Parameter	Setting
Ddn / Dup	REPC_C	25
Kc	REPC_C	0.1
Kpg	REPC_C	0.2
Kig	REPC_C	1.1
Kp	REPC_C	LFSM/FSM = 0.4 Q/V = 3
Ki	REPC_C	LFSM/FSM = 5 Q/V = 14
Qmin	REPC_C	-0.16
Qmax	REPC_C	0.42
fdbd1	REPC_C	LFSM = -0.01 FSM = 0.0
fdbd2	REPC_C	LFSM = 0.008 FSM = 0.0

All command signals need to be given as a function of the overall plant rating (50 MVA). MW setpoints are given via setting *Plant_pref* = 1.0 to obtain 50 MW export, and *Plant_pref* = -0.5 to obtain 25 MW import. MVAr setpoints are given in a similar manner with *Qref* = 0.33 to set 16.5 MVAr export and *Qref* -0.33 to set 16.5 MVAr import. The PF control method has to be set with in a similar manner to *Qref* as an equivalent MVAr, using the command *pfaref = 0.33* to achieve a PF of 0.95.

C. MW, MVAr and PF Setpoints

As part of an initial validation process, the system was checked for the ability to set the PPC for MW, MVAr and Power Factor (PF) setpoints. The MW setpoints were used to tune the proportional gain (K_{pg}) and integral gain (K_{pi}) of the

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active power control loop, and the MVAr setpoints were used to tune the proportional gain (K_p) and integral gain (K_i) of the reactive power control loop. For MW control, the PPC must be set with $FrqFlag = 0$. To permit operation in MVAr control mode the parameter *RefFlag* is set to 1, for operation in PF setpoint mode the parameter *RefFlag* is set to 2. The results can be seen in Fig. 3 & Fig 4.

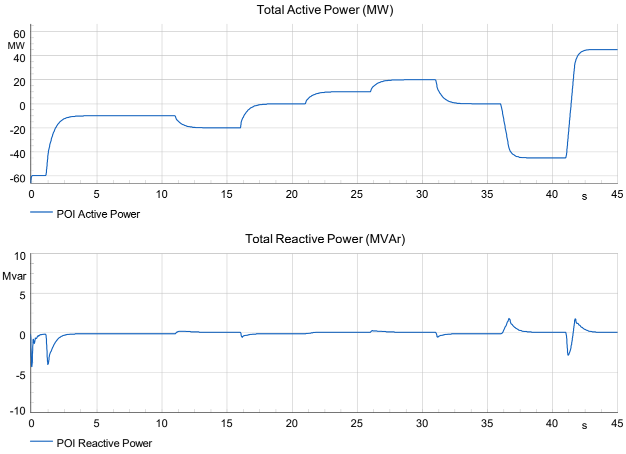

Fig. 3. Active Power Control

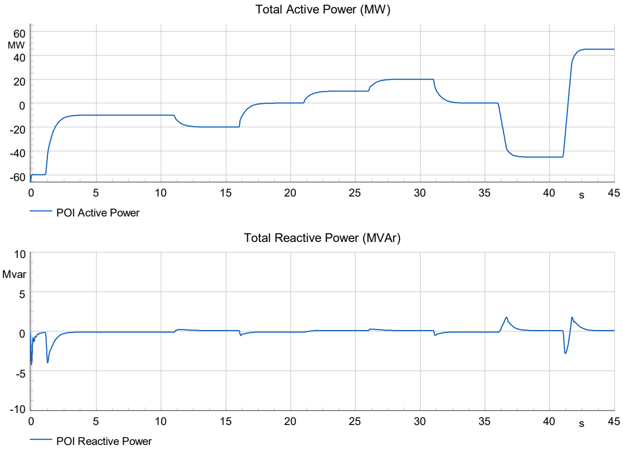

Fig. 4. MVAr Control

It was observed that the PF setting remains generator orientated during all commands, such that when the BESS moves into import mode, the reactive power returns to MVAr export, rather than becoming an import, and thus does not follow the true sign convention of a lagging PF being relative to a generator or load. This response is seen in Fig. 5.

D. LFSM Response

For the LFSM-O simulation study, the simulation requires an island condition to be setup, using an external synchronous machine and selection of plant load such that the frequency zenith reaches 52 Hz. The REPC controller is set with a droop slope of 4% via setting *Ddn* and *Dup,* and the *fdbd1* and *fdbd2* as indicated in Table II. For the UK Grid Code, the response should occur when the frequency rises above 50.4 Hz. The results of the simulation can be seen in Fig. 6, where the plant de-loads. A small transient dip is observed at the initial frequency change, which was not fully identified.

The LFSM-U simulation study uses the same parameters as the LFSM-O case; however, the plant is started at an initial condition of 80% of rating. The results of the simulation can be seen in Fig. 6, where the plant loads with a droop of 4%.

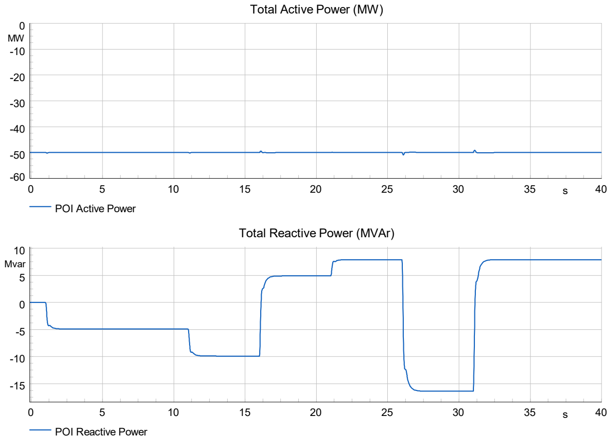

Fig. 5. Power Factor Control

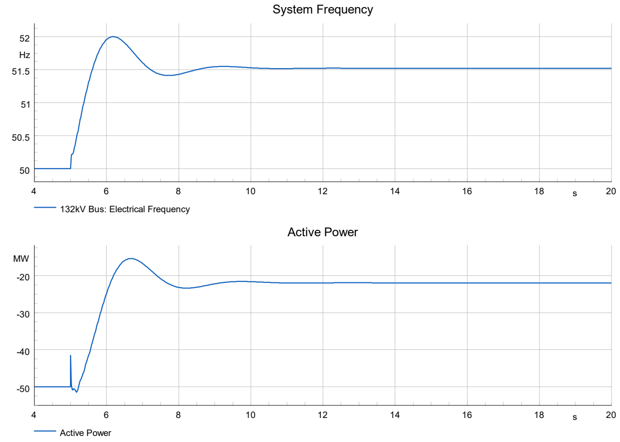

Fig. 6. LFSM-O Response

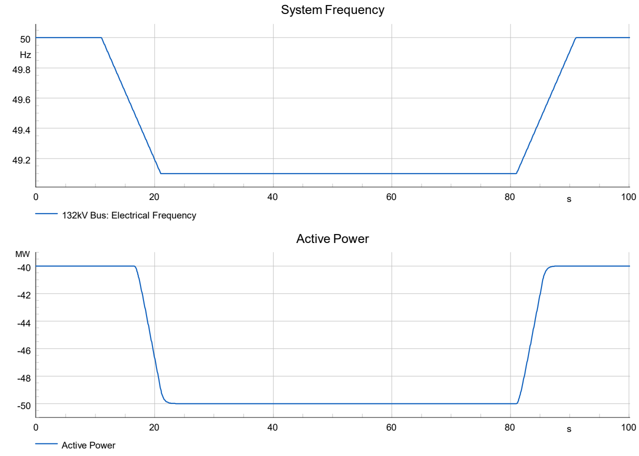

Fig. 7. LFSM-U Response

E. FSM Response

FSM response uses the same principles as the LFSM behaviour, however there is no deadband in the response characteristic. To implement the behaviour in the controller, the frequency deadbands *fdbd1* and *fdbd2* in the REPC module are reduced to 0.

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F. *QV Response*

The voltage control simulation study consists of a series of positive and negative voltage steps applied to the plant to show the plant MVAr response. To enable voltage control behaviour, the PPC must be set with *Refflag=1*, and care must be taken to ensure that the inverter controls do not have any QV response enabled. The PPC voltage droop response is set through parameter K_c to determine the slope of the response. Several unexpected behaviours were identified during this study: 1) The response was slightly asymmetrical for negative and positive voltage steps. 2) The values of K_p and K_i had to be re-tuned to much higher values, to give a satisfactory response, as noted in Table II. 3) The Q_{max} and Q_{min} values had to be adjusted to prevent overshoot. The results of the simulation can be seen in Fig. 8., where the plant adjusts its MVAr output, with a QV droop setting of 5%.

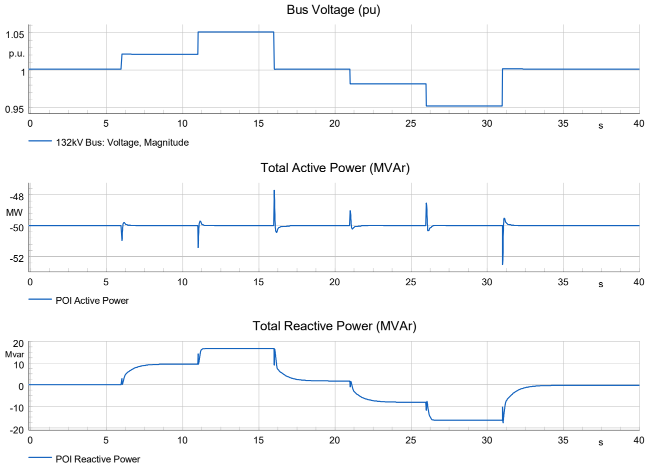

Fig. 8. QV Response – Voltage Steps

V. CONCLUSIONS & FURTHER WORK

The paper has shown that the use of generic WECC models can allow a good representation of IBR for most RMS scenarios, using a 50 MW BESS as a test network. The WECC model demonstrated that active and reactive power setpoint commands, power-frequency response and voltage-MVAr characteristics. A few small transient spikes were identified during some of the studies, but these are generally related to the step changes applied to setpoints. An unexpected detail was identified in the power factor control mode, where the power factor of the PPC is set based on the overall system rating, in a similar manner to an MVAr setpoint, and does not dynamically change between generator orientated and load orientated, as the BESS moves between export and import. One of the main challenges faced with the WECC model was correct configuration of the QV response characteristic, and some unexpected behaviour was identified, requiring specific setting of the Q_{max} and Q_{min} limits and different values of K_p and K_i to the values used for MVAr and power factor mode.

The system response for FRT events was not investigated, as these are faster transients, controlled by the inverter rather than the PPC; with the PPC output frozen during the FRT events and therefore of secondary importance for slower general RMS simulation run over several seconds. The ongoing general discussion on the suitability of RMS models for carrying out FRT studies is very active, and these are expected to be demonstrated with EMT simulations in the future. In principle it would be possible to define a reasonable approximation of an inverter FRT response with a correctly configured WECC controller. It is likely that such approach would require a more detailed and bespoke tuning and parameterisation approach validated against an EMT model fo to each site, gain confidence in the response.

Further work would be to extend the general WECC model concept into more complex analysis areas, such as overall frequency stability and voltage stability. There is also potential to use the models to carry out eigenvalue analysis to help identify if the large scale CFG deployment is altering, or creating, small signal stability problems.

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