SSEN

RESILIENCE AS A SERVICE (RAAS)

EVALUATION OF ISLANDED NETWORK BLACK START CAPABILITY - RAAS SCHEME

70078595-008
OCTOBER 2021

FINAL

SSEN

RESILIENCE AS A SERVICE (RAAS)

EVALUATION OF ISLANDED NETWORK BLACK START CAPABILITY - RAAS SCHEME

TYPE OF DOCUMENT: FINAL

PROJECT NO. 70078595-008

OUR REF. NO. 70078595-008

DATE: OCTOBER 2021

WSP

110 Queen Street
Glasgow
G1 3BX

Phone: +44 141 429 3555

Fax: +44 141 429 3666

WSP.com

QUALITY CONTROL

Issue/revision	First issue	Revision 1	Revision 2	Revision 3
Remarks	First issue	First Revision	Second Revision	Final
Date	14.05.2021	04.06.2021	22.06.2021	21.10.2021
Prepared by	Dimitri Vozikis (WSP) Abdullah Emhemed (WSP)	Dimitri Vozikis (WSP) Abdullah Emhemed (WSP)	Dimitri Vozikis (WSP) Abdullah Emhemed (WSP)	Dimitri Vozikis (WSP) Abdullah Emhemed (WSP)
Signature				
Reviewed by	Cameron Scott (WSP) Maciej Fila (SSEN) Sarah Rigby (SSEN)	Stewart Hynds (WSP) Maciej Fila (SSEN) Sarah Rigby (SSEN)	Stewart Hynds (WSP) Maciej Fila (SSEN) Sarah Rigby (SSEN))	Abdullah Emhemed (WSP)
Signature				
Authorised by				Manuel Castro (WSP)
Signature				
Project number	70078595-008	70078595-008	70078595-008	70078595-008
Report number	70078595-008	70078595-008	70078595-008	70078595-008
File reference				

CONTENTS

GLOSSARY

Abbreviation	Meaning
BESS	Battery Energy Storage System
CI	Customer Interruptions
CML	Customers Minutes Lost
DER	Distributed Energy Resources
DG	Distributed Generation
DNO	Distribution Network Operator
DSG	Diesel Synchronous Generator
EMS	Energy Management System
FCWT	Full Converter Wind Turbine
HV	High Voltage - voltage levels classified as HV are 11kV & 6.6kV
IIS	Interruptions Incentive Scheme
LV	Low Voltage - voltage levels less than 1kV AC or 1.5kV DC
PLL	Phase Locked Loop
PWM	Pulse-Width Modulation
PMCB	Pole Mounted Circuit Breaker
RaaS	Resilience as a Service
RoCoF	Rate of Change of Frequency
SHEPD	Scottish Hydro Electric Power Distribution
SSEN	Scottish and Southern Electricity Networks
THD	Total Harmonic Distortion
TOV	Temporary Over-Voltage
TS	Time Setting

EXECUTIVE SUMMARY

The Scottish and Southern Electricity Networks (SSEN) Resilience as a Service (RaaS) innovation project seeks to improve the reliability and availability of distribution networks in remote locations through services procured from a third party owned Battery Energy Storage System (BESS). The RaaS concept has the potential to provide black start capability and enable islanded operation of the local electricity network during power interruptions. This will improve customers' security of supply and reduce Customer Interruptions (CIs) and Customers Minutes Lost (CMLs) [1]

The RaaS project will demonstrate the integration of a BESS and associated Energy Management System (EMS) at a site on SSEN's Scottish Hydro Electric Power Distribution (SHEPD) 11kV rural network, with Drynoch primary substation selected as the potential trial site [2].

The network modelling studies undertaken by WSP for the RaaS project intend to evaluate and analyse the general technical requirements and challenges associated with the implementation of the RaaS scheme. The studies include assessments of steady state performance and dynamic stability, transient inrush current phenomena and black start requirements, and earthing and fault protection studies. In addition to the Drynoch site, Kinloch and Mallaig are also assessed to provide a wider perspective relevant to future roll out of RaaS.

WSP's prior work within the project has identified and presented suitable model requirements and set out the required Test Cases for conducting the aforementioned project studies. Steady state and detailed transient models of the Drynoch and Kinloch networks have been developed and validated for different study types, including load flow, fault levels, transients (inrush currents), and frequency and voltage stability studies. Details of the Drynoch network model are presented in the Deliverable D2.2 'Modelling and Simulation Studies of Inrush Current Phenomena Associated with the Application of RaaS' report, and the Kinloch network model development is discussed in this report.

This report (Deliverable D2.3) evaluates the capability of the RaaS scheme to enable and deliver black start capability on the Drynoch and Kinloch distribution networks. The report provides detailed simulation studies required to assess the performance of the selected case studies during black start procedures provided by a third-party BESS. The assessment has included evaluation of customers' power outages durations, optimal customer restoration processes, and quality & continuity of supply on different loads.

Within the studies, the following sequences for the black start process have been considered:

- Reconnection of each radial feeder individually;
- Various cascaded customers reconnections (the feeder is sectionalised based on the location of the circuit breakers); and
- Ramping of the primary substation voltage with all customers connected.

For each case, customer AC voltages and currents, system frequency and duration of the black start sequences have been studied, and recommendations on optimal black start services are provided.

To assess the black start performance of each selected site, two key time durations have been considered - black start restoration time and transient settlement time.

The black start restoration time comprises the time required for starting-up the BESS and energising the associated 11kV bus, reconnecting customers, and resolution of supply voltage transients following the connection of customers. The transient settlement time is the time that is required for all the transients in the supply voltages to die away and the voltage Total Harmonic Distortion (THD) to be less than 4%. These time parameters have been used to optimise the black start procedures, thereby reducing the time off supply.

The key outcomes of the work are follows:

- In general, the simulation analysis and results have shown that integration of the BESS will enable the delivery of black start services to the Drynoch and Kinloch customers with acceptable restoration time and power quality.
- For Drynoch, the black start procedure could be optimised if feeder 11 is connected first followed by connection of feeder 12. This will ensure reduced settlement time when the customers are energised. The settlement time was found to be 1.5s, and this includes 1s delay between the closure of feeder 11 circuit breaker (CB) and feeder 12 CB.
- The BESS response (converter voltage response) affects the frequency transient. Faster controller voltage response (i.e.<30ms), leads to more pronounced frequency transients.
- For both the Drynoch and Kinloch networks, cascaded customer restoration sequences may reduce the inrush currents. However, voltage unbalances exist due to unbalanced loads. In addition, and according to the simulation results, cascaded customers restoration sequences have the highest settlement time (approximately 5.5 to 6 seconds for BESS energisation of the 11kV bus), depending on the signal communication delays between the restoration sequences.
- Prioritisation of critical/vulnerable loads for faster supply restoration is feasible with the assistance of the existing PMCBs to deliver cascaded customer connection sequences. This prioritisation leads to a positive effect on the black start service regarding the frequency transients and the continuity of supply.
- The incorporation of voltage ramping for black start service achieves smooth energisation and loading, minimising transients on frequency, currents and voltages. The initial synchronisation voltage between the BESS and the customers must be higher than 0.5p.u. (5.5kV RMS) to provide acceptable voltage margins for a variety of loads. The recovery settlement times are 3s to 4s, which are highly dependent on the voltage ramp rate.
- The BESS can achieve successful and seamless transition from Grid Forming to Grid Following operation (i.e. with transition time delay less than 20ms), synchronising to the supply grid and realising continuity of supply and uninterrupted operation.

The BESS scheme can achieve successful black start and network restoration without exceeding the nominal operational values (voltage and thermal limits) of the equipment on HV or LV sides. However, further investigations are required to evaluate the performance of protection schemes including selectivity, sensitivity, and discrimination during different stages of the black start procedure. This assessment will be completed within a subsequent piece of work.

1

PROJECT OVERVIEW

1 PROJECT OVERVIEW

The Resilience as a Service (RaaS) innovation project aims to enhance network resilience and security of supply in remote areas through services procured from a third party owned Battery Energy Storage System (BESS). The proposed scheme would re-establish supply to customers in the event of an outage on the upstream network, and allow local renewable energy assets to continue exporting power, until the Distribution Network Operator (DNO) can restore the network to conventional operation [1]. By developing this innovative energy solution, which combines energy storage, local renewables, smart grid controls, flexibility services and new commercial models, RaaS will improve security of supply for customers by reducing network outages.

1.1 BACKGROUND

The RaaS project will evaluate the technical feasibility and financial viability of the RaaS concept. This includes detailed evaluation of the technical aspects of the scheme to understand the potential interactions with existing network assets, and to determine the suitability of using a BESS to enable stable islanded operation in the event of a loss of grid supply, to provide black start capability, and to perform smooth transition to normal operation when the grid supply is restored.

The project aims to demonstrate the integration of a BESS and associated Energy Management system (EMS) on SSEN's Scottish Hydro Electric Power Distribution (SHEPD) 11kV rural network, with Drynoch primary substation selected as the potential trial site [2].

WSP have been appointed to deliver three of SSEN's technical work packages, as follows:

SSEN Work Package 1 (SWP1) - To undertake detailed modelling and technical feasibility studies and determine the general technical requirements associated with implementation of the RaaS concept.

SSEN Work Package 2 (SWP2) - To conduct modelling and simulation studies to evaluate potential inrush currents and transients which could be experienced during the RaaS black start sequences and determine the technical feasibility of RaaS black start functionality.

SSEN Work Package 4 (SWP4) - To investigate the impact of RaaS scheme implementation on the performance of the distribution network protection and control schemes and provide recommendations on the schemes' settings and design.

1.2 SCOPE OF THE REPORT

This D2.3 report forms part of RaaS SWP2 and presents the modelling and simulation work undertaken by WSP to evaluate the feasibility of delivering black start services by a BESS connected to Drynoch and Kinloch distribution networks [2].

The PowerFactory models of Drynoch and Kinloch distribution networks developed for SWP1 and SWP2 have been used to undertake the studies required for this deliverable. The models have been refined with further enhancement to the BESS control model to enable black start feasibility studies.

This included the implementation of different voltage control response time capabilities by the BESS converter.

1.3 REPORT STRUCTURE

The report is structured as follows:

- Overview of sites selected for assessment (Section 2);
- Summary of the Test Networks for the Drynoch and Kinloch sites (Section 3);
- Description of the model refinement and enhancement process for the Drynoch and Kinloch sites (Section 4);
- Test Cases for SWP2 black start requirements (Section 5); and
- Concluding results and recommendations (Section 6)

2

OVERVIEW OF THE SITES SELECTED FOR ASSESSMENT

FINAL

2 OVERVIEW OF THE SITES SELECTED FOR ASSESSMENT

Five locations were shortlisted as potential trial sites by SSEN and E.ON, as shown on the map in Figure 2-1 and detailed in [2]. In consultation with SSEN, three of these sites have been put forward for modelling assessment - Drynoch, Kinloch and Mallaig. The distribution network selected for potential demonstration of a RaaS scheme is Drynoch, while feasibility studies will also be performed for Kinloch and Mallaig sites. Each of these sites have unique attributes and features relevant to demonstrating the potential benefits of RaaS and delivery within project timeframes and budget, as follows:

- **Drynoch** has a good level of distributed generation (DG) (around 0.73 MVA), and the current Incentive Interruption Scheme (IIS) figures (CIs/CMLs) indicate that customers would benefit from a RaaS scheme, further, there is sufficient space within the substation compound for installing the BESS unit (although this will not be the case for Business as Usual (BaU) application of RaaS, location within the substation is pragmatic for the trial to support project delivery and ongoing appraisal of the demonstration scheme.

- **Kinloch** has high ISS figures, and relatively long overhead lines.

- **Mallaig** has high ISS figures, high number of faults, and good level of DG (0.8 MVA).

Figure 2-1 - Selected site locations in relation to Glasgow (marked in red) 1) Drynoch, 2) Kinloch, 3) Kishorn Hill, 4) Lochinver, 5) Mallaig [2]

3

TEST NETWORK AND SCOPE OF BLACK START STUDIES

3 TEST NETWORK AND SCOPE OF BLACK START STUDIES

This section describes the scope of RaaS black start technical feasibility studies and the associated test cases used to conduct the analysis.

3.1 SCOPE OF RAAS BLACK START STUDIES

The RaaS scheme will be designed to improve the security of supply of an 11kV network (following a network fault on the 33kV bus) via a set of rules and conditions. These will include starting up the BESS; powering auxiliary systems (alarms, control units, protection schemes, etc.) and primary substation loads (transformers, converter filters, etc.); re-energising distribution network assets (HV feeders, secondary transformers and customer loads); stabilising and maintaining the resultant islanded network; and finally synchronising and reconnecting to the main supply grid.

The black start sequence could potentially be delivered through a number of alternative approaches related to both BESS converter control response time and different scenarios to reconnect customer loads. The BESS converter design and the selection of restoration strategy will have a direct impact on power outage duration, quality and continuity of supply, and the robustness of the formed network during black start procedures.

The simulation studies presented in this report have been undertaken to investigate these impacts. PowerFactory time-domain simulation models of the selected SSEN Drynoch and Kinloch networks have been used to evaluate the different procedures, including harmonic and unbalance content on the network voltages, reconnection durations, and optimal recovery of priority loads.

The work has also investigated a number of additional measures which could be given consideration to achieve optimal black start and network recovery capability with regard to customer priority, reduced outage duration, and the swift establishment of good/acceptable power quality. The measures could include but are not limited to the following:

- BESS soft-start to control transient and inrush current magnitudes, rate of current change (di/dt), and rate of change of voltages (dv/dt) to suitable values during black-start and network re-energisation stages.
- Controlled closing time of the energising circuit breaker (e.g. using point-on-wave (PoW) switching).
- Tele-controlled reconfiguration of the associated 11kV network.

3.2 TEST NETWORKS DESCRIPTION

The Test Networks used for the report studies represent the SSEN Drynoch and Kinloch 11kV distribution networks.

Drynoch 33/11kV primary substation supplies customers via two main 11kV radial feeders with multiple secondary transformers to step down the voltage to 0.4kV (three-phase system) and 0.46kV (two-phase system). The network also hosts three DG units which are connected to the radial network between Drynoch and Dunvegan (labelled as feeder 12 in Figure 3-3). A simplified schematic layout of the Drynoch network representing the application of RaaS is provided in Figure 3-1.

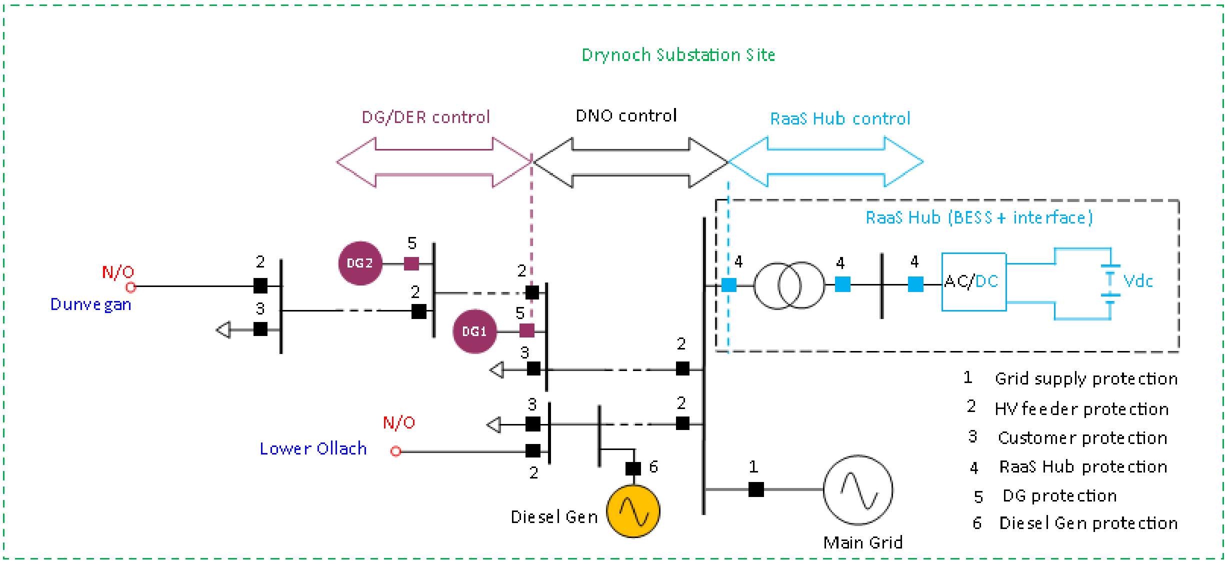


Figure 3-1 - Simplified schematic layout of SSEN Drynoch site

At Kinloch, the 33/11kV primary substation supplies all customers via a single 11kV radial feeder which has multiple step-down transformers to 0.4kV (three-phase system) and 0.46kV (two-phase system). Figure 3-2 provides a simplified schematic layout of the Kinloch network representing the application of RaaS.

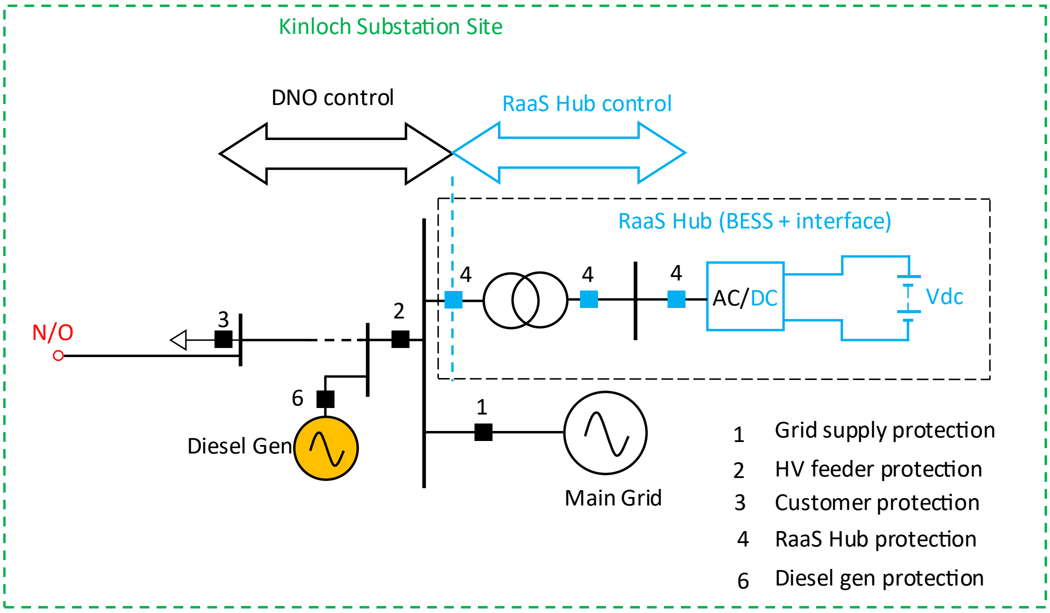


Figure 3-2 - Simplified schematic layout of SSEN Kinloch site

3.3 TEST CASES SUMMARY

In consultation with SSEN, a set of Test Cases has been developed and used to study the technical feasibility of delivering black start services via RaaS scheme. The selected Test Cases are detailed in the WSP RaaS Test Cases for SWP1, SWP2, and SWP4 document (reference 70078595-005 **Error! Reference source not found.**, and cover the following assessments:

- Feasibility of black start operation resulting from reconnection of different levels of customers to the primary substation energised by the BESS only (acting in Grid Forming mode to establish the islanded network).
- Feasibility of BESS control transition from Grid Forming to Grid Following mode by resynchronisation with the main grid supply when the grid returns to normal.

The sequences of customer reconnections are achieved with Pole Mounted Circuit Breakers (PMCBs) located at various places on the 11kV feeders (see the red numbers in Figure 3-3 and Figure 3-4 for Drynoch and Kinloch respectively). The standard cascaded connection of customers is performed by closing the CBs from 1 to 9 for both Drynoch and Kinloch networks.

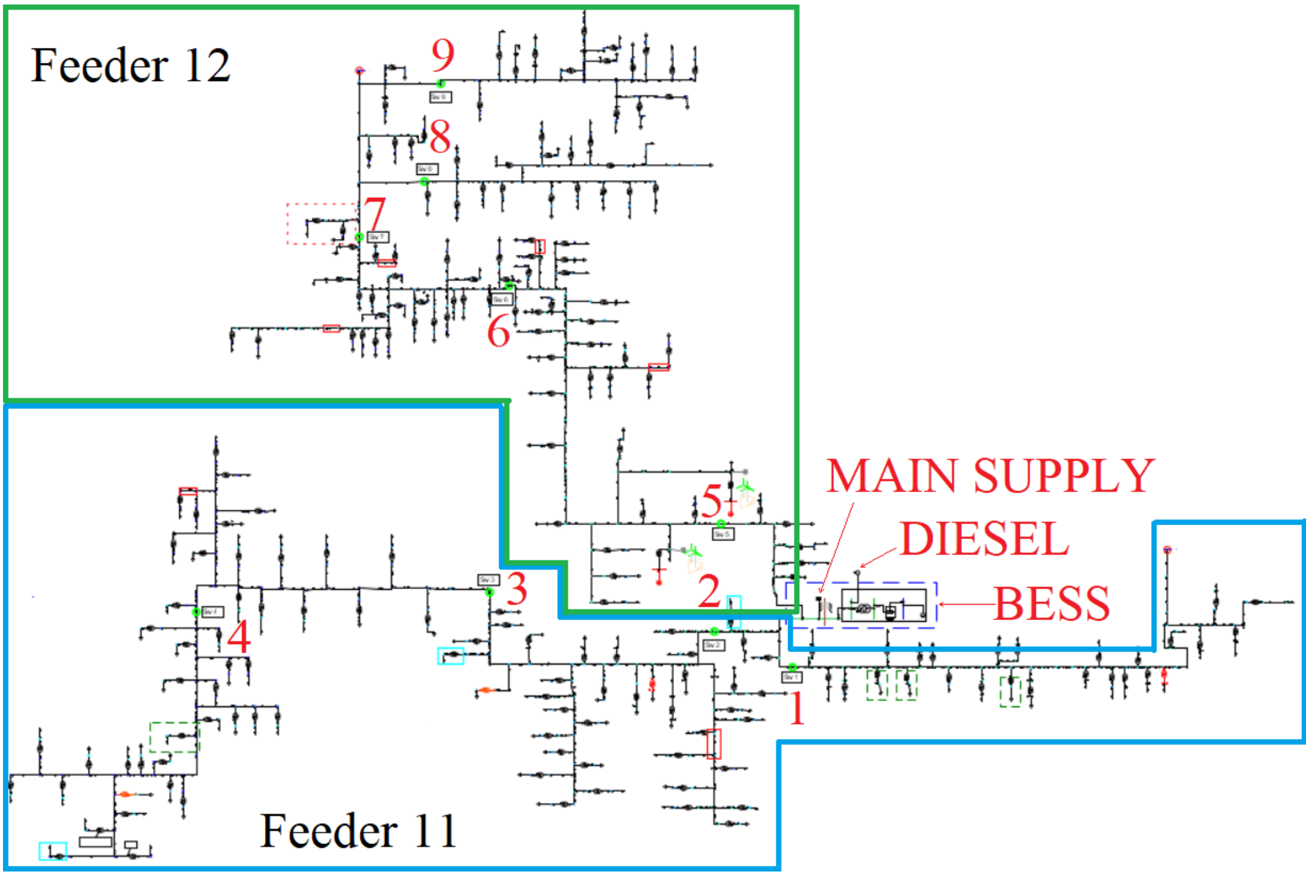


Figure 3-3 - Drynoch Test Network PowerFactory model layout

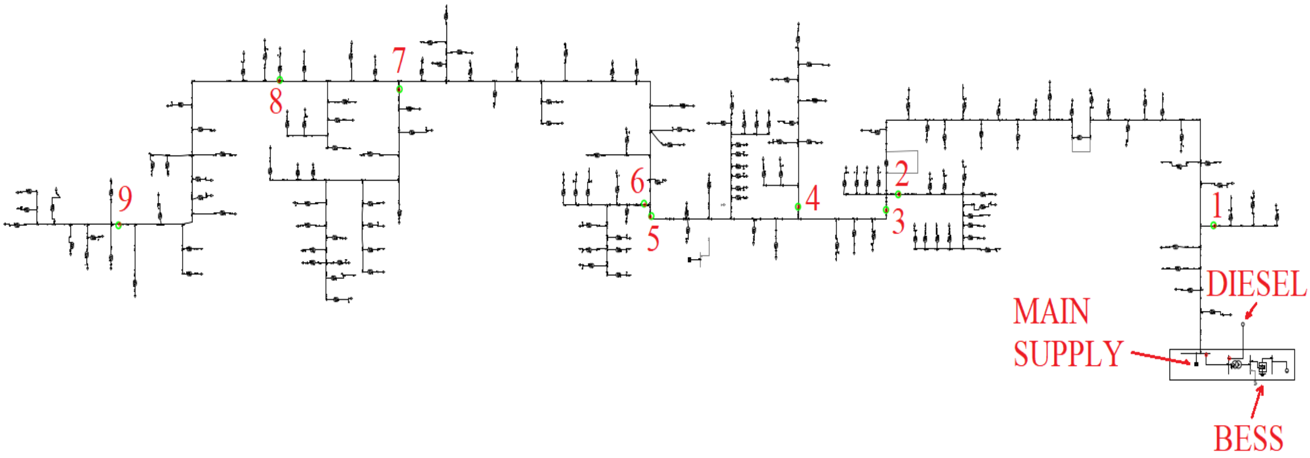


Figure 3-4 - Kinloch Test Network PowerFactory model layout

3.3.1 BLACK START OPERATIONAL SEQUENCES EVALUATED

The black start sequence could be delivered through a number of alternative approaches related to different scenarios for reconnecting customer loads and to BESS converter control response times.

The following customer connection sequences were considered for the BESS Grid Forming mode studies:

- For the Drynoch network, the customers of feeders 11 and 12 (see Figure 3-3) are connected in a time sequence, and for the Kinloch network there is only a single feeder connection.
- The customers are connected in 9 stages through a cascaded sequence of PMCB switching (for the number and location of CBs see Figure 3-3 and Figure 3-4).
- The customers are connected when the HV feeders' breakers are kept close, and the BESS is designed to establish the required voltage and frequency through a ramping function.

Each case also considers two BESS voltage control responses during Grid Forming mode:

- Converter fast voltage response with settling time Ts = 0.03s.
- Converter slow voltage response with settling time Ts = 0.3s.

3.3.2 GRID FORMING TO GRID FOLLOWING CONVERTER MODE TRANSITION

Following black start completion, a transition from islanded to grid connected operation will be considered as a part of the test cases. In this transitional condition the BESS converter control mode will change from Grid Forming to Grid Following by establishing a synchronisation angle through a Phase Locked Loop (PLL). This will enable the BESS to synchronise with the main grid supply once it is available.

3.4 ASSUMPTIONS AND SOURCE OF DATA

3.4.1 MODEL DATA

Most of the data implemented into the DIgSILENT PowerFactory Test Network models has been provided by SSEN. Open source typical data was also used for any missing parameters from SSEN's SINCAL model.

The validation of such data has previously been reported in RaaS project deliverable D2.2 'Network Model Development and Validation for RaaS Feasibility Studies' **Error! Reference source not found.**.

3.4.2 MODEL ASSUMPTIONS

The following assumptions have been considered during model development and subsequent simulation studies:

- All LV customer loads are modelled as a lumped demand.
- DG units have been modelled as an aggregated source based on the modelling data imported from in the original SSEN SINCAL model.
- Transformer magnetisation characteristics are identical for distribution primary and secondary transformers. A Flux-current saturation magnetisation curve (obtained from literature) has been implemented. In addition, and during all the studies the remaining residual magnetisation in three-phase transformers has been assumed to be phase A = 0.5 p.u., phase B = 0.5 p.u., and for phase C = -1 p.u., while in single-phase and two-phase transformers the residual flux was assumed to be 1 p.u.
- A 2MW diesel generator model (aggregation of 2x1 MVA assets) has been developed for modelling as a temporary source together with the BESS.
- The worst-case scenario for energisation currents can be achieved by closing the CB on the primary of the BESS transformer when the phase A voltage is equal to zero.
- The Point on Wave (PoW) switching operation is determined by the voltage upon phase C, where all phases operate simultaneously.
- The inrush current capacity and limitations were determined from the RaaS FEED report provided by SSEN [5].
- The two-phase secondary substation transformers are distributed evenly across the network to provide a relatively balanced 11kV network.
- PoW switching is applied to the CBs connected at the beginning of 11kV feeders.
- The operation delay between each PMCB, including communication delay and operation validation, is set to 1s.

- At the time of writing there is no detailed information on different customer types that could be used to apply different customer prioritisation strategies, consequently, a number of secondary substations have been randomly selected as critical/vulnerable to study the impact of load restoration prioritisation during black start procedures.

For the BESS, as the specific system to be implemented has not yet been selected, no detailed information is available with regard to hardware implementation, control systems, and system design, therefore the following assumptions have been considered:

- The model is based on controlled voltage sources (i.e. not a detailed semiconductor switching model), thus the lower level control Pulse-Width Modulation (PWM) is not required.

- The battery has been modelled as an ideal DC source and interfaced to the AC grid via a DC/AC converter, and therefore voltage drops due to battery non-linearities during the power transfer have not been considered.

- The converter controller operates at 20kHz sampling frequency.

- The transition between operational modes (Grid Forming and Grid Following) is considered with a variety of delays - 0ms, 20ms, 100ms, 1s, 5s.

- To compensate for the limited information on the BESS design characteristics, the BESS control model has been developed to cover a range of operational responses, to reflect different potential control and hardware implementations.

4

DEVELOPMENT OF TRANSIENT MODEL OF THE SELECTED CASE STUDY

4 DEVELOPMENT OF TRANSIENT MODEL OF THE SELECTED CASE STUDY

This section presents the process of developing a suitable PowerFactory transient model for studying inrush current issues which may be experienced within the SSEN Drynoch test network. The following key activities were undertaken.

4.1 MODEL APPRAISAL FOR REFINEMENT

The model developed by WSP in SWP1 was refined using a gap analysis assessment to evaluate the suitability for modelling transient inrush currents and determining black start requirements.

Through the gap analysis, it was found that the transformers models were not adequate for evaluation transient inrush currents. In order to provide accurate magnitudes and harmonic content of inrush currents, representative magnetisation curves have therefore been added to the models of each secondary transformer and the model of the BESS transformer. Relevant transformer data was obtain from the assumptions and results of the FEED report [5], and characteristics of the magnetisation curve were drawn from generic transformer data obtained from literature as reported in [6].

To provide a more detailed representation of the BESS, the BESS converter model has been modelled as a controlled voltage source (see below for validation). At the time of writing manufacturer specific BESS converter details were not known (topology, AC filter, switching frequency, DC capacitance, and DC-DC converter), as a result the model is based on an average converter model, neglecting the high frequency switching functions.

The inner control loops of the BESS converter are also presented to provide a detailed description of the entire control system. Further, the Grid Forming controller has been improved by incorporating the functionality of a current limiter to the BESS model, providing active limitation of the inrush currents.

Another challenge was the lack of controller models for the DGs connected to the network. This was addressed by assuming typical controller capability for the wind turbines.

4.2 MODEL DEVELOPMENT

This section provides detail on the development of the enhanced model to support black start assessment.

4.2.1 MODELLING OF TRANSFORMER NON-LINEARITY

For modelling non-linear phenomena in inrush currents, core saturation characteristics need to be included in the transformer model. The equivalent circuit of the transformer model is shown in Figure 4-1 where the non-linear magnetising reactance (X_m) represents the saturation characteristics of the transformer. The saturation curve was implemented using an approximated polynomial function [6], similar to the Modelling and Simulation studies of inrush currents document with reference to 70078595-007 **Error! Reference source not found.**.

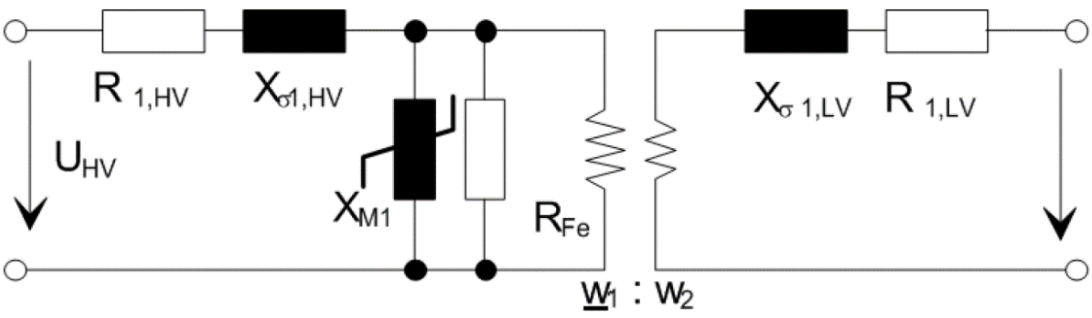


Figure 4-1 - Equivalent circuit of the transformer model used for inrush currents studies

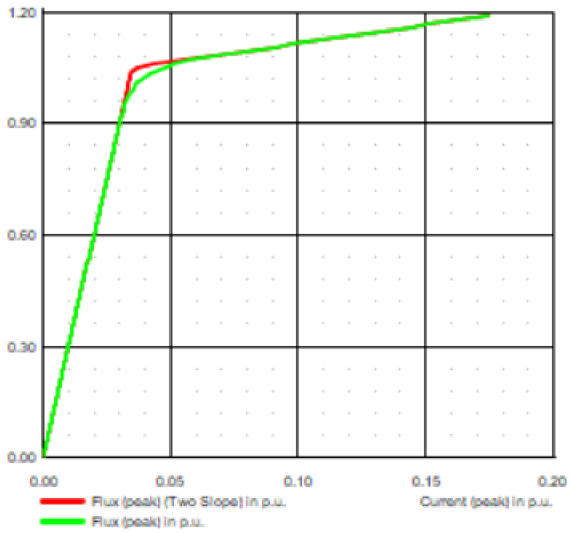


Figure 4-2 - Magnetisation curve characteristic

To increase the fidelity of the simulation, the transformer magnetising flux that remains in the core after the transformer has been de-energised has been set using generic characteristics.

4.2.2 MODELLING OF THE RAAS BESS CONTROL SYSTEM BEHAVIOUR

This section provides a description of the BESS control model developed for this work, which can provide regulation in Grid Forming and Grid Following operating modes as voltage source and current source respectively. The measurements considered for both modes of operations are Active and Reactive power values, the RMS grid voltage, and the grid frequency.

4.2.2.1 Grid Following mode

In Grid Following mode, the outer controller sets the reference values for the inner controller. This is achieved by measuring the AC voltages and currents to sustain desirable converter operation regarding active, reactive power, voltage magnitudes, and frequency angle.

In Grid Following mode, there is also the capability of reducing fault current contributions in addition to providing negative sequence currents during unbalanced conditions. The frequency and the voltage phase angle must be detected at the BESS converter connection point to synchronise the conversion and control system with the grid.

This action is performed by the Phase Locked Loop (PLL). The positive and negative sequence components are extracted through a-b-c to d-q transformation, fed with the sign of the angle from the PLL as shown in Figure 4-3 below. The two reference currents are inputs for the current controller and the current controllers are identical for both positive and negative sequences.

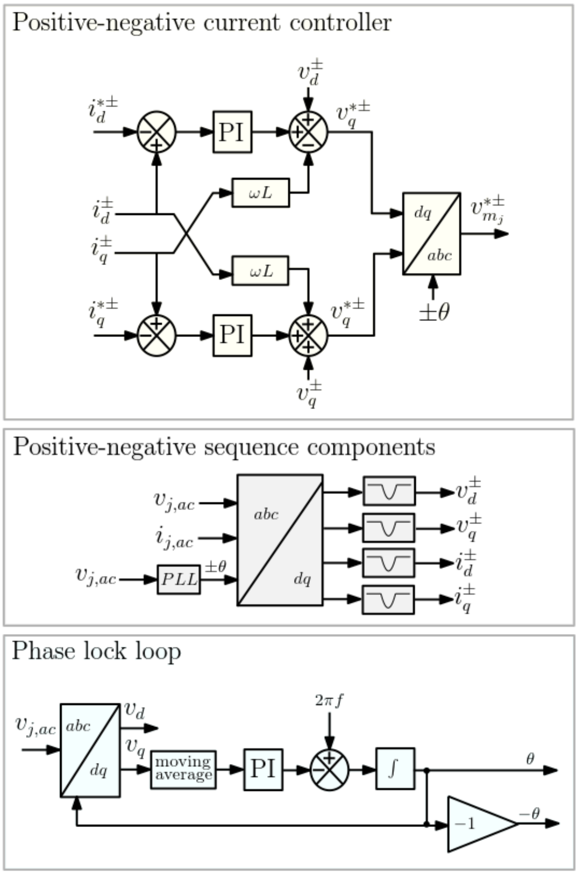
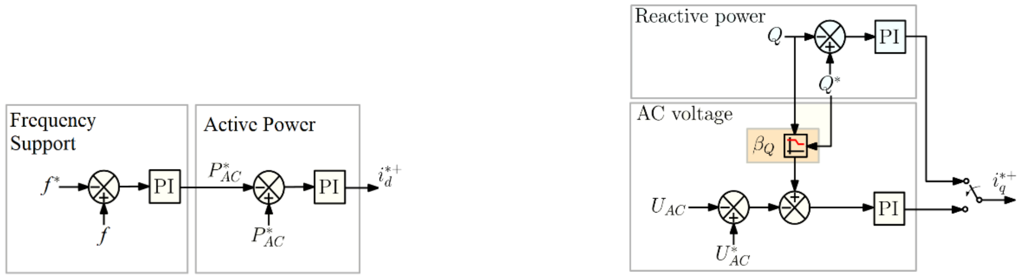


Figure 4-3 - Grid Following model block diagram

The reference set-points for the positive d-q sequence current controller were determined from the set of outer controllers. The reference for the d component of the current controller can be set according to the real power extraction or the output of a frequency/power droop controller, shown in Figure 4-4(a).

The reference for the q component can be set according to the rms voltage values, the reactive power or a voltage/reactive power droop controller is shown in Figure 4-4(b). Figure 4-5 shows the ability of the BESS to provide power reference according to the charging or discharging operation.



(a) (b)

Figure 4-4 - Outer level controller (a) Power controller with frequency support, (b) Reactive power and grid voltage controller

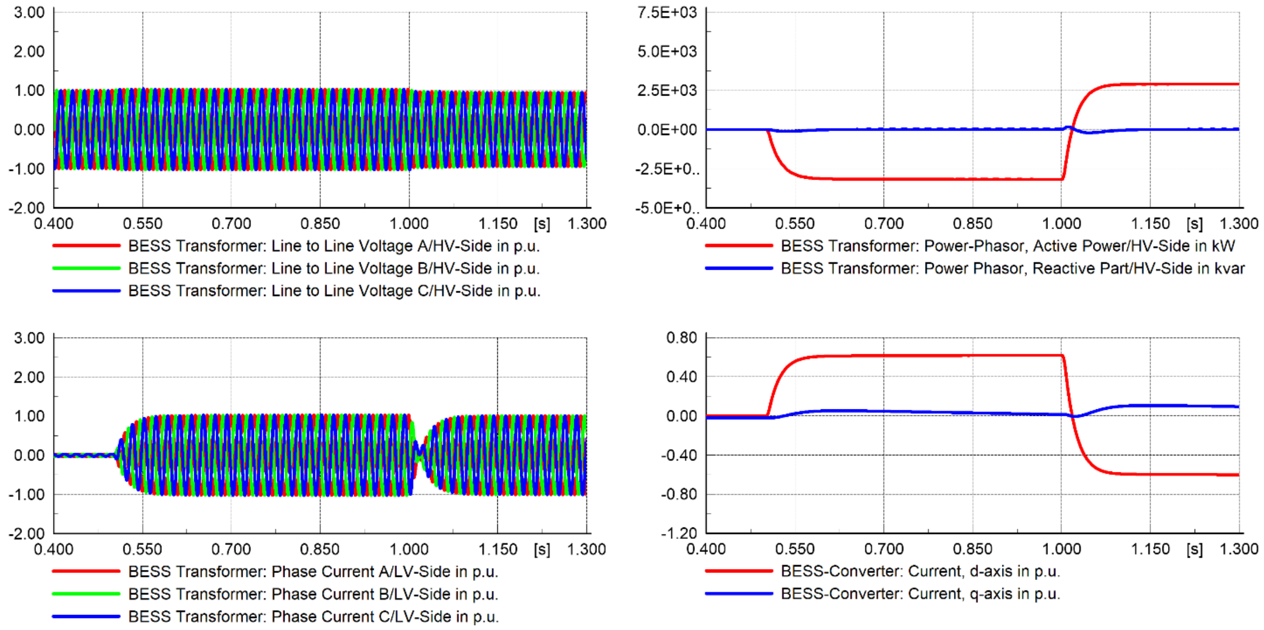


Figure 4-5 - Outer level control response

The reference set-points for the negative d-q sequence current controller can vary according to the scheme or the operator requirement. The BESS is able to withstand various internal imbalances, as the sizing of either voltage or currents during AC unbalance is covered by the current thermal limits and voltage insulations threshold.

As a result, the principle applied is to balance the AC-side converter currents which is crucial for the safety of the AC grid. Consequently, both components of the negative sequence current are suppressed to zero with reference equal to zero. Figure 4-6 shows the ability of the BESS to provide negative sequence currents to balance the currents, during an unbalanced AC fault.

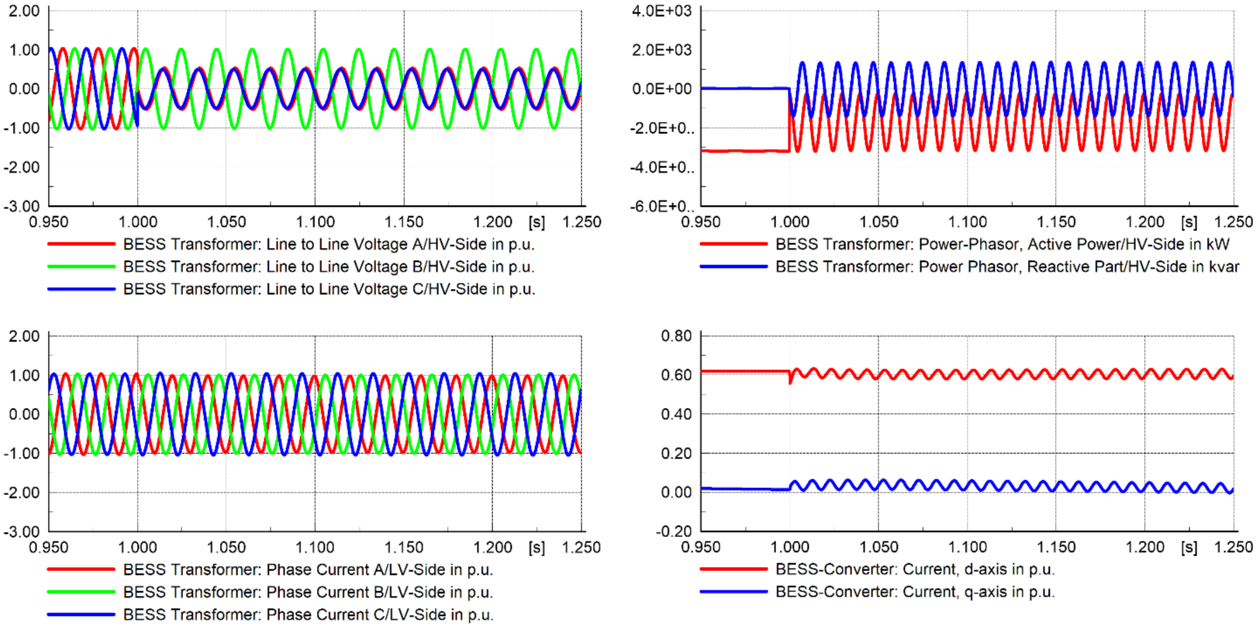


Figure 4-6 - Response of negative sequence controller during unbalance operation

In order to reduce any potential overloading, the current references are limited. The limited current references are compared to the calculated current reference. The scheme of limiting the reference currents depends on the application of the BESS. Figure 4-7 provides an illustrative example how the BESS station limits the current fault contribution during a symmetrical three-phase fault.

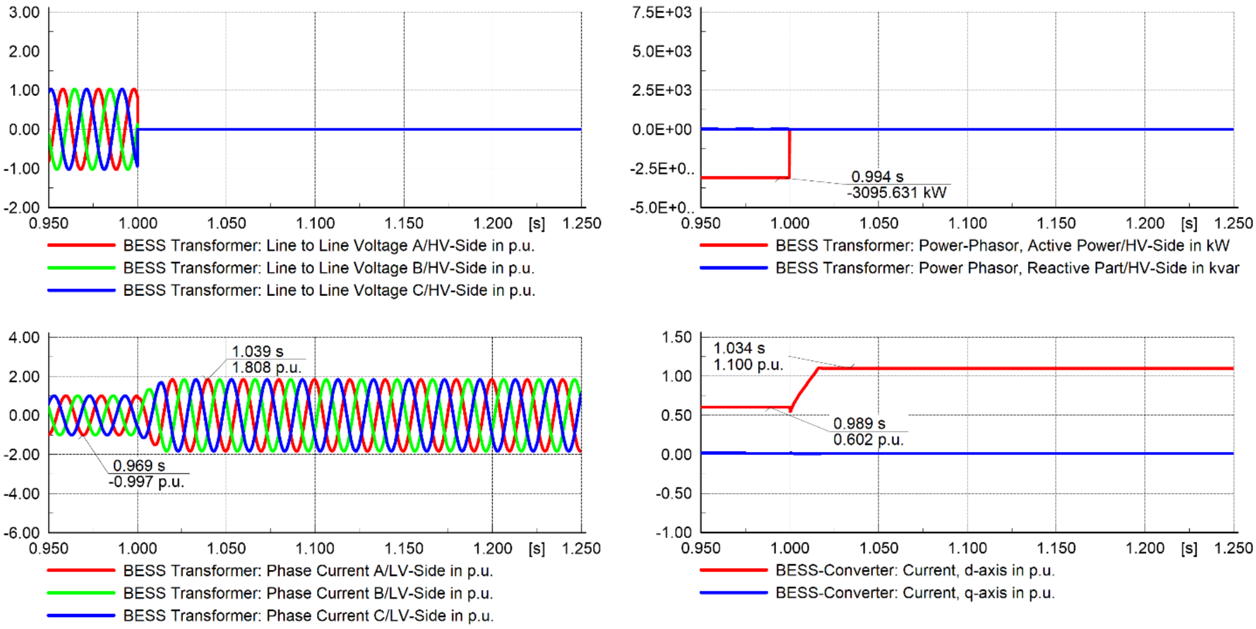


Figure 4-7 - Current limitation during three-phase fault

4.2.2.2 Grid Forming mode

The converter can produce its own AC voltage waveform independent of the AC system. The converter can be connected to an AC system with passive load or with asynchronous generation (Wind Turbine). Grid Forming operation dictates the angle reference from a fixed frequency reference.

In this case the converter directly controls the AC voltage magnitude according to a fixed frequency (oscillator) as shown in Figure 4-8, without being able to control the active power extraction. Figure 4-9 shows the ability of the BESS station in Grid Forming mode to set the grid voltage on an islanded system with only loads, achieving a black start operation. Figure 4-10 shows the ability of the BESS station in Grid Forming mode to limit the currents during a symmetrical three-phase fault, on an islanded network with passive loads.

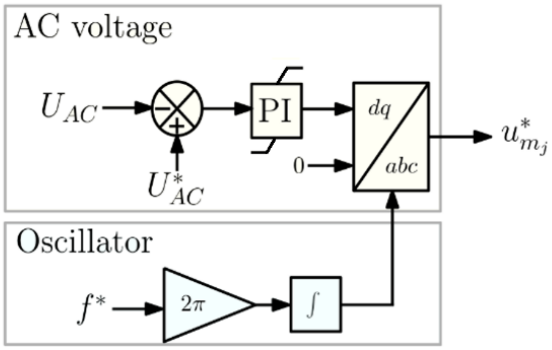


Figure 4-8 - Grid Forming controller

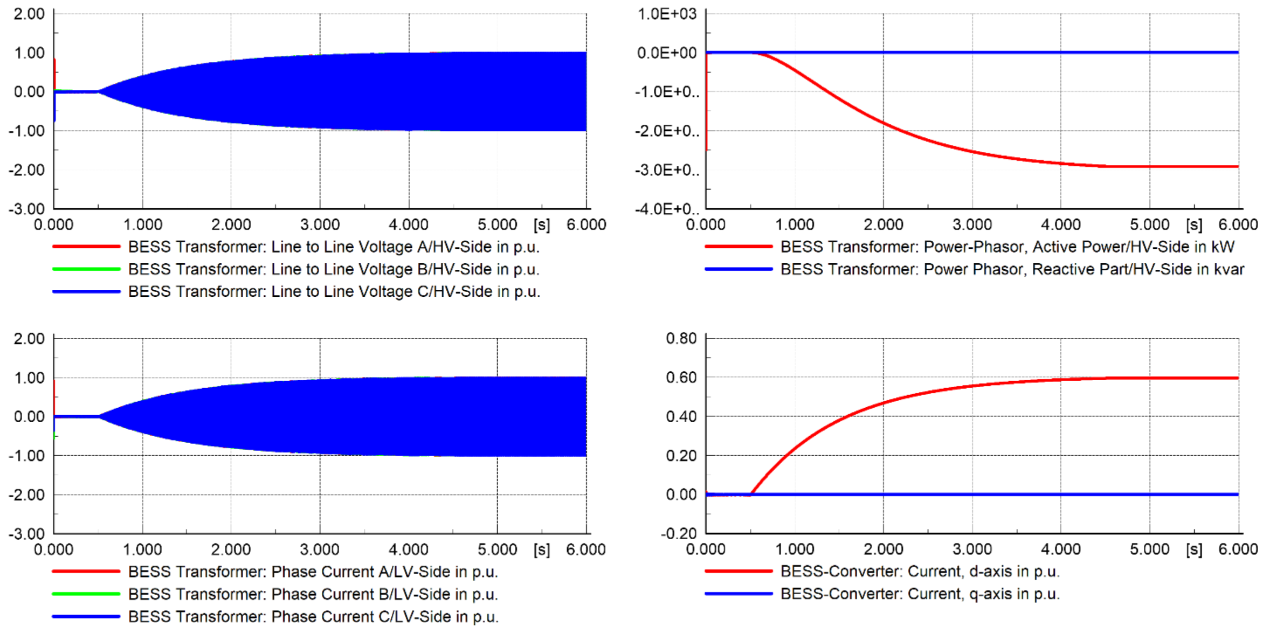


Figure 4-9 - Establishment of voltage on Grid Forming controller

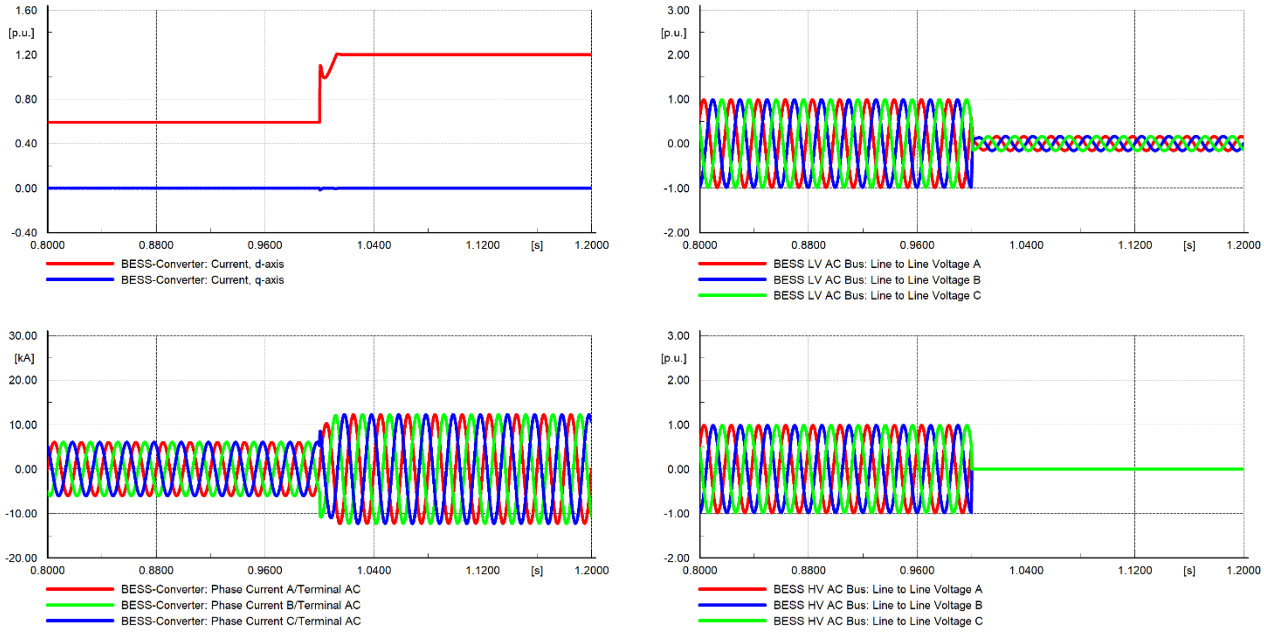


Figure 4-10 - The effect of current limiter during a symmetrical three-phase fault on Grid Forming controller

In conclusion, the overall functionalities of the BESS system are as follows:

Grid Following mode:

- Active power control with frequency support and, either reactive power or AC voltage control (P-f/Q or U), where P is the real power, f is the electrical frequency, Q is reactive power, and U is AC voltage;
- Max converter rating or adaptive current limiter; and,
- Negative sequence controller for unbalanced grid operation and asymmetrical faults (single and phase-to-phase faults).

Grid Forming mode:

- AC voltage with frequency control (V/f);
- Black start operation;
- Current limitation; and,
- Islanded operation.

Transition:

- Ability to swap modes between Grid Following and Grid Forming operation according to the grid condition (main grid, islanded network BESS only, and islanded network with diesel generator).

4.2.3 MODELLING OF DIESEL SYNCHRONOUS GENERATOR

The Diesel Synchronous Generator (DSG) model is connected to the BESS 11kV busbar for providing inertia, voltage, and frequency support during black start, islanded network operation and energisation process. The DSG operates temporary for improving the responses of transient phenomena. A high level illustration controller of the DSG layout is shown in Figure 4-11.

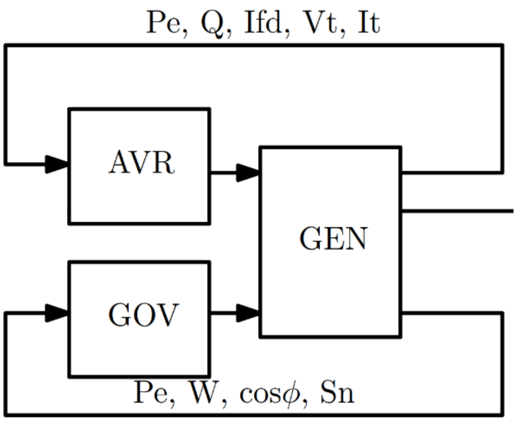


Figure 4-11 - Synchronous Machine model

4.2.4 MODELLING OF DISTRIBUTED GENERATION CONNECTED TO EACH SITE

The Kinloch network does not contain any DG, while at Drynoch there are two wind generators connected to the radial network between Drynoch substation and Dunvegan.

The two sources of distributed generation (DG) within the Drynoch network have been modelled as aggregated sources. SSEN has stated that these are Type 4 wind turbine generators. Consequently, each generator was modelled as a synchronous generator interfaced to the distribution network via a full back to back converter and an equivalent step-up transformer.

The controller model applied for a Type 4 generator is shown in Figure 4-12. This is a typical controller for a Full Converter Wind Turbine (FCWT), which is provided within the PowerFactory model library.

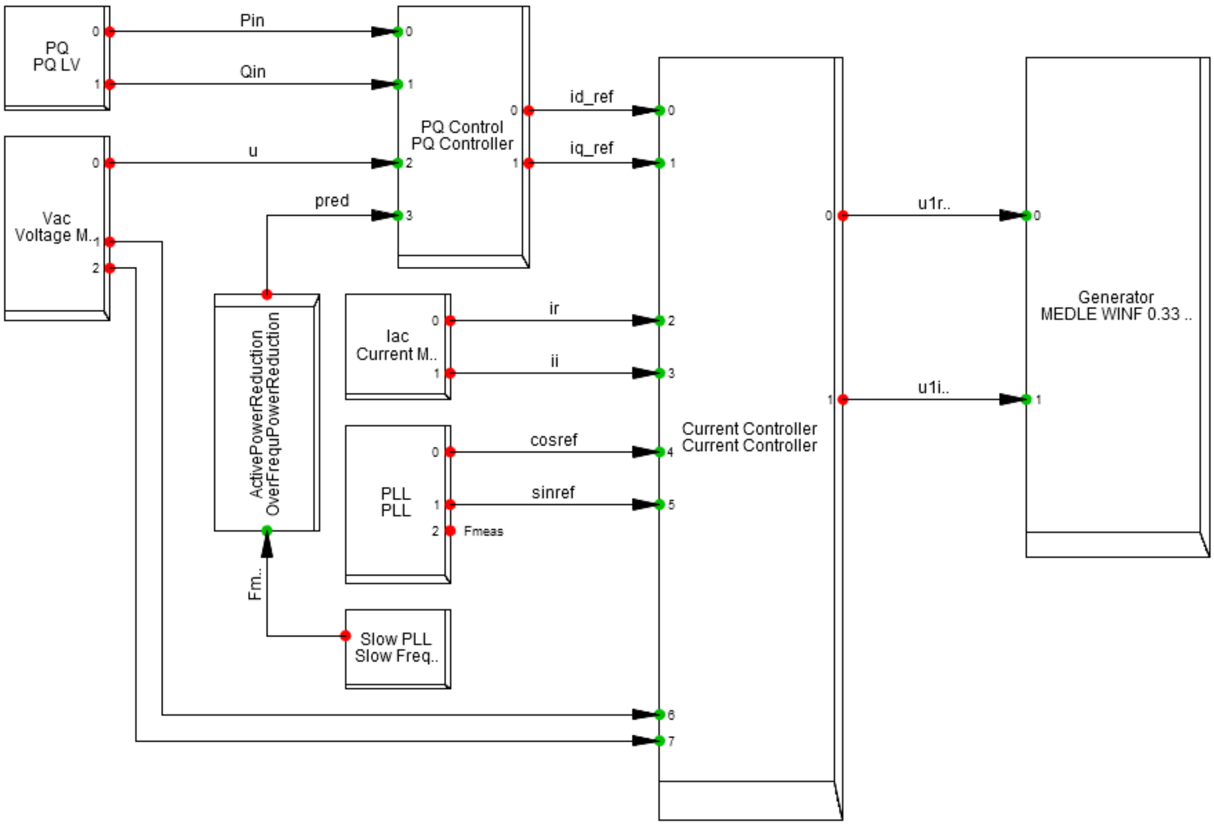


Figure 4-12 - Layout of the control scheme used for the Full Converter Wind Turbine DG model

As can be seen in Figure 4-12, the controller contains similar functional blocks to that of the BESS controller. However, the settings for the controller are in line with that employed by a Type 4 generator. The DG controllers have been tuned and have demonstrated a stable operation of both DG units connected to the Drynoch site.

4.2.5 MODELLING OF HV FEEDERS

As set out in RaaS SWP1 D1.2 “RaaS Sites Review and Technical Modelling Requirements” **Error! Reference source not found.**, a frequency-dependent line model has also been developed and applied to the network HV feeders. Full frequency-dependent line models are normally required to simulate transient studies. However, with comparison to PI-section line, there was no major difference between the two models’ transient performance, primarily due to the relatively short lengths of the feeders on the network. Secondly, there are a number of two-phase circuits on the network and PI sections can be used for two-phase systems, unlike the frequency-dependent model type which can be implemented only to the three-phase system.

Therefore, all the two-phase feeders of the developed Test Network model have been modelled as PI-section, and the three-phase feeders as frequency-dependent.

5

BLACK START STUDIES

FINAL

5 BLACK START STUDIES

This section presents the detailed black start studies for the Drynoch and Kinloch distribution networks. In the studies, it is assumed that the primary substations 11kV main busbar is already energised by the BESS, and the network and customers restoration are achieved by using remotely controlled CBs. Also, due to the limited information on critical/vulnerable customers, random secondary transformers are identified as critical loads to be prioritised for a faster recovery. Options to deliver optimal black start with regard to reduced outage duration and power quality are also considered.

5.1 DRYNOCH SITE - BLACK START AND ENERGISATION OF THE HV FEEDERS IN SEQUENCE

5.1.1 BESS WITH SLOW CONTROLLER RESPONSE

This analysis represents the situation where the converter controller will need up to 0.3s to bring the network voltage back to normal following the connection of customers. Figure 5-1 shows the results of reenergisation of one 11kV feeder of Drynoch (labelled as Feeder 11 in Figure 3-3) followed by the reconnection of the other HV feeder (Feeder 12 in Figure 3-3). The time delay between the reconnection of the two feeders was assumed to be 1s.

During the connection of feeder 11 at t=2s, a voltage transient with significant voltage sag appears with a magnitude of 0.2 p.u. (2.2kV RMS) and transient underfrequency 44.4Hz.

At t=3s feeder 12 was connected, and a similar voltage transient is observed. However, the voltage sag is of a magnitude 0.68 p.u. (7.48kV RMS) with an over-frequency event of 50.6 Hz. During the synchronisation of feeder 11, the load is not fully balanced, and therefore a voltage unbalance occurs between t=2s and t=3s. The Total Harmonic Distortion (THD) values of the BESS HV voltage, at t=4s, t=5s and t=7s, are 12.1%, 3.8% and 1.9% respectively. Therefore, the reference voltage and system frequency with acceptable power quality were restored after t=5s (i.e. the total black start and restoration duration is 3s in this case).

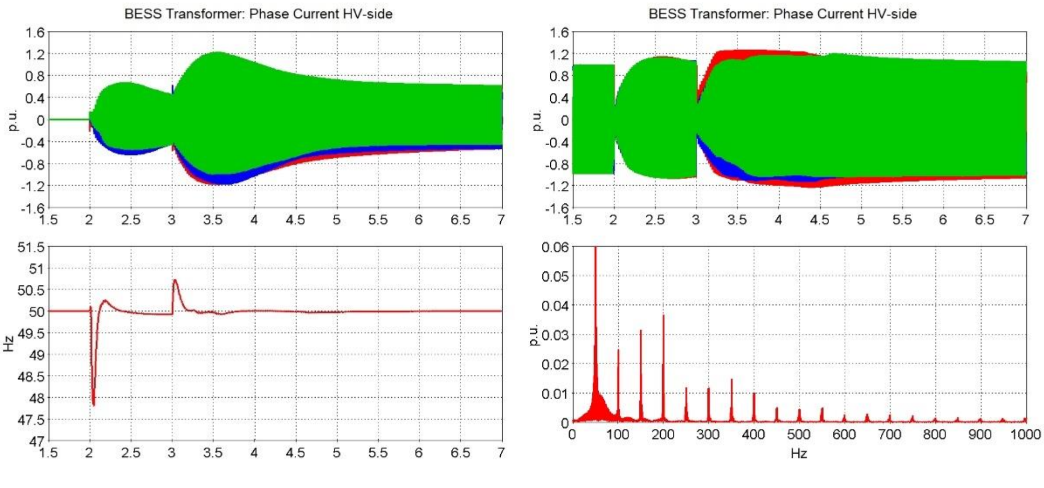


Figure 5-1 - Black start service of feeder 11 and 12 on the Drynoch network with slow converter response

5.1.2 BESS WITH FAST CONTROLLER RESPONSE

With this scenario the BESS converter controller will need only 30ms to bring the network voltage to normal following the connection of customers.

Figure 5-2 shows the black start and restorations of feeder 11 customers in sequence with feeder 12 customers of the Drynoch network.

Feeder 11 was connected at t=2s, and a short duration of 0.05s voltage sag of 0.2p.u. (2.2kV RMS) was experienced. In this scenario, a transient underfrequency up to almost 43Hz was noticed as shown in Figure 5-2. Feeder 12 was then connected at t=3s, and a very short undervoltage accompanied by a short transient and a TOV of 1.2p.u. (18.7kV peak) event were recorded. The THD values of the BESS primary voltage at t=4s, t=5s, and t=7s, have been found to be 9.5%, 5.1% and 1.9% respectively. The established voltage and frequency of the network is established at t=3.5s with total duration of 1.5s. The overall customer restoration was achieved at 4.5s, thus it was 0.5s faster than the black start service with a slow BESS converter response.

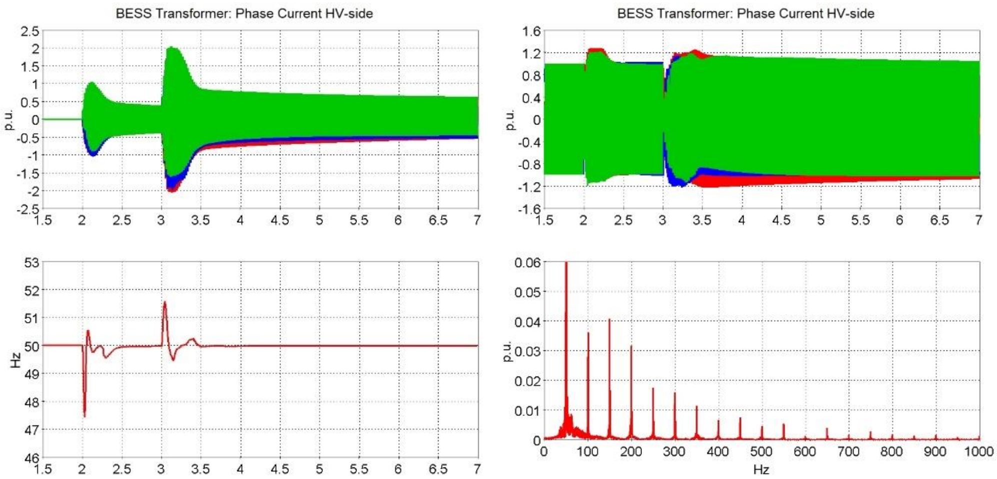


Figure 5-2 - Black start service of feeder 11 and 12 on the Drynoch network with fast converter response

5.2 BLACK START OPERATION ON KINLOCH NETWORK WITH FEEDER CONNECTION.

5.2.1 BESS WITH SLOW CONTROLLER RESPONSE

Figure 5-3 shows the outputs from black start of the single feeder on the Kinloch network. In this case, the BESS converter voltage response controller was set to slow response for stabilisation on Grid Forming operation (i.e. 0.3s). During the connection of the site feeder at t=1s, a voltage transient with significant voltage sag appeared (remaining voltage was only 0.1 p.u., 1.2kV RMS) and this lasted for only 0.4s. The THD of the BESS HV voltage at t=3s is 1.9%. Therefore, the black start service established the reference voltage and frequency at t=3s (i.e. with total restoration time of 1s).

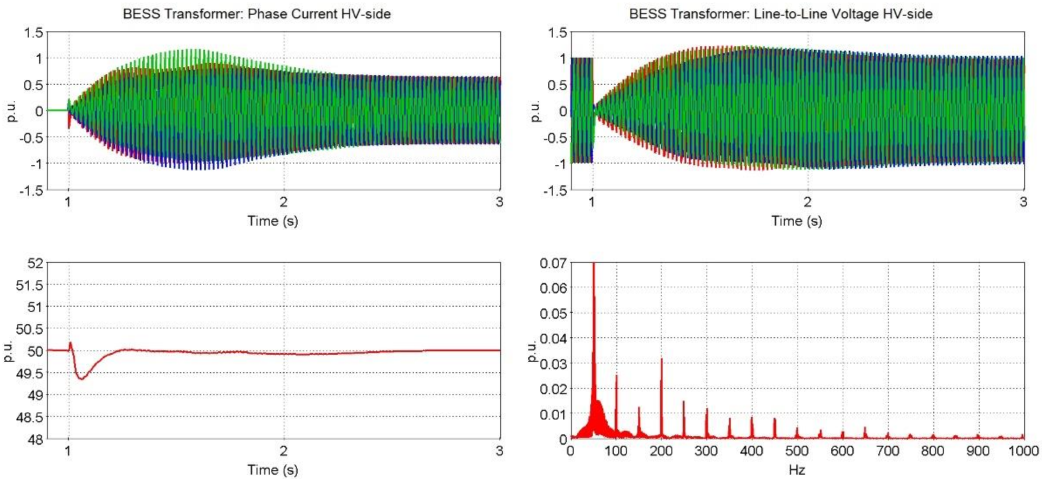


Figure 5-3 - Black start service on the Kinloch network with slow converter response

5.2.2 BESS WITH FAST CONTROLLER RESPONSE

Figure 5-4 below shows the outputs from black start operation of the single feeder of the Kinloch network when the BESS is set to fast response (30ms) during Grid Forming operation mode. When the entire feeder customers were connected at t=1s, a short duration voltage transient with significant voltage sag was experienced in the simulation studies. The voltage dropped to 0.4 p.u. (4.7kV RMS) for 0.1s. The THD of the BESS HV voltage at t=3s was found to be 1.6%. Therefore, the reference voltage and frequency together with customer supply were established at t=3s.

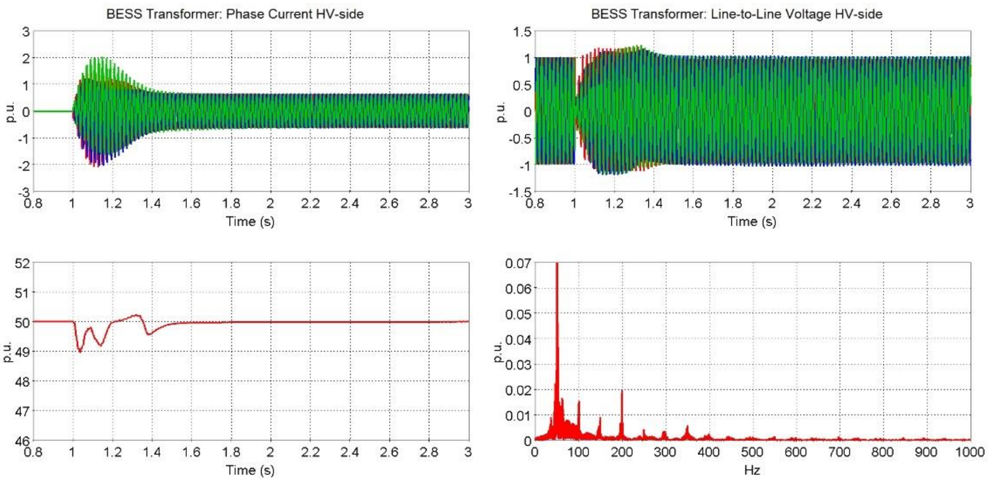


Figure 5-4 - Black start service on the Kinloch network with fast converter response

5.3 BLACK START OPERATION ON DRYNOCH NETWORK WITH CASCADED SEQUENCE OF CUSTOMER CONNECTIONS

5.3.1 BESS WITH SLOW CONTROLLER RESPONSE

During this power restoration scenario, the Pole-Mounted Circuit Breakers (PMCBs) are switched on in a sequence in accordance to order of the CBs numbers in Figure 3-3 in Section 3. Each CB operates with a 0.5s time delay from the previous. The CBs switching sequences are assumed to start at simulation time t=1s and ends at t=6.5s. The benefit of the cascaded CBs sequence is to enable the reduction of the resultant inrush currents as a smaller portion of the total customers is synchronised with the BESS at a time.

Figure 5-5 below shows the simulation results of black start operation with cascaded customer connections of the Drynoch network site when the BESS controller was set to slow response during Grid Forming operation mode.

The maximum voltage deviation has been observed between t=4.5s and 5.5s, with voltages of phase a, b and c to have values of 1.02 p.u. (11.2kV RMS), 0.86p.u. (9.4kV RMS), and 0.68 p.u. (7.4kV RMS) respectively. The THD values of the BESS primary voltage at t=8s, t=9s, and t=10s are 4.0%, 3.2%, and 2.5% respectively. The frequency experience milder transients compared to the previous cases with the entire feeders' connections. The overall duration for the power quality recovery and voltage and frequency stabilisation is 6s.

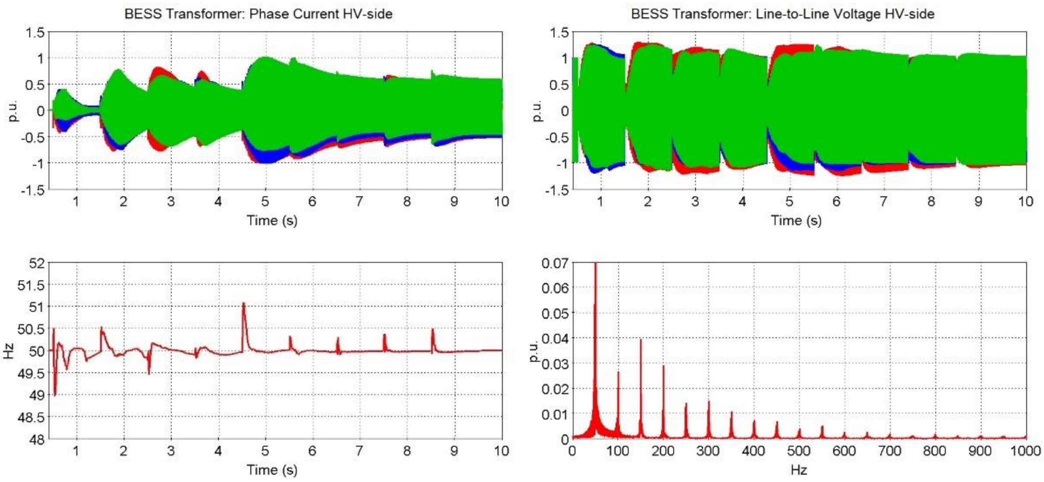


Figure 5-5 - Black start service with cascaded customer connection on the Drynoch network with slow converter response

5.3.2 BESS WITH FAST CONTROLLER RESPONSE

Figure 5-6 shows the black start operation simulation results with cascaded customer connections when the BESS controller was set to fast response on Grid Forming operation. The PMCBs operate in a sequence similar to the previous case. Operating in fast response with the cascaded connection the network experience high inrush currents, with maximum values of 2p.u. (545A RMS) magnitude and duration less of 0.5s. In addition, significant frequency transients and TOV magnitude of 1.4p.u. (21.7kV peak) exist, while voltage unbalances are also present due to an imbalance in the loads connected to the network during cascaded connection (reflecting the fact that the majority of LV loads are connected to single or two phase configurations, rather than a balanced three phase system). The THD values of the BESS primary voltage at t=8s, t=9s, and t=10s are 5.1%, 4.0%, and 3.1% respectively. The overall duration for power quality recovery, and voltage and frequency stabilisation, is 5.5s.

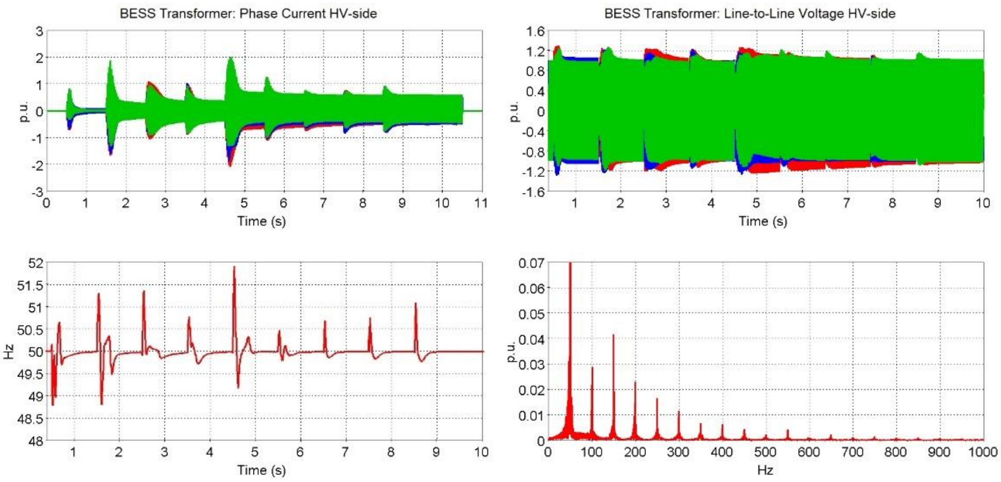


Figure 5-6 - Black start service with cascaded customer connection on the Drynoch network with fast converter response

5.3.3 OPTIMISATION OF CUSTOMERS SUPPLY RESTORATION

In this case the cascaded customer connection is optimised to prioritise the three-phase loads such as the Talisker Distillery and the DG interfacing transformers. The idea of this step is to establish reference voltage and frequency and reconnect critical loads in a faster manner in comparison to other customers. To achieve this, and with reference to Figure 3-3, the following switching sequences of the feeder 12 and 11 are required: Feeder 12 CB5, Feeder 11, CB2, CB1, CB3, CB4, CB6, CB7, CB8, and CB9.

Figure 5-7 shows the simulation results associated with a slow BESS controller response) re black start procedures and reconnection of critical customers was prioritised. In this case the THD values of the BESS primary voltage at t=8s, t=9s, and t=10s have been found to be is 3.0%, 2.4% and 1.9% respectively. The overall power quality, voltage, and frequency recovery duration time was 5.5s at t=6.5s.

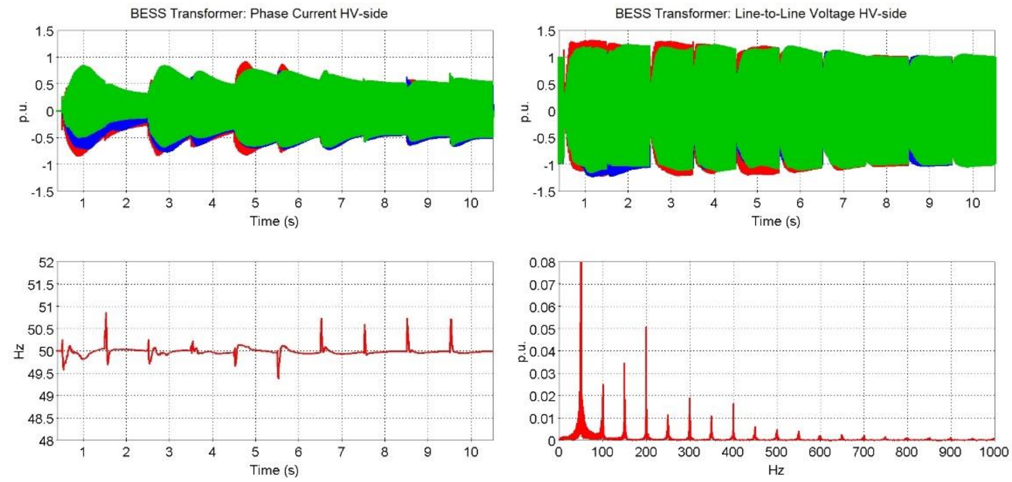


Figure 5-7 - Black start service with cascaded customer connection on the Drynoch network with priority on critical loads and slow converter response

Figure 5-8 shows the simulation results associated with a fast BESS controller response re black start procedures and reconnection of critical customers was prioritised. Compared to the slow converter response, in this case the inrush currents are of higher magnitude, while the frequency experience more sever transients. The THD of the BESS primary voltage at t=8s, t=9s, and t=10s, is 3.8%, 2.9%, and 2.3% respectively. The overall power quality, voltage, and frequency recovery duration was 5.5s.

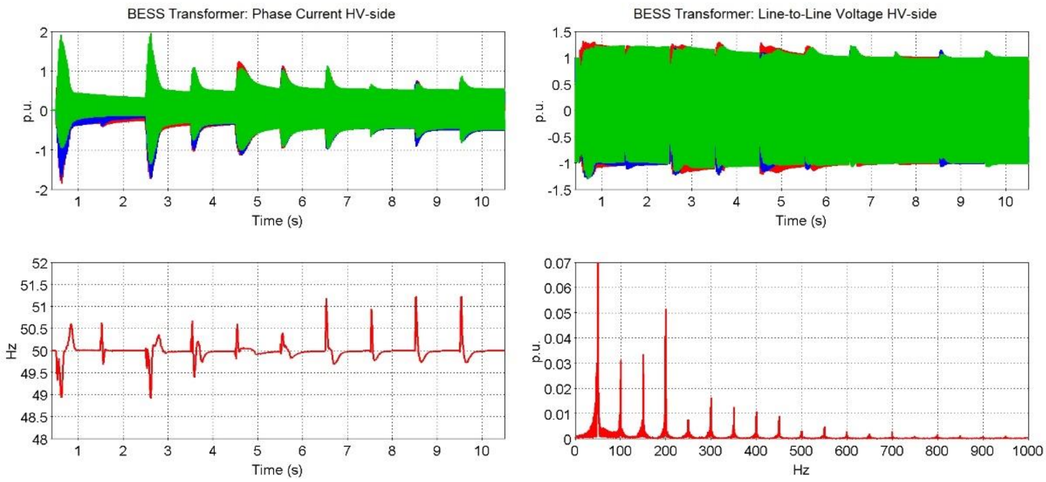


Figure 5-8 - Black start service with cascaded customer connection on the Drynoch network with priority on critical loads and fast converter response

5.4 BLACK START OPERATION ON KINLOCH NETWORK WITH CASCADED SEQUENCE OF CUSTOMER CONNECTIONS

5.4.1 BESS WITH SLOW CONTROLLER RESPONSE

Figure 5-9 shows the outputs of black start operation with cascaded customer connection for the Kinloch network with a slow BESS controller response for voltage stabilisation (i.e. 0.3s) on Grid Forming operation. The PMCBs operate in a sequence, according the numbered CBs shown in Figure 3-4. Each CB operates with a 0.5s delay from the previous, while the sequence starts at t=1s and ends at t=5.5s. The benefit of the cascaded CB sequence is the reduction of the inrush currents as a smaller portion of the total customers is synchronised with the BESS. However, a large portion of the customers consist of single and two-phase loads, which results in unbalanced operation until all costumers are connected. The THD of the BESS primary voltage at t=6s is 1.1%. The frequency experiences transients on every CB closure. The overall duration for the power quality recovery, and voltage and frequency stabilisation is 5s.

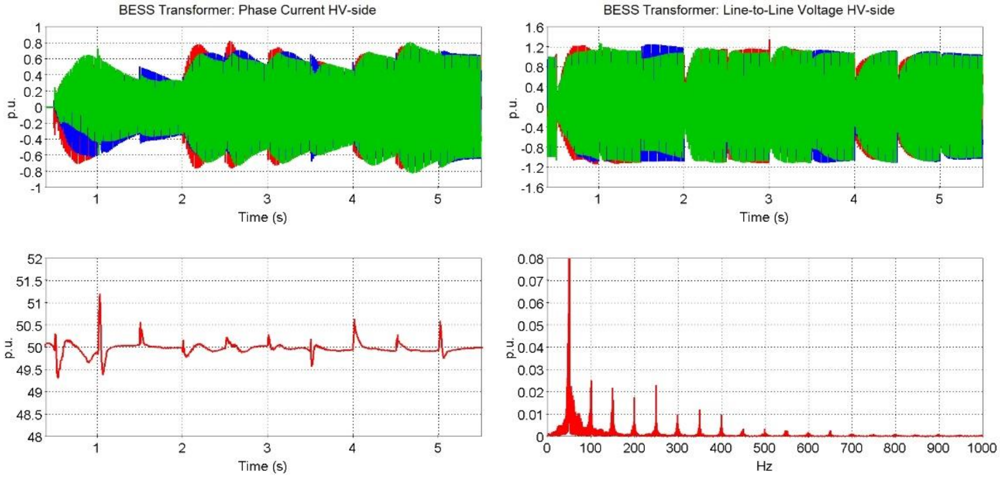


Figure 5-9 - Black start service with cascaded customer connection on the Kinloch network with slow converter response

5.4.2 BESS WITH FAST CONTROLLER RESPONSE

Figure 5-10 shows the black start operation with cascaded customer connection on the Kinloch network with a fast BESS controller response for voltage stabilisation (i.e. 30ms) on Grid Forming operation. As above, the PMCBs operate in a sequence of the numbered CBs shown in Figure 3-4. The inrush currents are higher from the case with the slower converter response, while the frequency transients are of higher magnitude on each CB closure. Voltage unbalances appear with increased TOV compared to the previous case. The THD of the BESS primary voltage at t=6s, is 0.8%. The overall duration for the power quality recovery, and voltage and frequency stabilisation is 5s.

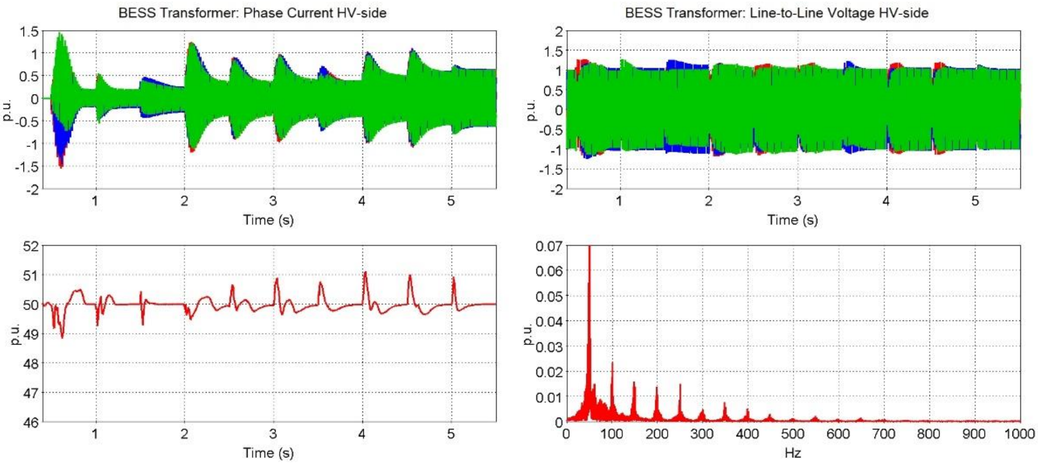


Figure 5-10 - Black start service with cascaded customer connection on the Kinloch network with fast converter response

5.5 BLACK START OPERATION ON DRYNOCH WITH RAMPING VOLTAGE OPERATION

Figure 5-11 shows the outputs from black start operation with all customers connected at once on the Drynoch network, and the voltage being established from 0 V by a ramp function. By incorporating a voltage ramp directly to load connections via the BESS, the inrush currents are limited to 1.25p.u. (340A RMS), overvoltages of 1.25p.u (13.7kV RMS) magnitude that last 2s appear, while the frequency does not experience any excessive transients. The total duration of voltage and frequency establishment is just at 3s at t=4s. The THD of the BESS primary voltage at t=5s, t=6s, and t=7s, is 6.2%, 5.3% and 4.8% respectively.

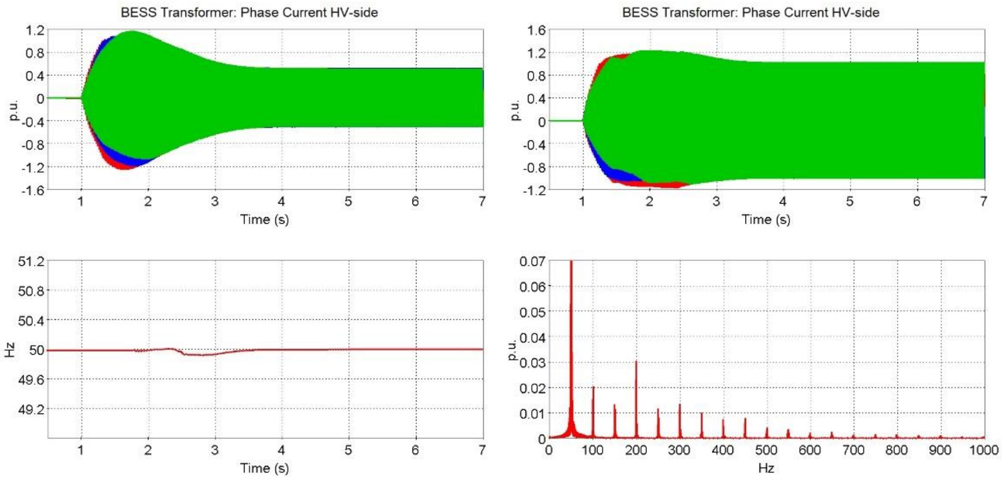


Figure 5-11 - Black start with ramping voltage operation Drynoch network with all customers connected

Figure 5-12 shows the outputs from black start operation of feeder 11 in sequence with feeder 12 on the Drynoch network, where the voltage initially is established at 0.5 p.u. (5.5kV RMS). Feeder 11 feeder 12 are connected to BESS at t=4s and t=6s respectively. After a certain period at 6s, where all customers are synchronised with BESS, the voltage is established to its nominal value 1 p.u. (11kV RMS) through a ramping function. By incorporating this sequence, it is possible to synchronise the loads on reduced voltage, achieving reduced current, voltage and frequency transients, and a smooth energisation during black start. Also, the initial connection at 0.5 p.u. (5.5kV RMS) voltage is practically more desirable compared to the zero-voltage connection, as is safer for particular customers' loads e.g. switched power supply, motors etc. The THD of the BESS primary voltage at t=9s is 3.8%.

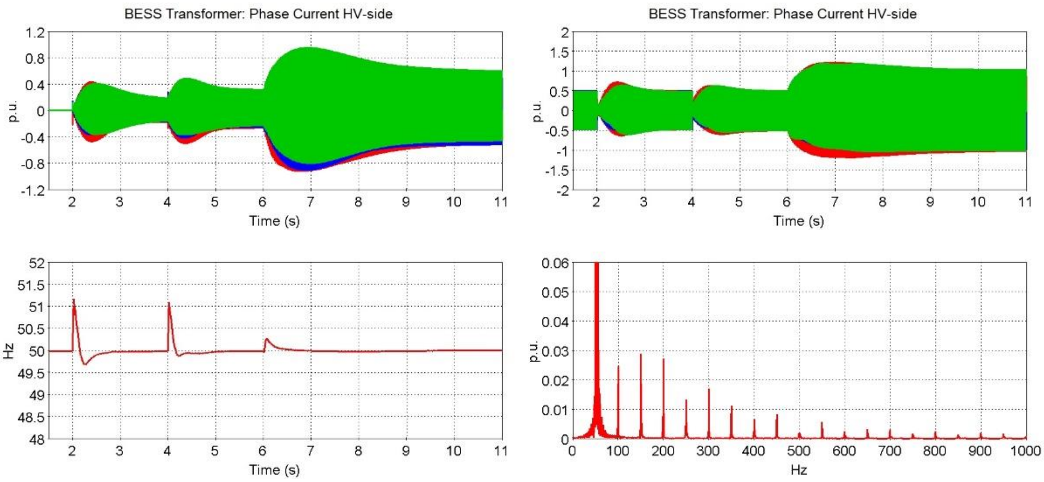


Figure 5-12 - Black start with two stage voltage development on the Drynoch network

5.6 BLACK START OPERATION ON KINLOCH WITH RAMPING VOLTAGE OPERATION

Figure 5-13 shows the outputs from black start operation with all customers connected at once on the Kinloch network, and the voltage being established by a ramp function. By incorporating a voltage ramp directly to load connections via the BESS, the inrush currents are limited, the frequency does not experience any excessive transients. The total duration of voltage and frequency establishment is just at 2s at t=3s. The THD of the BESS primary voltage at t=3s, is 1.4%.

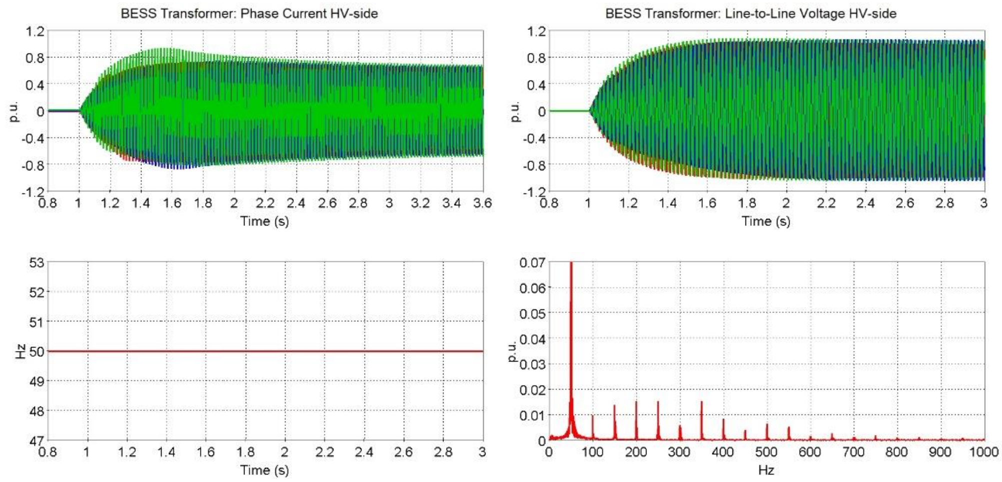


Figure 5-13 - Black start with ramping voltage operation in Kinloch network with all customers connected

Figure 5-14 shows the outputs from black start operation of Kinloch network where the initial voltage is established at 0.5 p.u. (5.5kV RMS). After a certain period at 2s, with all customers connected to the network supplied by the BESS, the voltage is established to its nominal value 1 p.u. (11kV RMS) through a ramping function. Although a significant transient appears on the first synchronisation of the customers with the BESS, overall reduced current, voltage and frequency transients are achieved, and a smooth energisation during black start. The THD of the BESS primary voltage is 1.5% at 4s.

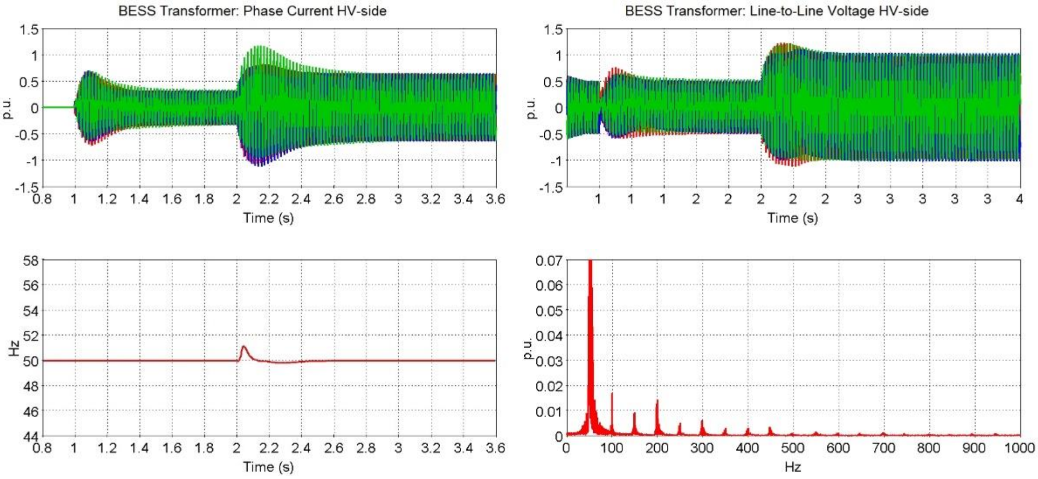


Figure 5-14 - Black start with two stage voltage development on the Kinloch network

5.7 GRID FORMING TO GRID FOLLOWING MODE TRANSITION ON THE DRYNOCH NETWORK

Figure 5-15 shows the outputs during the transition from Grid Forming to Grid Following operation. In this event, a zero-delay operation is adopted, considering the control modes transition. At t=3s, the main grid is reconnected to the Drynoch network, and the BESS transitions from a self-frequency defined device to synchronisation with the main grid through the PLL. During this transition the BESS withdraws the provision of power to the network as the main grid supply reconnects. During the transition the primary BESS voltage experiences a short undervoltage of 0.8 p.u. (8.8kV RMS), while a transient current appears for two fundamental cycles until the PLL synchronise to the grid. Consequently, a relatively small frequency transient appears on the BESS busbar (see Figure 5-15).

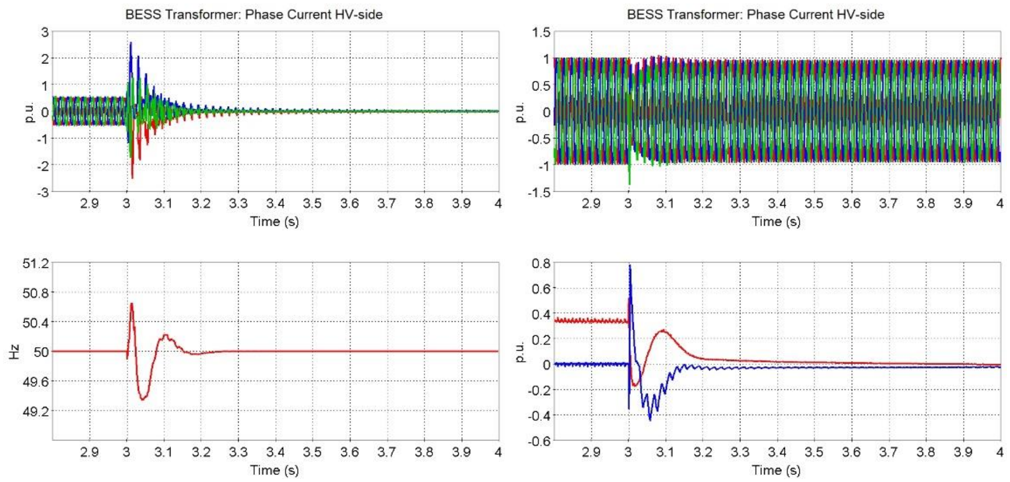


Figure 5-15 - Grid forming to grid following mode transition on the Drynoch network

5.8 GRID FORMING TO GRID FOLLOWING MODE TRANSITION ON THE KINLOCH NETWORK

Figure 5-16 shows the operation during mode transition on the Kinloch network from Grid Forming to Grid Following operation. As with the Drynoch network, a zero-delay operation is adopted, consideration the control modes transition. At t=2s, the main grid in reconnected to the Kinloch network, and the BESS transitions from Grid Forming to Grid Following mode and synchronises with the main grid. During this transition the BESS stops providing power to the network. A low magnitude undervoltage event appears, at 0.9 p.u. (9.9kV RMS) with relatively high frequency overshoot (up to 10% higher than the nominal value) of the islanded network frequency. To avoid the trip of the DGs connected to the islanded network during the transition from Grid Forming to Grid Following mode and associated transient change in the frequency, in this case the DGs' frequency-based protection would need to be deactivated.

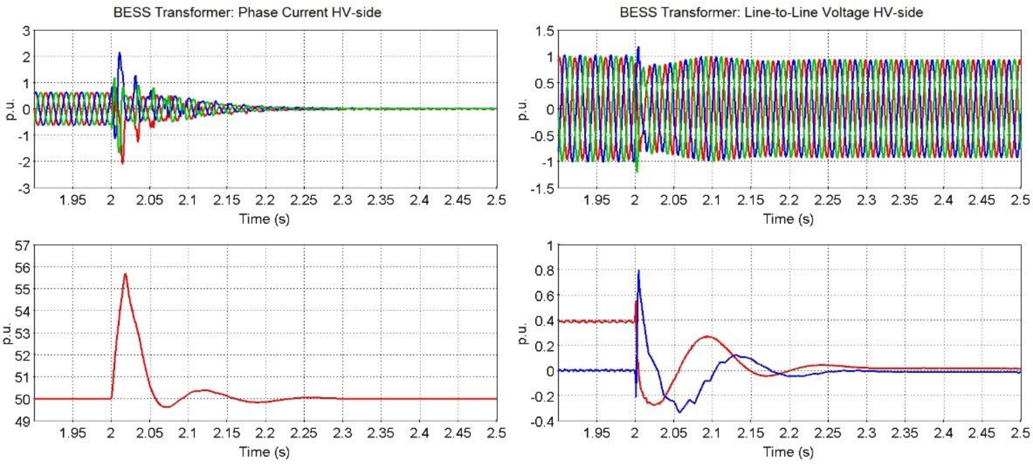


Figure 5-16 - Grid Forming to grid following mode transition on the Kinloch network

6

CONCLUSIONS AND RECOMMENDATIONS

6 CONCLUSIONS AND RECOMMENDATIONS

This report has presented the outcomes of modelling and simulation studies undertaken to evaluate the impact of black start associated with the application of a RaaS BESS scheme on rural electricity networks. The case studies considered in this report are SSEN's Drynoch and Kinloch primary substation distribution networks. A detailed model of each site and a corresponding transient model of the operation of the RaaS BESS was developed and used for the studies.

Various operational configurations for black start on the Drynoch and Kinloch networks have been considered. The configurations included black start operation with energisation of feeders (i.e. one by one), black start with various cascaded customer restoration procedures, soft start through BESS voltage ramping, and smooth transition from Grid Forming to Grid Following mode. The results obtained from these models have been evaluated based upon key factors that affect both the outage duration and the quality & continuity of supply on different loads.

The black start energisation of each feeder achieves a fast load connection at 1.5s. The results have shown that response of the BESS converter (fast and slow) can directly influence the magnitude and duration of transient under-voltages on the network, and have less impact on the TOV and frequency transients on the islanded network. In all cases, transients in the frequency of the islanded network were very limited and insignificant. However, when the islanded network was reconnected to the main grid (i.e. changing from Grid Forming to Grid Following), the frequency of the islanded network experienced relatively higher transients. This means that associated frequency-based protection schemes (such RoCoF) of the DGs connected to the site might require deactivation during the transition from islanding to grid-connected mode. This in turn will prevent the DGs from being unnecessarily disconnected.

The implementation of various cascaded customer restoration sequences allowed for a reduction of inrush currents and reduction in the magnitude of the frequency transients. However, due to the nature of the networks having single and two phase connected loads, portioned connection of the loads may lead to unbalanced voltage which may affect the overall power quality until all loads are connected.

It is possible to prioritise different customer loads to provide a reduction of outage duration for critical loads. However, the cascaded load connection sequences have the highest power quality recovery duration at 5.5s to 6s.

Black start through voltage ramping has a positive effect on the reduction of voltage, current and frequency transients by providing a smooth energisation and loading. However, connecting customers from zero voltage may jeopardise particular loads (such as switched mode power supplies, small grid connected converters, LED lighting, etc), therefore a two-stage voltage ramping process would allow for both direct customer connection and smooth energisation. The duration of the sequences is satisfactory at 3s and 5s, relative to the other black start sequences assessed.

Finally, the BESS can provide transition between Grid Forming and Grid Following operation without exceeding the equipment's nominal values, although a short current transient is observed until the converter synchronises to the main grid supply. This control mode transition can be achieved without blocking, resetting or disconnecting the BESS from the busbar.

Next steps

The Mallaig model is currently in the development phase and will be tested and developed using the experience gained from the Drynoch and Kinloch case studies. The sensitivity or protection schemes during the black start sequences will be explored within SWP4.

7

REFERENCES

7 REFERENCES

[1]. “Resilience as a Service - SSEN Phase 1 Scope of Works Document”, SSEN, 2020

[2]. “Resilience as a Service - Site Selection Report”, E.ON (E2a.1), 2020

[3]. RaaS SWP1 D1.1, “RaaS Sites Review and Technical Modelling Requirements”, WSP (Document 70078595-005), 2021

[4]. RaaS SWP1 D1.2 “Network Model Development and Validation for RaaS - Feasibility Studies of Drynoch Distribution Network”, WSP (Document 70078595-006), 2021

[5]. “RaaS Front End Engineering Design (FEED) report V2.0”, E.ON (E2a.2), 2020

[6]. Jansen, C. P. J., Slootweg, J. G., & Groot, de, R. A. C. T. (2005), “Calculation of transformer inrush currents occurring during the energizing of the Public Grid after a major black out”. In Proc.Power Tech, 2005 IEEE, Russia, St. Petersburg, 27-30 June 2005 https://doi.org/10.1109/PTC.2005.4524439

[7]. “PowerFactory user Manual,” DIgSILENT, 2019

[8]. RaaS SWP2 D2.2 “Modelling and Simulation Studies of Inrush Current Phenomena Associated with the Application of RaaS - Drynoch Distribution Network”, WSP (Document 70078595-007), 2021

110 Queen Street
Glasgow
G1 3BX

wsp.com