Making the Smart Grid Real

Report 1

A functional design & testing specification report for the

DRZ controller

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1 Introduction

This report focuses on the DRZ control software design to achieve DRZ blackstart of a Microgrid. In this case the Microgrid is defined as a subset of the distribution network, isolated from the main grid. This Microgrid could range in size from a few busbars to an entire GSP as the energisation process completes.

This is one of four reports on the DRZ Control System:

1. DRZ Control System Overview
2. DRZ Report 1: Functional design for the DRZ Controller
3. DRZ Report 2: Communications requirements for DRZ; and
4. DRZ Report 3: Control Interfacing requirements for the DRZ system

The “DRZ Control System Overview” provides an overview of the system and the design rationale. While this report focuses on the DRZ software functionality, it can be deployed in a variety of architectures to suit the specific deployment model and communications availability of each DNO. Refer to “DRZ Control System Overview” for the various deployment models.

The following section outlines ZIV’s approach to producing a viable Control System Design that meets the DRZ functional and performance requirements.

1.1 Design Drivers

The following drivers have influenced the overall solution design.

1.1.1 Cost

a. Capital Costs

With a focus on cost, ZIV has designed the solution to integrate with as much of the existing ANM infrastructure that is currently deployed and re-use existing software modules already developed with the utilities themselves.

b. Scheme Deployment Cost

The DRZ Controller architecture is data driven. The controller algorithms are model based and adapt automatically to changes in the electrical model. The architecture allows for efficient roll-out because a common algorithm is used across all schemes which adapts automatically to the model of the network. This reduces design, engineering, and test/validation costs on every scheme deployed.

c. System Maintenance Costs

One of the particular features of the DRZ Controller that the design must address is the long service life and low duty cycle. The controller is expected to be on standby for many years and operate reliably when required. However, over time the electrical network will continually change, along with the assets, DERs and demand profiles. Data aging is a problem that needs to be addressed in the system design. The DRZ controller is designed to minimise the work required to maintain the system and ensure that it operates successfully when called upon after years on standby.

1.1.2 Maintenance (Model / Maintenance)

The DRZ controller is designed to minimise to work required to maintain the system and ensure that it operates successfully when called upon after years on standby.

a. Adaptive Model Based Algorithm

The DRZ Controller architecture is data driven. The controller algorithms are model based and adapt automatically to changes in the electrical model. The architecture allows for simple and fast uploading of new network models to keep the controller in sync with the physical network.

b. Self-Testing

The system includes a self-test capability. Using a current model of the network, the DRZ Controller can automatically run through a simulated DRZ sequence to verify if the planned sequence is still valid after each change to the network, providing an opportunity to create a new restoration sequence either manually or automatically.

c. Automatic DRZ Sequence Generation

The DRZ Controller has the capability to automatically generate start-up (restoration) sequences. The algorithm analyses the network and various DER capabilities and auto-generates a sequence of tasks that maximises the energisation capability whilst minimising the risk.

This feature reduces the maintenance costs of the system by automating complicated and repetitive tasks and improves overall system resilience as it provides a method of generating a new start-up sequence in the event that the existing sequence cannot complete due to external factors such as equipment or communications failure.

1.1.3 Level of Automation

The DRZ system is designed to operate as a sequence of fully manual or fully automated tasks, or as a hybrid combination of both. Some elements of the blackstart sequence cannot be automated today, however over the service life of the control system the level of automation will change and the system is designed to minimise the engineering cost to support this. By supporting automated processes, the control system can significantly improve speed and reliability of realtime functions and reduce the ongoing engineering costs of configuration and testing.

a. **Speed** – automated DRZ sequences can provide faster restoration than manual processes and are less prone to errors particularly if a widespread blackout has occurred when multiple schemes must be dispatched in parallel.

b. **Reliability** – Network models can change frequently and the realtime availability of DERs can be variable, therefore the DRZ sequence must be adaptable and be able to response to changing conditions. A rigid automatic or manual approach can fail if it can’t adapt to the changing circumstances in realtime.

c. **Cost (re-engineering)** – As the network changes and the DERs change the system will need to be re-engineered to ensure that the system is aware, ready and capable of completing a DRZ sequence.

1.2 Blackstart Process Overview

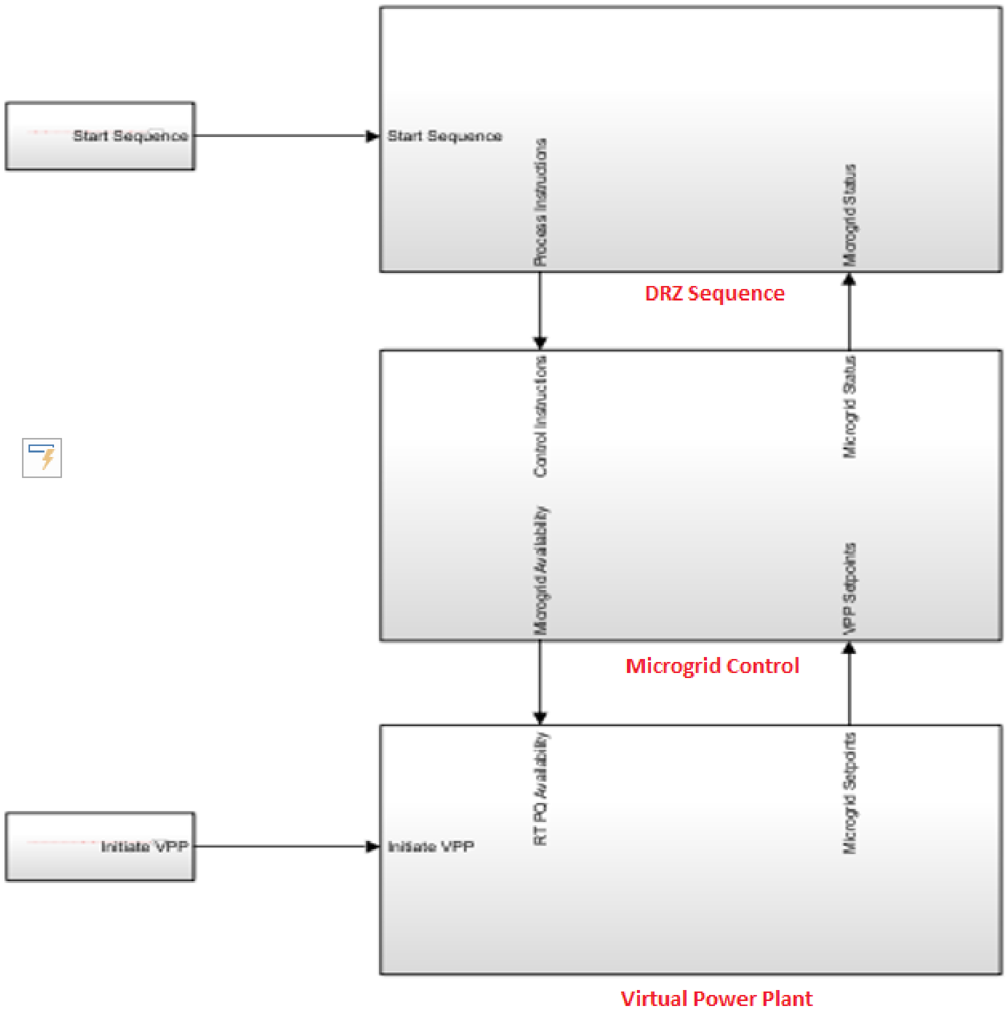
Blackstart involves the gradual process of energising a self-contained network area from de-energised state to fully powered.

Once energised this self-contained network essentially becomes a microgrid. This microgrid includes sections of the distribution network which might be as large as a single GSP area and comprise a diverse set of demands and DERs.

The microgrid must remain energised for up to 7 days and be capable of; if called upon; providing support to neighbouring microgrids or the transmission grid. It does this by acting as a Virtual Power Plant at the point of delivery.

The entire process of blackstart consists therefore of three discrete phases as shown below.

1. DRZ Sequence - gradual energisation of the network
2. Microgrid Control - maintaining the energised network at each stage of energisation as a microgrid
3. Virtual Power Plant - providing a virtual power plant service (on demand) to an external network.

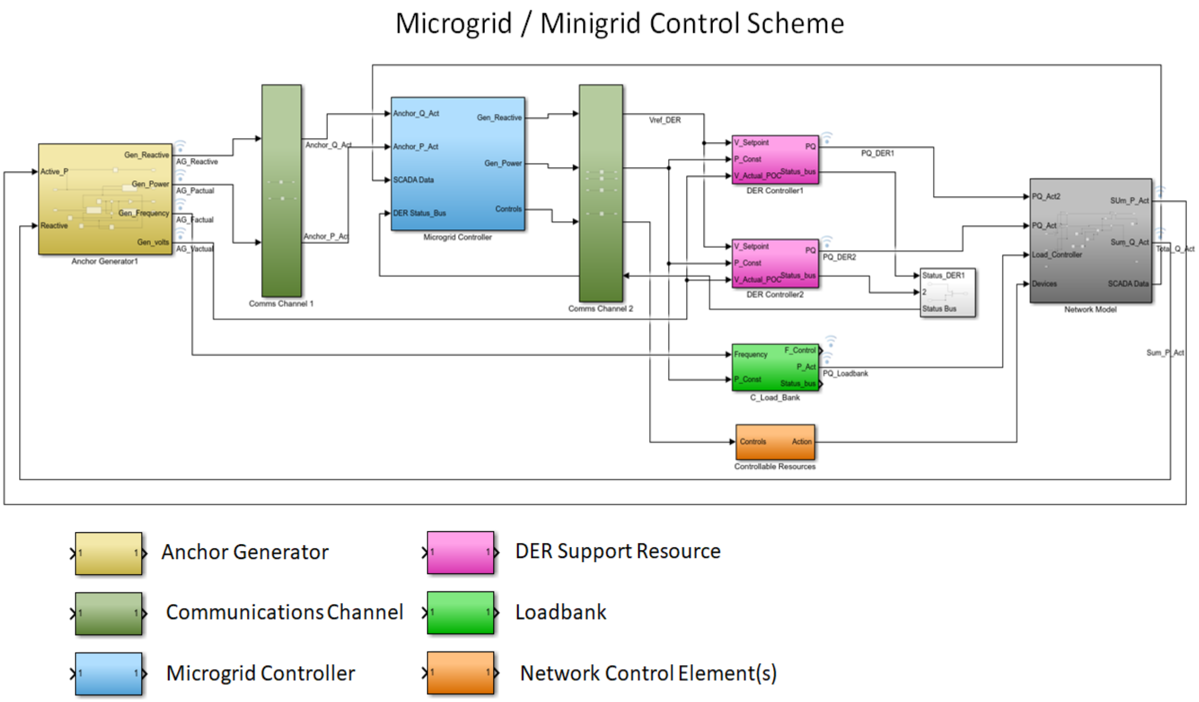


The DRZ Controller consists of three modules dedicated to the control of each of these three phases. This report provides detail on the functionality of these three modules.

2 DRZ Control System

The DRZ control scheme consists of an Anchor Generator and supporting DER resources, controlled by a Microgrid Controller shown in the following diagram. In addition, other network control devices such as Load banks, tap changers, Capacitor Banks etc. are utilised by the controller where available.

The control system diagram includes communications (Comms Channel 1) between the Microgrid Controller and the Anchor Generator and communications (Comms Channel 2) between the Microgrid Controller and the other DERs and network control devices. This allows the system to be described independently of where the Microgrid Controller is physically located and allows the system to be modelled with the Microgrid Controller in different locations and the system performance to be analysed.



The following sections focus on the Microgrid Controller and its internal software components required to deliver the DRZ re-energisation process. Separate sections on each of the software modules are provided in later sections of this report

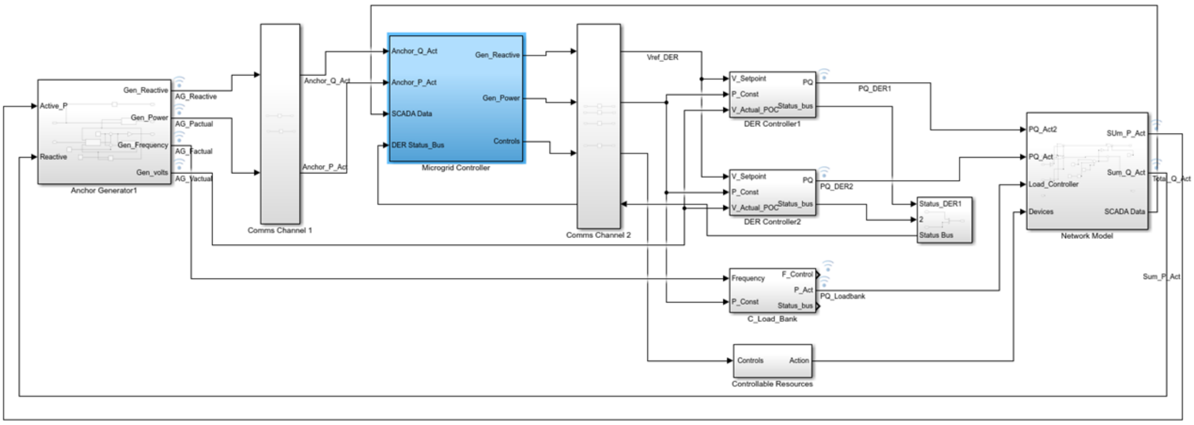
2.1 DRZ Controller Overview

The DRZ Controller is the control system for establishing the Microgrid, expanding the Microgrid, re-synchronising the Microgrid with the main grid and then acting as a Virtual Power Plant to provide MW and MVAr services to the main grid.

The main function of the DRZ Controller is to maintain the network voltages and frequency within the operating limits and all network assets within their safe operating range (frequency, voltage, MW and MVAr) both as the power island is expanded and when re-connected to the main grid and operating as a Virtual Power Plant.

A more detailed description the DRZ Controller Software is provided in the following sections.

Microgrid Controller



The operation of the DRZ Controller can be split into three primary operating modules:

DRZ Main Software Modules	Description
1. **Workflow Scheduler**	Executes a set of workflow actions to start-up and expand the Microgrid
2. **Microgrid Controller**	Manages the Microgrid to ensure that the Anchor Generator has sufficient headroom to react to sudden network changes
3. **Virtual Power Plant**	Once it is re-connected to the transmission grid it can operate as a Virtual Power Plant providing Active and Reactive Power Services to the transmission grid

The Workflow Scheduler is a batch process and the other two modules are continuous process. All three processes can run independently and in parallel.

Workflow Scheduler - The Workflow Scheduler pro-actively executes a set of workflow actions to start-up or expand the microgrid. Actions must be performed such that system instability is prevented or minimised. Microgrid Sequencing include:

- Anchor Generator Start-up
- DER Start-up
- Block Loading Actions

Microgrid Controller Module - The Microgrid Controller actively manages the network in response to changing network conditions or unplanned / unforeseen events that can lead to system instability. It manages the Anchor Generator output to ensure that it is maintained at the desired operating point with sufficient headroom and foot room to react to any sudden changes on the network.

These changes can include: -

- Drop / increase in load
- Drop / increase in generation
- Breaker Trip (Load loss)

Virtual Power Plant Module - Once the Power Island has re-connected to the main grid it can operate as a Virtual Power Plant providing Active and Reactive Power Services to the main grid at the Point of Connection to support the expansion of the main grid.

These primary modules are supported by the following support modules

DRZ Support Modules	Description
1. Predictor	Forecasts future demand levels and DER output based on date, time, and weather forecasts.
2. Network Analysis Engine	Performs steady state analysis and transient analysis on the network in real time to ensure the network is within safe operating limits and that any proposed actions won't cause any network instabilities

2.2 Workflow Scheduler Overview

A workflow is a set of business activities that are ordered according to a set of procedural rules to deliver a service – in this case network Blackstart. The requirement for this software module is to manage a workflow controlling how distributed energy resources can be used to restore power in the highly unlikely event of a total or partial shutdown of the UK National Electricity Transmission System.

A workflow model is the definition of a specific workflow. The solution should be provided using a workflow model that uses DERs in conjunction with an anchor generator in two significant process phases, Stabilisation and Growth. These phases are used to energise and maximise the generation and demand connected. These phases are described in more detail in subsequent sections.

A workflow model is defined by the resources being utilised and the sequence of tasks being performed. Resources in this context are DERs of different types such as Batteries, Windfarms, Solar Farms or Flexible Demands or other ancillary equipment such as breakers and tap changers etc. Tasks are the specific actions or sequence of actions carried out on the available resources – examples of which can include opening/closing breakers or ramping generation / demand.

Since each network area (DRZ) has a different physical configuration and set of available resources, the workflow model for each DRZ will be different, comprising its own specific resources and tasks.

The Workflow Scheduler is responsible for establishing, verifying, and dispatching the workflow instructions to perform a successful re-start of a DRZ Zone.

Any instructions in the Workflow sequence can be configured as:

- Manual
- Automated with manual initiation

In advance of each step in a Workflow, the Workflow Scheduler will analyse the transient and steady state effect the actions will have on the network and will advise the operator of the risk level associated with action. The operator can then decide whether to proceed to the next step or take alternative actions.

By analysing the network, ZIV’s Workflow Scheduler can also determine alternative actions and present these to the operator.

2.3 Microgrid Controller Overview

A microgrid consists of a minimum of one Synchronous Generator (Anchor Generator) in Isochronous Mode which may be supported by a range of other DERs (batteries, solar / wind farms, load banks, capacitive/reactive support devices, etc.) and a range of ancillary equipment (tap changers, breakers, etc.). A microgrid connects to the grid at a Point of Connection or point of common coupling. The microgrid can have several potential coupling points which may allow it to connect to a higher voltage level like the main grid, or to connect to other peer-microgrids to form a larger unit. The objective of the Microgrid Controller is to maintain grid stability and maintain the voltage and frequency within regulatory limits.

Therefore, the Anchor Generator voltage and frequency must be controlled such that these limits are not breached during steady state or transient conditions.

The Microgrid Controller actively manages the network in response to changing network conditions (e.g. drop/increase in generation/demand) or unplanned / unforeseen events (e.g. breaker trip) that can lead to system instability. This is standard operation for ZIV's ANM software as deployed across the UK and internationally.

2.4 Virtual Power Plant Module Overview

After subsequent Growth Phases, the DRZ energises the network up to the Point of Connection at a transmission Grid Supply Point (GSP). At this point, through direct liaison with the TSO, the distribution island can begin to establish a voltage at transmission level.

Once the Power Island has re-connected to the main grid it can operate as a Virtual Power Plant providing Active and Reactive Power Services to the main grid at the point of Connection to support the expansion of the main grid. The VPP manages the output of the individual DERs within the DRZ to deliver the required service levels at the Point of Connection. The VPP Module will calculate the sensitivity of each DER to deliver the service at the Point of Connection and provide an aggregated service to the TSO.

The DRZ network is modelled as a Virtual Power Plant which can provide Active Power dispatch and/or Reactive Power which can be provided as a direct dispatch or as a self-dispatching voltage support service.

The overall algorithm consists of two separate sub-modules for the different service provisions:

- P_Mode – Provides Real-time Active Power Service
- V_Mode – Provides Real-time Reactive Power Service. This is implemented through a voltage droop characteristic in non-synchronous DERs and through the automatic voltage regulator (AVR) in synchronous DERs.

The VPP Module can provide both services (Active Power and Reactive Power) simultaneously. Therefore, separate service requests can be sent for each service. When the VPP is running, the Microgrid Controller is operating in parallel managing responses to all disturbances within the microgrid, or externally from the transmission network.

This is standard operation for ZIV's Virtual Power Plant developed in conjunction with UKPN and National Grid ESO for their Power Potential Project.

2.5 Predictor Overview

The Predictor Module takes data including historical demand and generation data, historical and forecast weather data (including temperature, wind and irradiance data etc) local to each generator, to generate a prediction for all generation and demands on the system. The predictor module uses historical data in a training phase, during which time it is trained to build a predictive model based on a wide range of historical input parameters. Once trained, the predictor module can integrate real-time weather and weather forecast updates, date and time information, and current network data to predict the behaviour of each generator and load on the network.

In the DRZ Controller this prediction can be used for:

1. Predicting the loads for Blockloading
2. Predicting the required output of the Anchor Generator
3. Predicting the available active and reactive power services of the VPP

These will be covered in more detail later in section 8 of this report.

2.6 Network Analysis Engine Overview

The Network Analysis Engine comprises two main elements:

- Steady State Analysis
- Transient Analysis

The Steady State Analysis is continuously invoked by the Microgrid Controller and the Virtual Power Plant when they're active to analyse the network operation in real time and determine if any actions are required to ensure the network operates within safe operating limits. The analysis will check voltage, MW and MVar limits against all network assets and for different running arrangements (e.g. N-1).

The Steady State Analysis and Transient Analysis is invoked by the Workflow Scheduler when analysing the risk associated with any workflow actions. It analyses the proposed new state and the transition to the new state to ensure that any proposed actions will not cause any steady state or transient instabilities. It can then present a risk level to the operator before any action is taken. Alternatively the Scheduler can perform the sequence of tasks automatically or the sequence can be set up to include a mixture of manual and automatic tasks.

2.7 DRZ Control Strategy

DRZ can be described as a process workflow with each DRZ Zone having its own unique workflow(s) to establish and grow the microgrid to a Point of Connection where it can expand to a larger microgrid or connect to the transmission grid.

Workflow tasks can be grouped together into collections known as Phases. Phases are a specific set of tasks that are grouped together in a sequence to achieve a specific outcome.

The DRZ Workflow consists of four main Phases.

- Initiation Phase
- Voltage Stabilisation Phase
- Growth Phase(s)
- Transmission Energisation Phase

To achieve this functionality ZIV's DRZ Controller includes three primary software modules: -

- Workflow Scheduler
- Microgrid Controller
- Virtual Power Plant Module

In response to a Blackstart event the operator can initiate the required DRZ Workflow from the Workflow Scheduler. This will identify the sequence of actions to be taken to establish and expand the microgrid and whether manual actions are necessary at each step. It will perform steady state and transient analysis on any proposed actions and advise on the risk level associated with the actions and request confirmation from the operator before proceeding.

The Microgrid Controller is continuously managing the network in real time, responding to changing network conditions (e.g. drop/increase in generation/demand) or unplanned / unforeseen events (e.g. breaker trip) and adjusting generation and demand to maintain the network within safe operating limits. This is working in parallel with the Workflow Manager which is expanding the microgrid and the network area being managed by the Microgrid Controller.

After subsequent Growth Phases the Workflow Manager energises the network up to the Point of Connection at a transmission Grid Supply Point (GSP) where it can be re-connected to the transmission grid. Once connected to the transmission grid, the DRZ acts as a Virtual Power Plant service provider to provide support for other GSPs or Microgrids and aid wider transmission energisation. The VPP Module calculates and manages the provision of these aggregated services at the Point of Connection to the transmission grid.

2.7.1 DRZ Sequence Planning

Based on the learning from the power system studies outlined in Section 4, a control strategy can be derived to safely perform the blackstart energisation of any microgrid.

The control system should: -

- Identify DER support resources which can help the anchor generator.
- Identify which DERs are forecast to be able to provide effective and stable active and reactive power output.
- Define energisations paths to each support resource (DER). The overall control system architecture is designed to allow manual or automatic generation of the energisation paths. Automatic sequence generation is defined in section 5.3.
- Calculate the BLRF risk factor associated with each blockload (Circuit Breaker). Based on the current network state, availability of DERs and their generation capacity, the control system calculates the realtime blockload capability of the microgrid which includes the anchor and any supporting DERs. It does this using the transient analysis capability of the network analysis engine, which operates in realtime. Based on the expected blockload associated with each circuit / transformer, the controller determines whether it is safe or not to energise each individual circuit. Each blockload action presents a risk which can be described objectively as a Block Load Risk Factor (BLRF) which can be stated as follows:

[redacted]

When the Block load of an individual circuit exceeds the Microgrid's capability the BLRF is greater than 1. Lower BLRF factors represent safer energisation steps and can be used to inform either manual or automated energisation processes.

- Energise low risk paths / paths (manual or automated) where all blockloads are possible and overall risk factor is low, to get DERs energised to provide further support. It is normal to connect the Controller to the SCADA/DMS System via the ICCP protocol which allows it to send controls via the SCADA/DMS System to the circuit breakers. If it is not possible to achieve a direct or indirect connection to the Circuit Breaker then the Blockload Phase can be set up as a Manual Phase and the action can be performed by the Control Engineer via the SCADA /DMS System and manually confirmed within the DRZ workflow.

- When DERs are energised the BLRF risk factor associated with each blockload (Circuit Breaker) should be recalculated as the addition of DERs support will improve AG capability making subsequent paths possible/less risky.

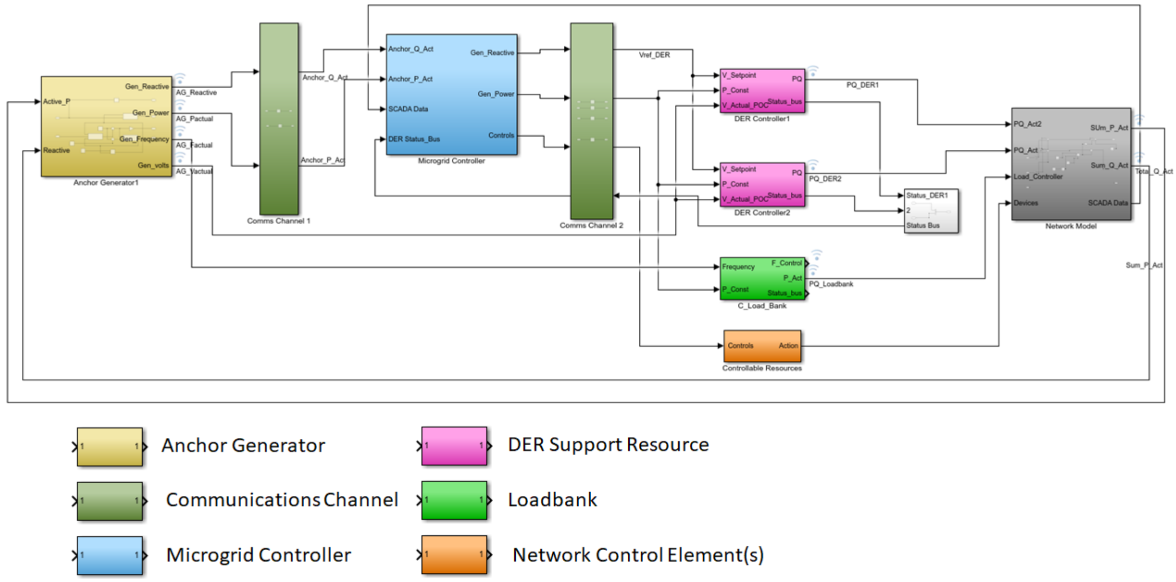
- Energisation should continue to each DER as new energisation paths become viable.

- Anchor generator output should be kept in the middle of its operating range to provide sufficient margin from is maximum and minimum operating points, which requires realtime balancing of Anchor Generator output, supporting DER output and demand.

- Capability should be provided to include for fast acting demand disconnect if the anchor generator approaches its maximum operating output noting that the principles of block-loading apply equally to de-loading demand.

3 Network Components

The following sections introduce the various network elements (e.g.Anchor Generator, supporting DERs, Load banks, tap changers, Capacitor Banks etc.) that may be controlled by the DRZ Controller to re-energisation the network.

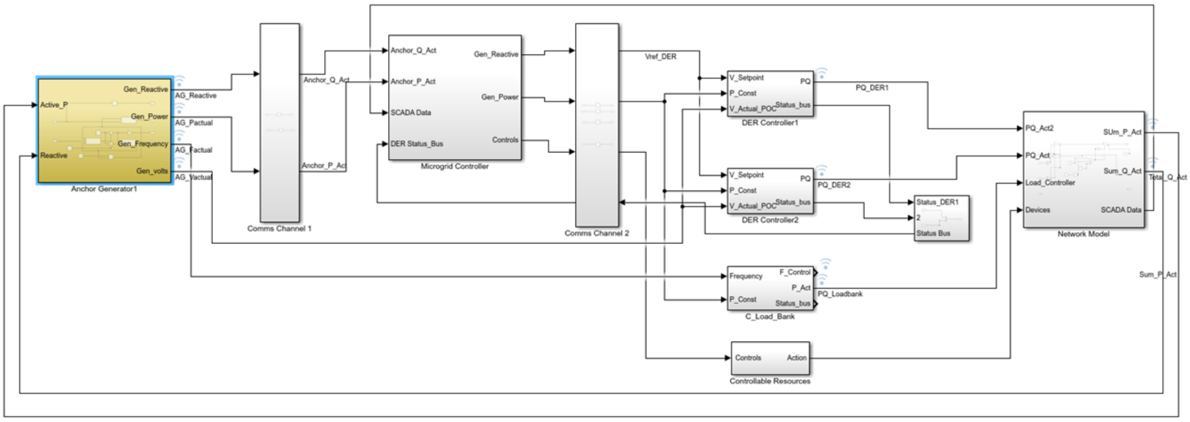


Microgrid / Minigrid Control Scheme

Control System Components	Description
1. Anchor Generator	Voltage and frequency forming Generator
2. Support DERs	Additional DERs used to support the Anchor Generator
3. Load Bank	Continuous/discrete load used for loading the Anchor Generator and expanding the microgrid
4. Controllable Ancillary Equipment	Ancillary network equipment, e.g. Tap-Changer, Capacitive / reactive supports etc.
5. Communications	Communications between DRZ Controller, Anchor Generator, and other equipment
6. DRZ Controller	DRZ Control System

3.1 Anchor Generator

Anchor Generator



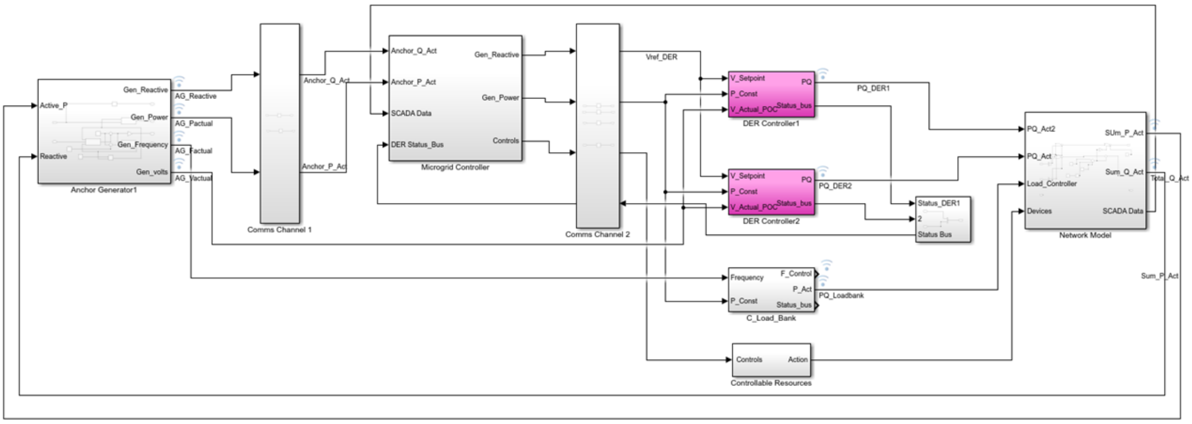
The Anchor Generator is the fundamental Distributed Energy Resource (DER) used in the control scheme to form a Microgrid. This DER is normally running in base load mode.

This DER is the voltage forming and frequency forming Generator and when the control scheme is operating as a microgrid it will operate with other DERs to provide sufficient active and reactive power to perform a gradual controlled energisation of the microgrid.

3.2 Support DERs

The Anchor Generator may not have sufficient active power, reactive power and blockloading capability to energise the Microgrid on its own and maintain stability, so additional DERs will be used to supplement the Anchor Generator.

Support DER Resources



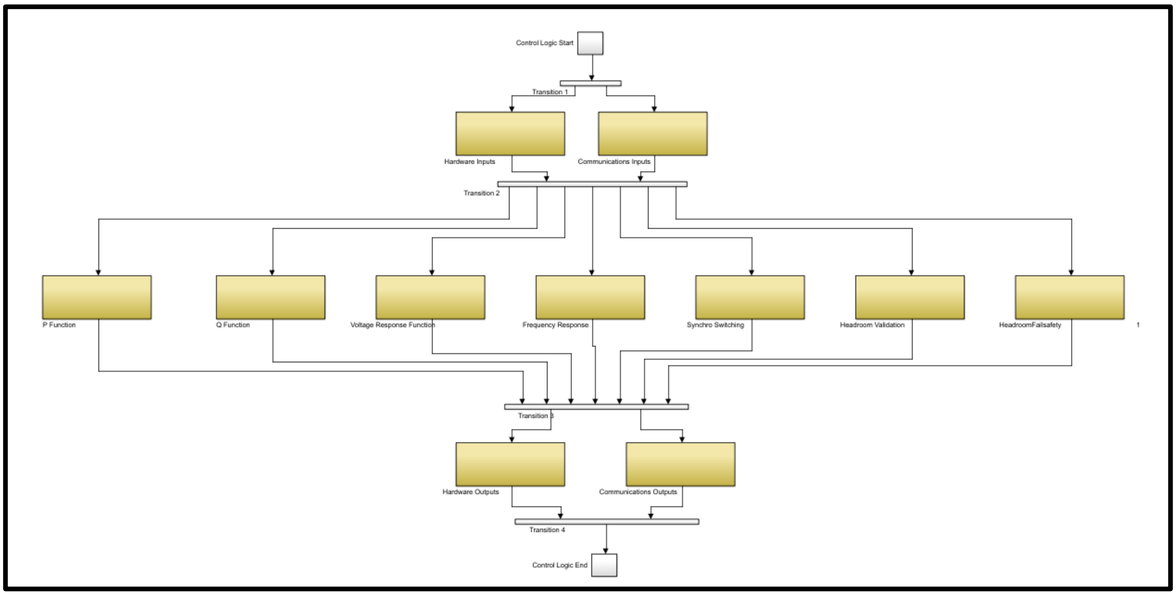
The Microgrid Controller determines the appropriate droop mode setpoints for these DERs and dispatches them in real time. Setpoints are calculated in realtime in response to changing conditions such as changing demand or varying DER output. As well as realtime setpoint dispatch, DERs can also support self-dispatch functions where; when voltage mode is selected; they provide fast reactive power response to changing connection voltage. The DER reactive power output can still be controlled by dispatching a different voltage setpoint.

The Level 1 / DER Controller is designed for either a standalone DER controller or the integration of the DER into a wider ANM or Enhanced Energy Automation System.

As a standalone controller the unit can provide a range of autonomous functionality including managing import/export power at the connection point based on local generation and load behind the connection point. It can independently manage the voltage levels at the point of connection within defined limits. It can monitor the operation of the DER to ensure it remains within the permitted P/Q operating limits and can alarm or disconnect the DER based-on transgressions.

When integrated as part of a wider ANM or Enhanced Energy Automation System it can provide much more functionality including continuous MW/MVAr control, self-dispatch Voltage/Frequency control based on triggers, synchro-check breaker operation, and failsafe operation with TTL (time to live timeouts).

Time to live timeouts are used to monitor the status of communication links between DERs and their super-ordinate controllers. This is the maximum time a DER may be out of communication with its controller before failsafe action is taken.



The diagram above show the individual control functions that are implemented locally in the DER Controller. DERs may comprise different technologies such as wind, solar, battery, flexible loads, and they generally support some, or all, of the following operating modes

- P Mode
- Q Mode
- Voltage Mode (Droop Response)
- Power Factor Mode
- Frequency Droop Response

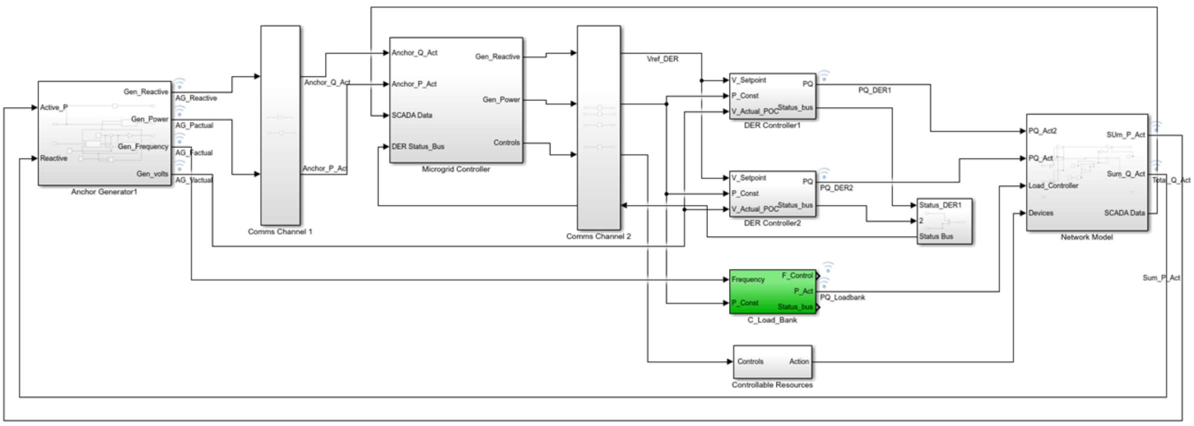
If the DER does not directly support some of these operating modes, the Level 1 Controller provides some of these services. A summary of the functionality provided by the Level 1 Controller is outlined in the table below.

Level 1 Controller Functionality	**Description**
MW Control	Issues MW Control Setpoints
MVAr Control	Issues MVAr Control Setpoints
Automatic Tap Change Control	Automatic Tap Change to maintain voltages within limits
Voltage Droop Control supported by DER	Manage DER Voltage Droop setpoints based on system requirements
Voltage Droop Control provided by Level 1 Controller	Provide Voltage Droop response from the Level 1 Controller based on MVAr control of the DER
Frequency Droop Control supported by the DER	Manage DER Frequency Droop setpoints based on system requirements. DER operating on active power setpoint with a frequency droop setting. The DER is curtailed to create headroom and set to minimise effect of wind variability.
Frequency Droop Control provided by the Level 1 Controller	Provide Frequency Droop response from the Level 1 Controller based on MW control of the DER
Under Frequency Constraint (Load Shedding)	Load shedding based on frequency drops
Synchro-Control	Synchronised control at two locations based on GPS time
Synchro-check	Monitoring and setpoint control of external Synchro-check Relay
Delayed Auto-Reclose	Sequenced timed delayed reclose of a circuit breaker

For a full description of the functionality of the Level 1 Controller please refer to DRZ Report 3.

3.3 Load Bank

Load Bank



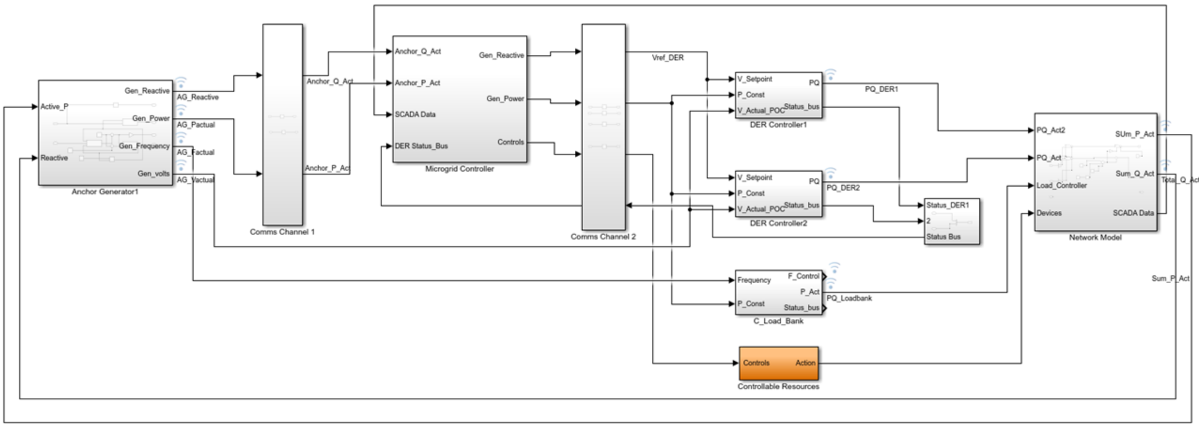
A Load bank is one method available to provide initial load to start the anchor generator. This can be one of two types, depending on the technology:

- Continuous
- Discrete

The load bank is also used during stable microgrid operation to assist in block-loading the Anchor Generator. Some load banks may also be able to provide additional services such as self-dispatching Voltage or Frequency Response.

3.4 Controllable Ancillary Equipment

Controllable Resources



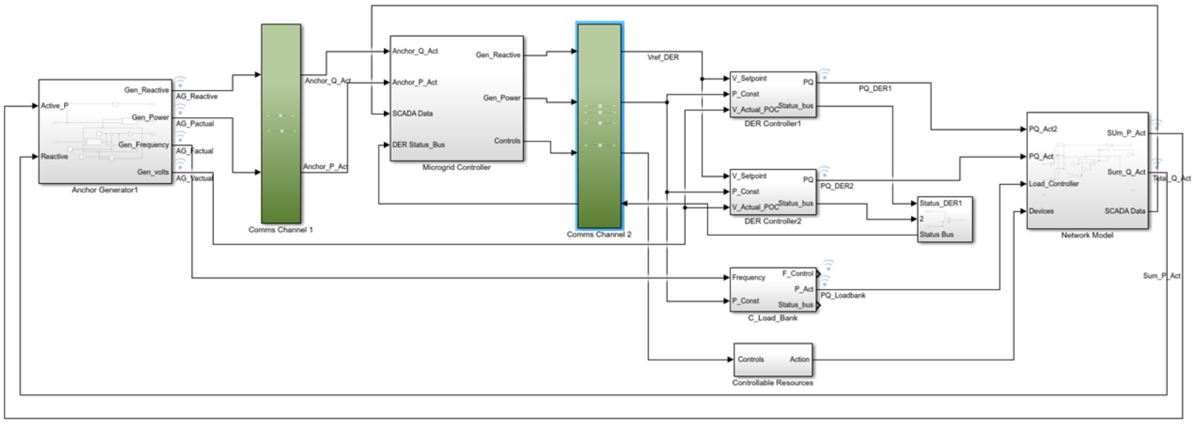
One of the objectives of the control system is to maintain all voltage levels throughout the microgrid within the required operating range. In addition to the Supporting DERs, other support equipment may be available to the control scheme to achieve this, including such items as: -

   i. Anchor Generator Tap-Changer
  ii. MSC / MSR Switching Devices
 iii. Substation On-Load Tap Changers
 iv. SVC/Statcoms

3.5 Communications Channels

The scheme design must allow for key components of the system to be deployed in different locations depending on different factors such as, the operating model, available communications, architecture and location of DRZ Controller and the physical location of the Anchor Generator and Support DERs.

Microgrid Communications Channels



ZIV's control architecture is flexible and supports different deployment models. The deployment model chosen will result in different communications scenarios.

Depending on the communications medium, communications protocols and number of devices sharing a channel, different latencies will be introduced.

ZIV has performed Power systems modelling and Control systems modelling to determine the relative impact of communications on the stability of a Microgrid.

The different deployment options and the relative impact of the latencies on the overall system performance is provided in DRZ Report 2.

4 Power System Study / Phase 2 Evaluation System

4.1 Design Methodology

The following design process has been followed in producing the DRZ Control System Design.

Network Model Building: ZIV has built and integrated the Chapelcross DRZ Zone network model into its development and production platform.

Perform Power Systems Analysis: Using the DRZ Zone network model ZIV has performed steady state and transient analysis of the network area to evaluate and establish the most appropriate control strategy for DRZ. The details and the overall evaluation and conclusions of the power system studies are included in the following sections.

Produce Design / Implementation plan: Based on the power system analysis a control system design has been formulated. This has been outlined in Section 2 of this document. Section 2 outlines the main functional components of the DRZ Control Scheme. Based on our analysis ZIV has decided to base its design on 2 existing Business As Usual (BAU) modules that exist in its standard control library. These modules are the Microgrid and Virtual Power Plant (VPP) Modules. The Workflow Module will be enhanced to support Manual and Automatic operation of the DRZ process and will support the requirement to perform self-test and in the future, adapting building of the energisation sequence.

Build Wireframe / Demo system : To ensure that the main requirements of the control system can be met by the design, ZIV routinely builds a test platform to challenge all the design assumptions and check that the main functional and performance requirement can be fulfilled by the design. This ensures that the design requirements are achievable and that the control system will perform as expected with significantly reduced project risk and implementation time. The details of this Phase 2 Test Platform are provided in Section 4.6 of this document.

Design Documentation: Based on the evaluation of the design using the test system, the design has been finalised and outlined in 3 separate reports. This report DRZ Design outlines the software components that specifically relate to the DRZ process. DRZ Communication outlines the communications requirements and evaluates different deployment options and DRZ Systems Integration report outlines the hardware and interface requirements to host the software components.

Requirements Definition: Based on final design derived from the process outlined above, the critical requirements have been extracted and outlined in a summary report DRZ Control System Overview. This report outlines the key functional requirements of the DRZ system that should be considered by any control system provider. With each requirement ZIV also provides a rationale for that requirement and a summary of how that requirement is met by the design provided by ZIV.

4.2 Power System Study – Chapelcross

In microgrids, DER units; notably inverter-connected wind turbines and photovoltaics (PV) that do not provide rotational inertia; outnumber the conventional synchronous generator capacity and the assumption that grid inertia is sufficiently high with only small variations over time is not valid for power systems with a high asynchronous DER capacity.

This has implications for frequency dynamics and power system stability and operation. Frequency dynamics are faster in power systems with low rotational inertia, making frequency control and power system operation more challenging.

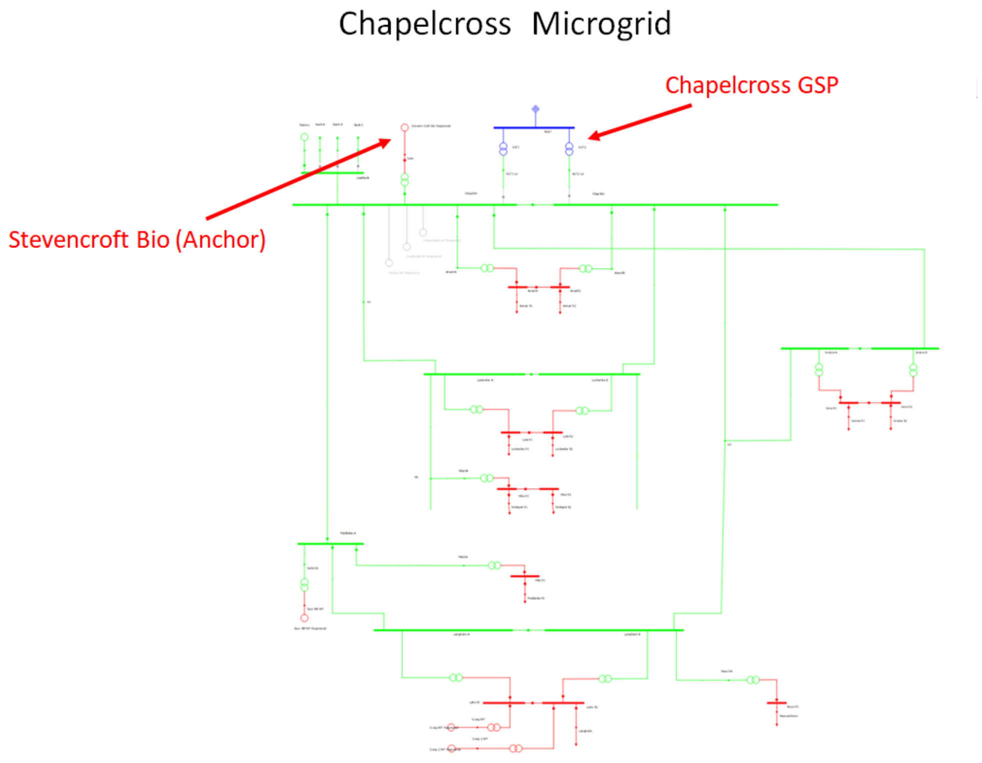
The design of the Microgrid Controller must consider the effect of low rotational inertia on the microgrid's stability and operation.

4.3 Chapelcross Network Description

The Chapelcross network is a typical example of one that may be able to participate in black start operations. The 33kV radial distribution network supplies several demand substations and includes six wind farms. The network also includes a 50MW synchronous biomass generator making it suitable for black start operation.

The network has sufficient embedded generation to be able to support the expected system demand with the potential to export power under favourable wind conditions.

Chapelcross is connected directly to the SPT transmission system through two 132/33kV SGTs. For the purposes of the power system studies a load bank, battery system and STATCOM have been included.

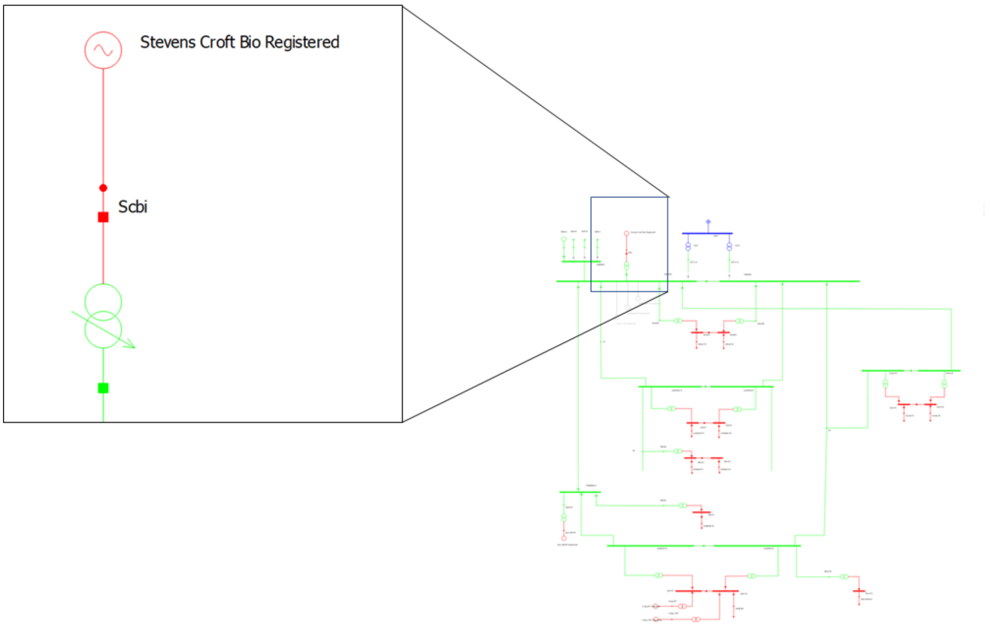


4.4 Chapelcross – Active DERs

The following generators are present in the Chapelcross Network and are assumed they will participate in the microgrid and blackstart process.

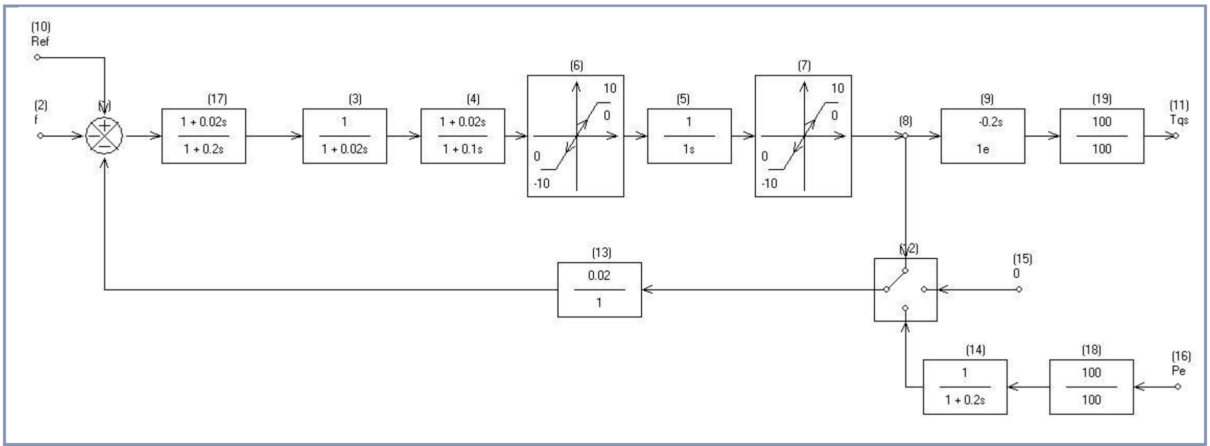
4.4.1 Stephens Croft Bio – Anchor Generator

Stephens Croft – Anchor Generator



Stephen Croft Anchor Generator has been modelled as follow: -

Block Diagram



Woodward Diesel Governor

Parameters

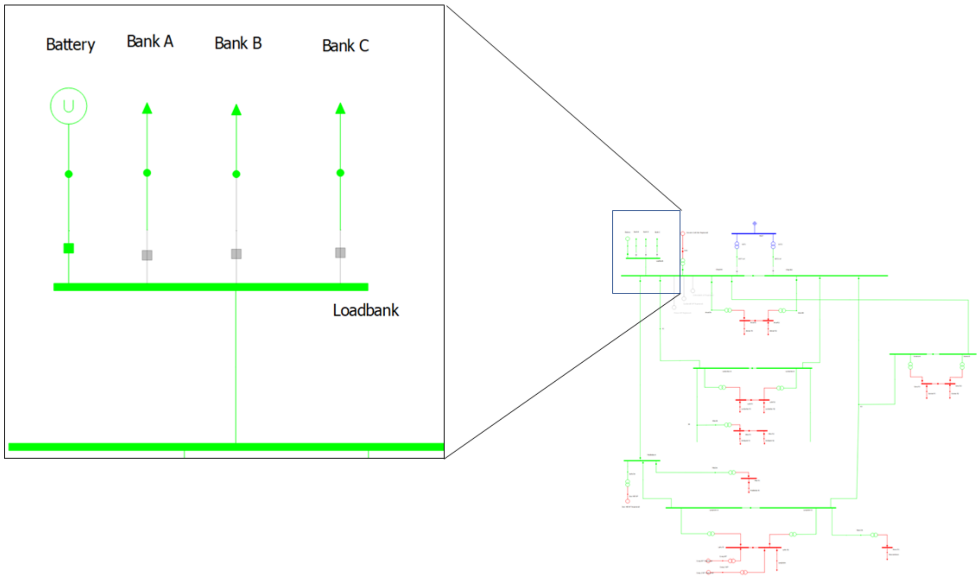
Block	Name	Default Value	Typical Range	Units	Description
17	T1	0.02	0 to 25	secs	Governor time constant
17	T3	0.2	0 to 10	secs	Governor time constant
4	T4	0.02	0 to 25	secs	Governor time constant
3	T5	0.02	0 to 10	secs	Governor time constant
4	T6	0.1	0 to 0.5	secs	Governor time constant
6	Tmin	-10.0	-0.05 to 0.5	MW per unit	Minimum governor output limit
6	Tmax	+10.0	0 to 1.5	MW per unit	Maximum governor output limit
5	K	1	15 to 25		Governor gain
7	Tmin	-10.0	-0.05 to 0.5	MW per unit	Minimum governor output limit
7	Tmax	+10.0	0 to 1.5	MW per unit	Maximum governor output limit
9	Td	0.2	0 to 0.125	secs	Engine time delay
19	Output Scaling	100			Generator MVA / System MVA
13	Droop	0.02	0 to 0.1	Per unit	Droop gain
12	Mode	0			0 = Droop mode 1 = Isochronous mode
14	Te	1.0	0 to 1.0	secs	Power filter time constant
18	Input Scaling	100			System MVA / Generator MVA

Note: Anchor Generator performance will vary from microgrid to microgrid. Developing a procedure to correctly characterise each anchor generator will contribute to the system accuracy.

4.4.2 Loadbank

To provide the anchor generator with a starting load, a load bank has been added to the network model.

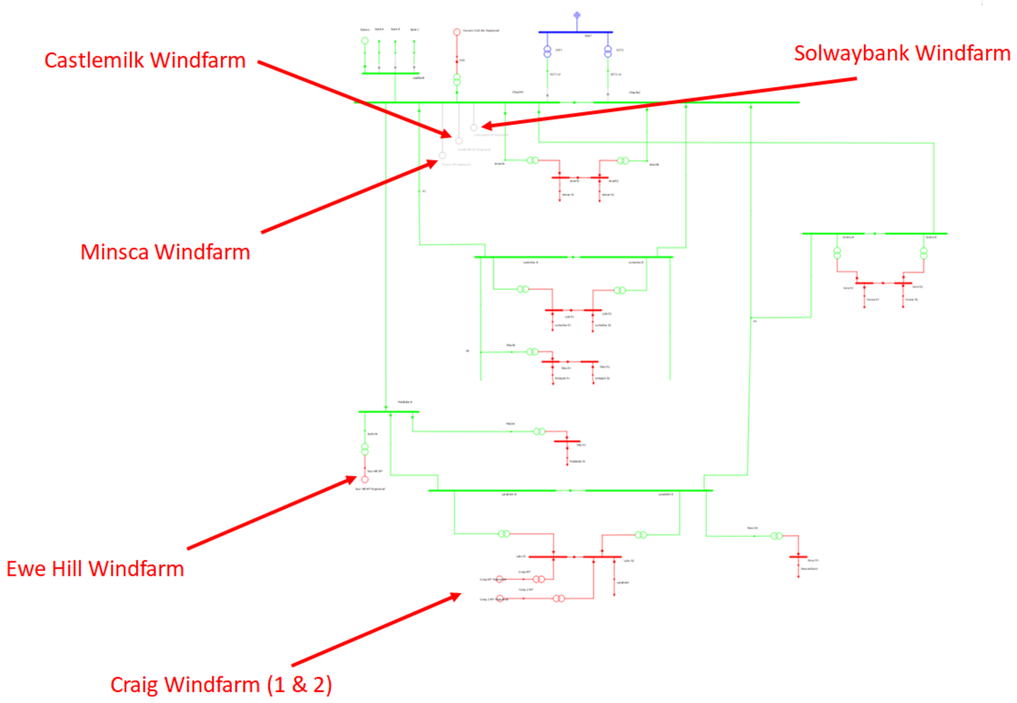
Loadbank at Chap3A1



4.4.3 Supporting DERs

The following DERs are present on the network and it is assumed that they are controllable for active and reactive power to evaluate different control strategies to mitigate the effects of block loading the Anchor Generator.

Chapelcross Supporting DERs



4.4.4 Supporting Battery and SVC Systems

In order to evaluate different control strategies to mitigate the effects of block loading the Anchor Generator some additional technologies that are not present on the actual Chapelcross network have been added to evaluate the effectiveness of those technologies in stabilising microgrids from a control perspective.

The following DERs have been added on the network and it is assumed that they are controllable for active and reactive power.

- Generic Battery System
- SVC System

4.5 General Conclusions from studies

ZIV has used the Chapelcross network as the basis of its steady state and transient loadflow analysis examining different scenarios outlined below to inform its design approach to applying a microgrid controller to the process of blackstart (DRZ).

4.5.1 Learning from Power System Studies

The following conclusions are evident from the evaluations carried out: -

- Low Inertia dominates the frequency behaviour of the microgrid.

- Anchor Generators have a finite block loading (MVA) capability based on their AVR and Governor settings which if exceeded can result in Generator tripping or voltage and frequency out of regulatory range.

- Some demands, if switched in, may exceed this level (MVA) and therefore cannot be switched in safely.

- Different technologies (DER) can significantly improve the AG (Anchor Generator) blockloading capability such as: -
    - Batteries
    - SVC
    - Loadbanks

  by providing fast active and reactive power support to the microgrid.

- The microgrid Blockload capability changes depending on the Anchor Generator, environment conditions and presence of support DERs at any given time. DERs can support the Anchor Generator during a blockload by providing active or reactive power support to improve the transient response and balance the overall demand and generation.

- Each blockload action presents a risk (Blockload Risk Factor - BLRF) which defines whether it is safe to perform a blockload. This figure is used to inform either a manual or automatic process whether it is safe to perform a particular blockloading action.

- There is a level of uncertainty in block demand and inrush calculations so an acceptable margin of error should be included. Estimation of Blockload size is discussed in section 8.4 of this document.

- Adding DERs to the microgrid improved the overall stability by improving the BLRF at each Circuit Breaker (Blockload).

- A method exists which can calculate BLRF in realtime for each Circuit Breaker to inform a safe manual or automated restoration process.

- Various methods exist to maximise Anchor blockload capability and hence customer restoration capability.

4.5.2 Power Study informing DRZ Energisation Strategy

Based on the learning from the power system studies a control strategy can be derived to safely perform a blackstart energisation of a microgrid.

The control system should: -

- Identify DER support resources which can help the anchor generator.
- Identify which DERs are forecast to be able to provide active and reactive power output.
- Identify which DERs are forecast to be able to provide fast or self-dispatching active or reactive power support for blockloading or VPP fast response.
- Define energisations paths to each support resource (DER).
- Calculate the BLRF risk factor associated with each blockload (Circuit Breaker)
- Energise low risk paths / paths (manual or automated) where all blockloads are possible and overall risk factor is low, to get DERs energised to provide further support.
- When DERs are energised the BLRF risk factor associated with each blockload (Circuit Breaker) should be recalculated as the addition of DERs support will improve AG capability making subsequent paths possible/less risky.
- Energisation should continue to each DER as new energisation paths become viable.
- Anchor generator output should be kept in the middle of its operating range to provide sufficient margin from is maximum and minimum operating points, which requires real time balancing of Anchor Generator output, supporting DER output and demand.
- Capability should be provided to include for demand disconnect if the anchor generator approaches its maximum operating output noting that the principles of block-loading apply equally to de-loading demand.
- Capability should be provided to include for fast acting demand disconnect in the event DER generation trips.

4.5.3 Power Study Examples

ZIV has performed the following transient studies as part of the overall analysis: -

Blockload - Transient Analysis

Blockload with DER Reactive Power support – Transient Analysis

Blockload with Synchro Switching – Transient Analysis

Blockload with SVC Support – Transient Analysis

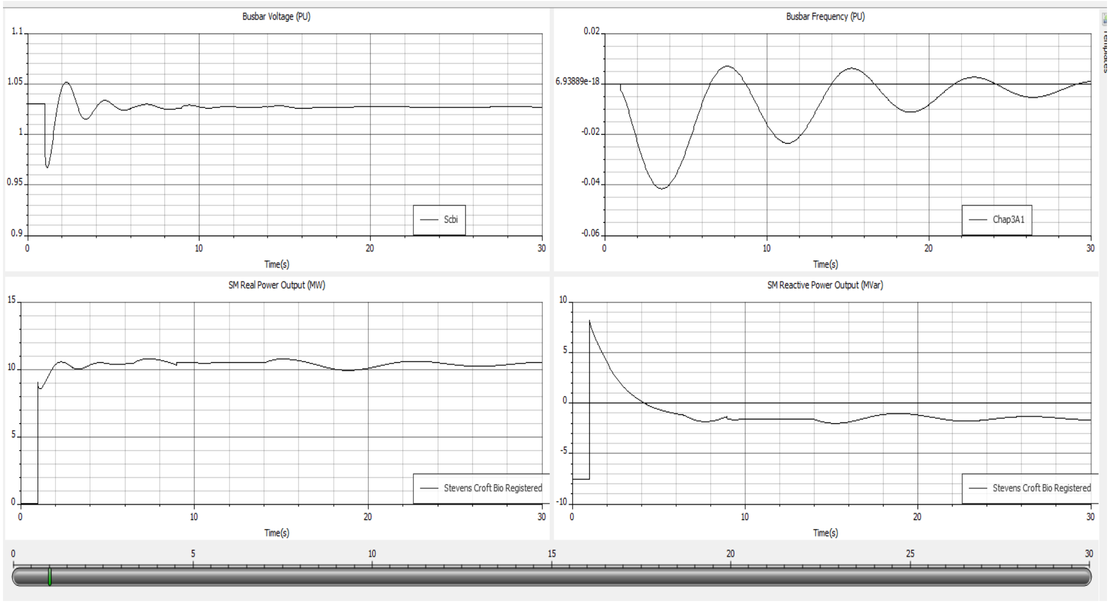
Blockload with Battery Support – Transient Analysis

Examples are provided below in the next section and a more complete description is provided in the Appendix at the end of this document.

4.5.3.1 Blockload Transient Analysis

Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load

Result: 4% frequency dip, 6% voltage dip (anchor generator)



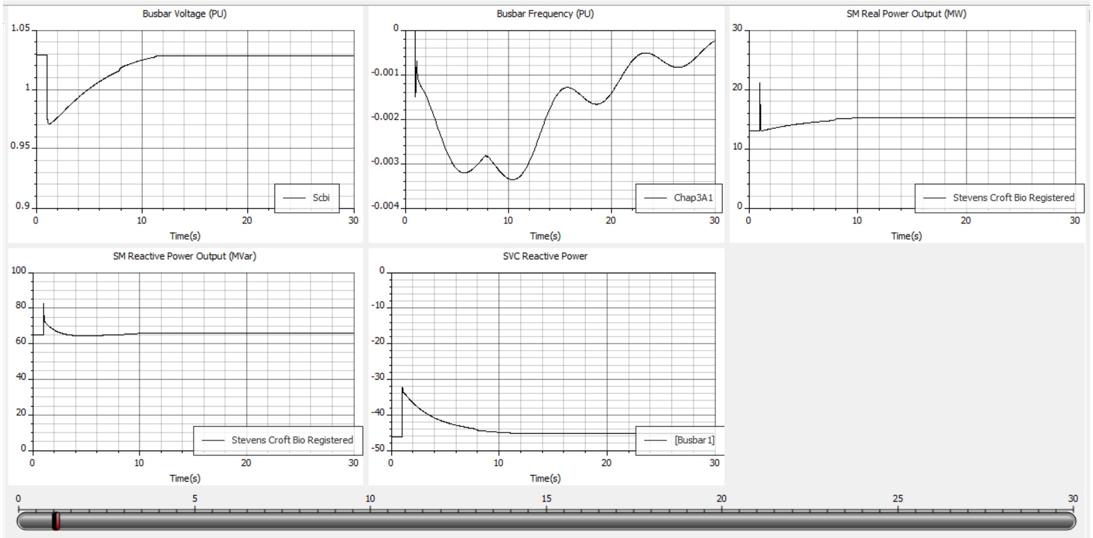
4.5.3.2 Blockload with Battery Support - Transient Analysis

Test Conditions: 19MVA Transformer Energisation with 19MW, 9.5MVAr LV Load, Battery Operation:

Results: 0.4% frequency rise, 6.0% voltage dip. This represents the maximum block load capability due to the voltage limits.

Note : The voltage limits referenced here are for comparison purposes. The voltage limits used during a blackstart are configurable and can be changed within the system.

Base case result without battery was 4% and 6% respectively for a 10MVA demand.



4.6 Phase 2 Evaluation Platform

Based on the power system studies summarised above, ZIV has implemented a Phase 2 Evaluation System; outlined below. This consists of a ‘Blackbox’ Controller; with all the DRZ control modules defined in this document; and a ‘Whitebox’ digital simulator which emulates the behaviour of the electrical network.

This Phase 2 evaluation system allows the full control schema to be tested and demonstrated. It also allows different network zones to be studied for the effects of network topology, communications latencies and Anchor Generator performance and supporting DER technologies on different energisation strategies.

The Phase 2 evaluation system allows the User Interfaces to be evaluated and a comparison to be made between manual and automated DRZ processes.

The evaluation system can also be configured to replicate different ‘ownership models’ to gain an understanding of the differing data interfacing requirements.

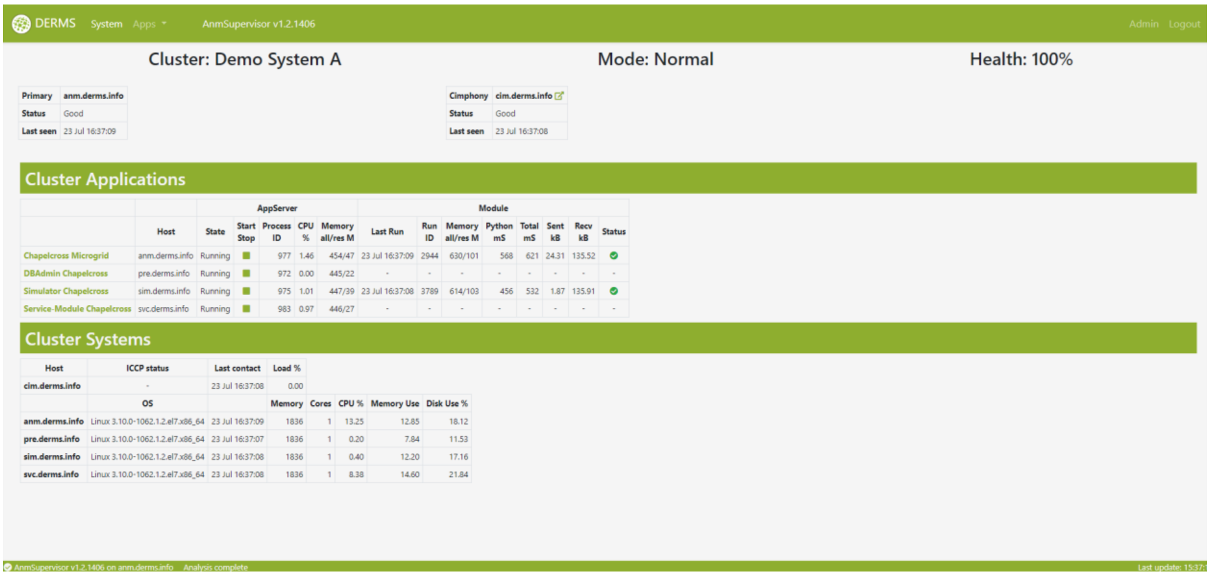
The simulator supports comprehensive software testing to be carried out. However, where the dynamic behaviour of different hardware components needs to be carried out, ZIV propose that hardware testing could be facilitated using an external simulation system capable of interfacing real time physical signals, such as an RTDS.

4.6.1 Blackbox DRZ Control System

The Blackbox Control System can be deployed on a Level 2 Substation Controller, Level 3 Enterprise System or Cloud based. For a detailed explanation of the Level 2 and Level 3 please refer to the DRZ Overview Report or DRZ Report 2.

The Cluster contains the following:

DRZ Software Modules	Description
1. Workflow Scheduler	Executes a set of workflow actions to start-up or expand the Microgrid
2. Microgrid Controller	Manages the Microgrid to ensure that the Anchor Generator has sufficient headroom to react to sudden network changes
3. Virtual Power Plant	Once it is re-connected to the transmission grid it can operate as a Virtual Power Plant providing Active and Reactive Power Services to the transmission grid
4. Predictor Module	The Predictor Modules uses weather forecasts and calendric data to predict the output of individual DERs and individual demand levels.



Cluster: Demo System A   Mode: Normal   Health: 100%

Primary	**anm.derms.info**
Status	Good
Last seen	23 Jul 16:37:09

Cimphony	**cim.derms.info**
Status	Good
Last seen	23 Jul 16:37:08

Cluster Applications

	AppServer						Module							
	Host	State	Start Stop	Process ID	CPU %	Memory all/res M	Last Run	Run ID	Memory all/res M	Python mS	Total mS	Sent kB	Recv kB	Status
Chapelcross Microgrid	anm.derms.info	Running	■	977	1.46	454/47	23 Jul 16:37:09	2944	630/101	568	621	24.31	135.52	✓
DBAdmin Chapelcross	pre.derms.info	Running	■	972	0.00	445/22	-	-	-	-	-	-	-	-
Simulator Chapelcross	sim.derms.info	Running	■	975	1.01	447/39	23 Jul 16:37:08	3789	614/103	456	532	1.87	135.91	✓
Service-Module Chapelcross	svc.derms.info	Running	■	983	0.97	446/27	-	-	-	-	-	-	-	-

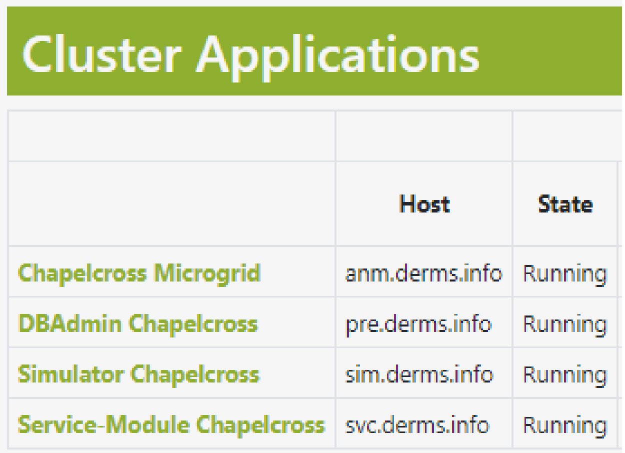
Cluster Systems

Host	ICCP status	Last contact	Load %				
cim.derms.info	-	23 Jul 16:37:08	0.00				
	OS		**Memory**	**Cores**	**CPU %**	**Memory Use**	**Disk Use %**
anm.derms.info	Linux 3.10.0-1062.1.2.el7.x86_64	23 Jul 16:37:09	1836	1	13.25	12.85	18.12
pre.derms.info	Linux 3.10.0-1062.1.2.el7.x86_64	23 Jul 16:37:07	1836	1	0.20	7.84	11.53
sim.derms.info	Linux 3.10.0-1062.1.2.el7.x86_64	23 Jul 16:37:08	1836	1	0.40	12.20	17.16
svc.derms.info	Linux 3.10.0-1062.1.2.el7.x86_64	23 Jul 16:37:08	1836	1	8.38	14.60	21.84

AnmSupervisor v1.2.1406 on anm.derms.info   Analysis complete   Last update: 15:37:

The Blackbox DRZ Control System includes two applications:

- The Chapelcross Microgrid Application includes the Microgrid Controller and VPP Controller
- The Service Module Chapelcross includes the Sequencer Application described in section 5 of this document.



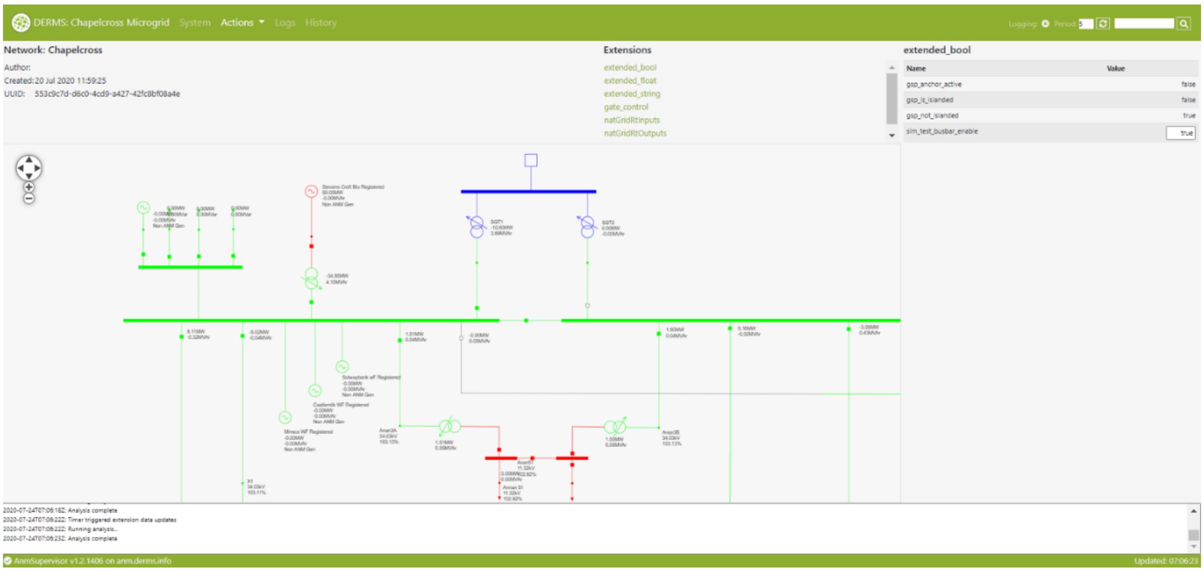
Cluster Applications

	Host	State
Chapelcross Microgrid	anm.derms.info	Running
DBAdmin Chapelcross	pre.derms.info	Running
Simulator Chapelcross	sim.derms.info	Running
Service-Module Chapelcross	svc.derms.info	Running

4.6.1.1 Chapelcross Microgrid Controller

This application runs the following modules

- Microgrid Controller
- VPP Controller
- Network Analysis Engine.



Network: Chapelcross
Author:
Created: 20 Jul 2020 11:59:25
UUID: 553c9c7d-d6c0-4cd9-a427-42fc8bf08a4e

extended_bool

Name	Value
gsp_anchor_active	false
gsp_is_islanded	false
gsp_not_islanded	true
sim_test_busbar_enable	true

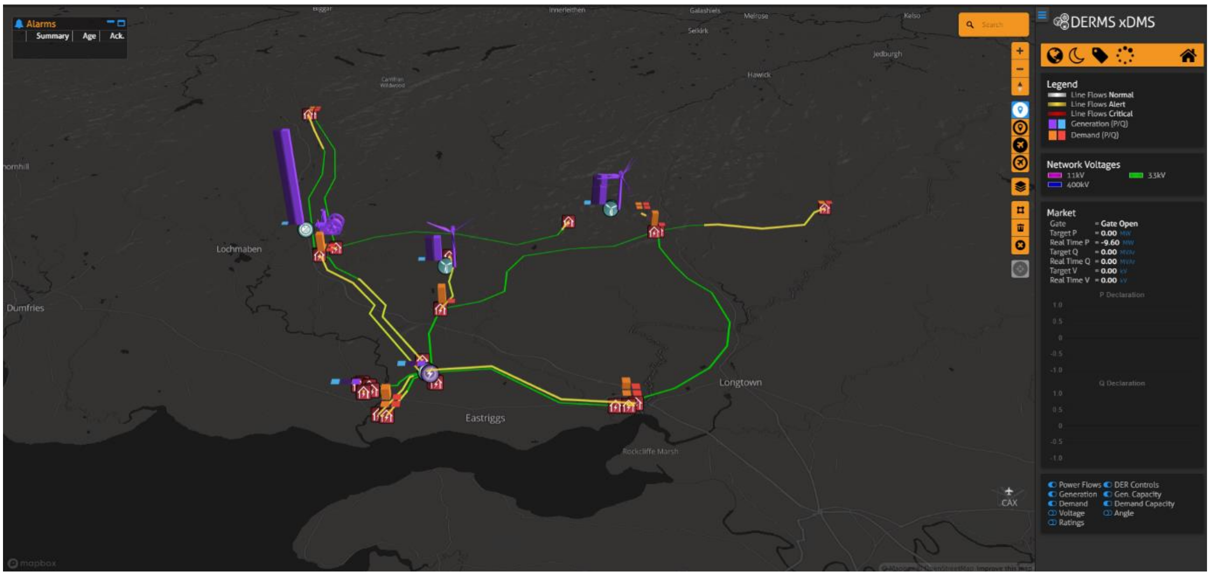
```
2020-07-24T07:06:18Z: Analysis complete
2020-07-24T07:06:22Z: Timer triggered extension data updates
2020-07-24T07:06:22Z: Running analysis...
2020-07-24T07:06:23Z: Analysis complete
```

AnmSupervisor v1.2.1406 on anm.derms.info

Updated: 07:06:23

The individual modules are described in detail in Sections 6 and 7 of this document. The screenshot above shows the loadflow analysis being performed in realtime using network data from the Network Digital Simulator described in 4.6.2 below.

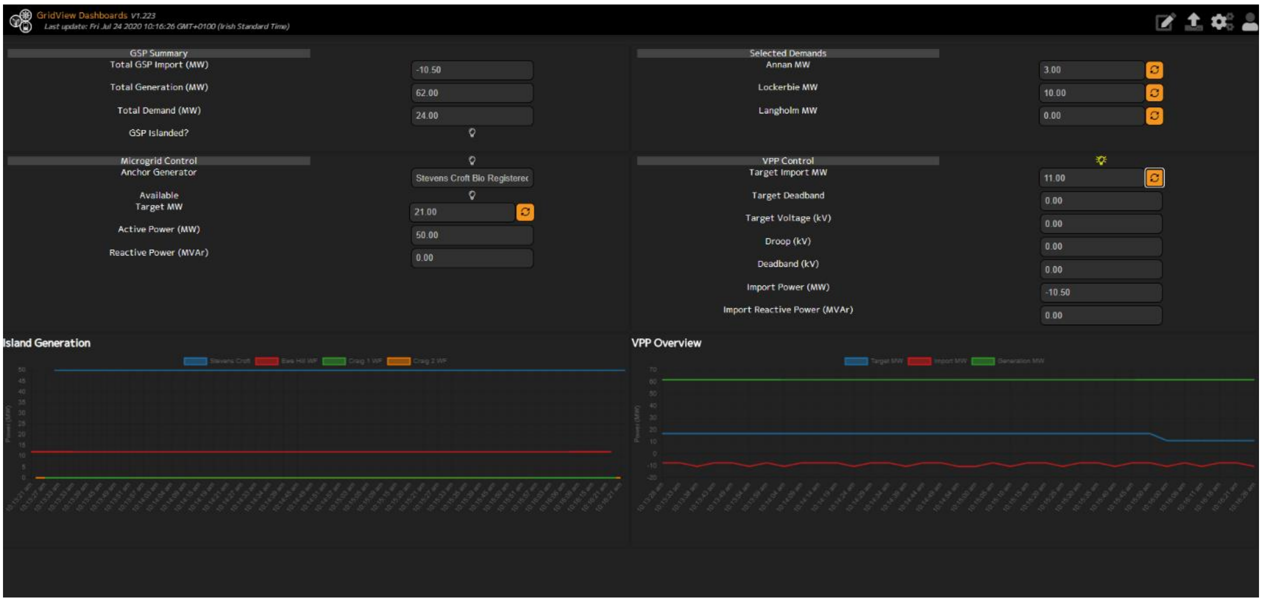
The results are visualised in realtime on the main display console shown below :-



Market
Gate = Gate Open
Target P = 0.00 MW
Real Time P = -9.60 MW
Target Q = 0.00 MVAr
Real Time Q = 0.00 MVAr
Target V = 0.00 kV
Real Time V = 0.00 kV

Dashboards are provided to allow the User to interact with the system. The dashboard shown below displays the status of the Microgrid and VPP modules and displays the key Anchor Generator and DER Active and Reactive Power Outputs.

Anchor Generator setpoint can be entered and when the VPP function is active – the volume of active and reactive power delivered by the microgrid can be dispatched from this interface.



Last update: Fri Jul 24 2020 10:16:26 GMT+0100 (Irish Standard Time)

GSP Summary
Total GSP Import (MW): -10.50
Total Generation (MW): 62.00
Total Demand (MW): 24.00
GSP Islanded?

Microgrid Control
Anchor Generator: Stevens Croft Bio Registerec
Available
Target MW: 21.00
Active Power (MW): 50.00
Reactive Power (MVAr): 0.00

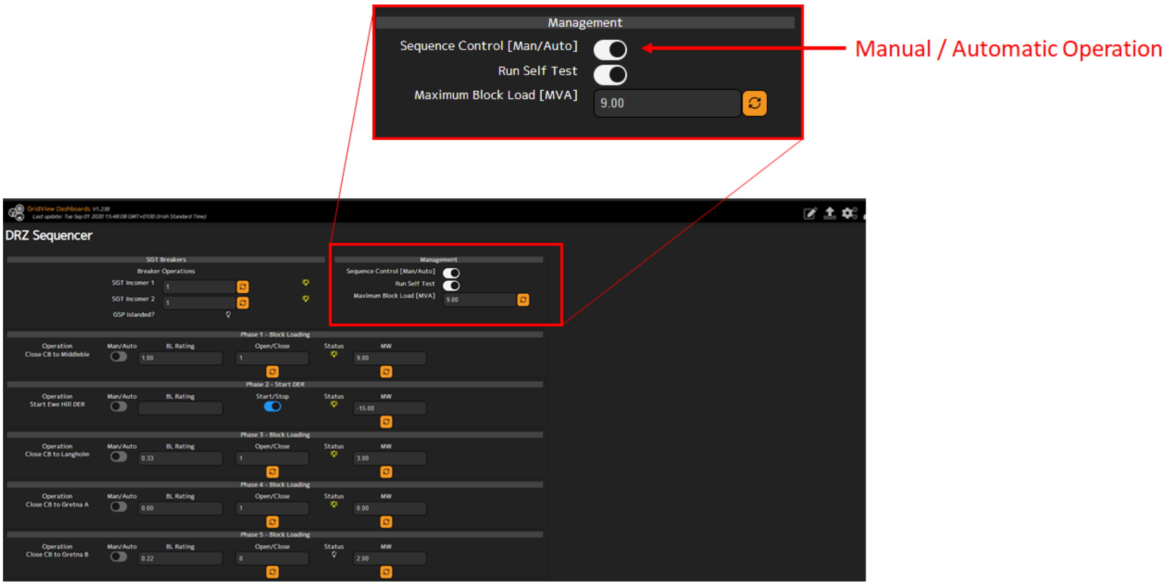
Selected Demands
Annan MW: 3.00
Lockerbie MW: 10.00
Langholm MW: 0.00

VPP Control
Target Import MW: 11.00
Target Deadband: 0.00
Target Voltage (kV): 0.00
Droop (kV): 0.00
Deadband (kV): 0.00
Import Power (MW): -10.50
Import Reactive Power (MVAr): 0.00

4.6.1.2 Service Module Chapelcross

This application runs the following modules :-
Workflow Scheduler

The workflow scheduler provides manual or automated control over the DRZ energisation sequence. This is described in detail in Section 5 of this document. The interface shown below allows the User to control the energisation sequence, performing blockload actions, starting DERs, etc.



Management

Sequence Control [Man/Auto]

Run Self Test

Maximum Block Load [MVA] 9.00

4.6.2 Whitebox Digital Network Simulation

To perform any system analysis, it is necessary to simulate the network operation and show how it reacts to change. To simulate the network operation, the best scenario is to model the entire network (or relevant sections of the network) as closely as possible, including network connectivity, asset ratings and equipment modelling. ZIV can import much of this data from a variety of existing sources to simplify the process.

For offline analysis it must be possible for the user to easily simulate some network changes (e.g. generation levels, load levels, breaker states, …) and observe the cascading effects that these changes would have on a live system.

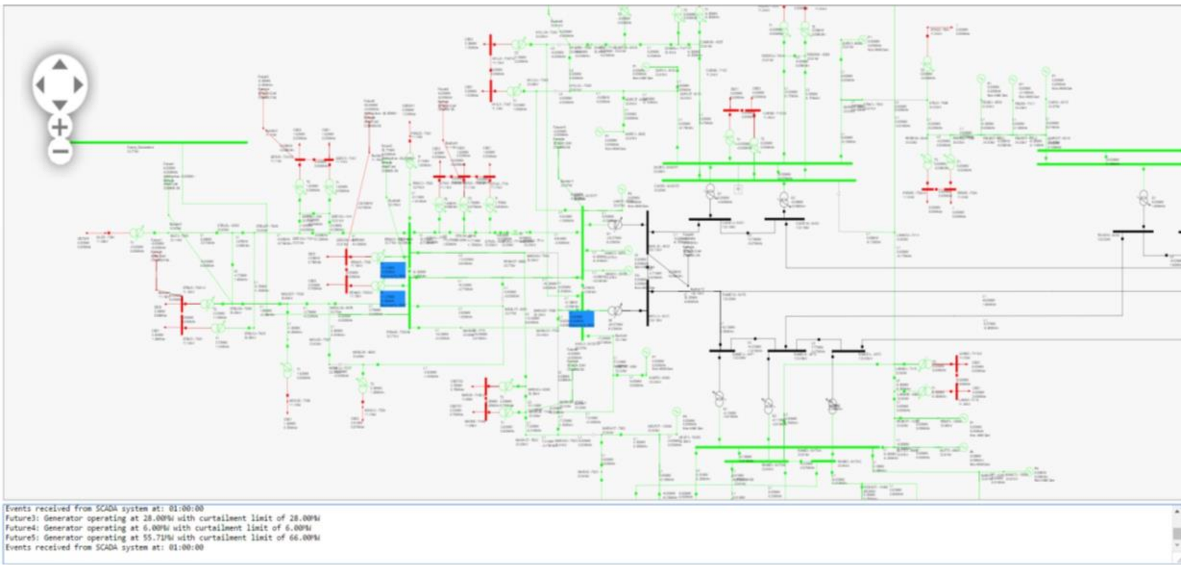
For on-line real-time analysis it must be possible to simulate potential network changes in real-time, analyse the effects that these could have and use this analysis to make real-time control decisions.

For offline simulation it is important to have time-domain simulation where you can observe the network reactions over time. For example, it is important to observe a network control scheme react to changing network conditions and observe generators ramping up or down in response as would happen in live operation. It is also important to be able to observe the cascading effects of a breaker operation due to protection operation in a time series of events.

To achieve this the simulation module mimics the network changes over time and feeds this back to the control system to emulate the real network SCADA data.

There is a requirement for both offline and online simulation modules. These simulation modules are used extensively by ZIV for testing complex energy automation systems to ensure correct and safe operation under any simulated network conditions.

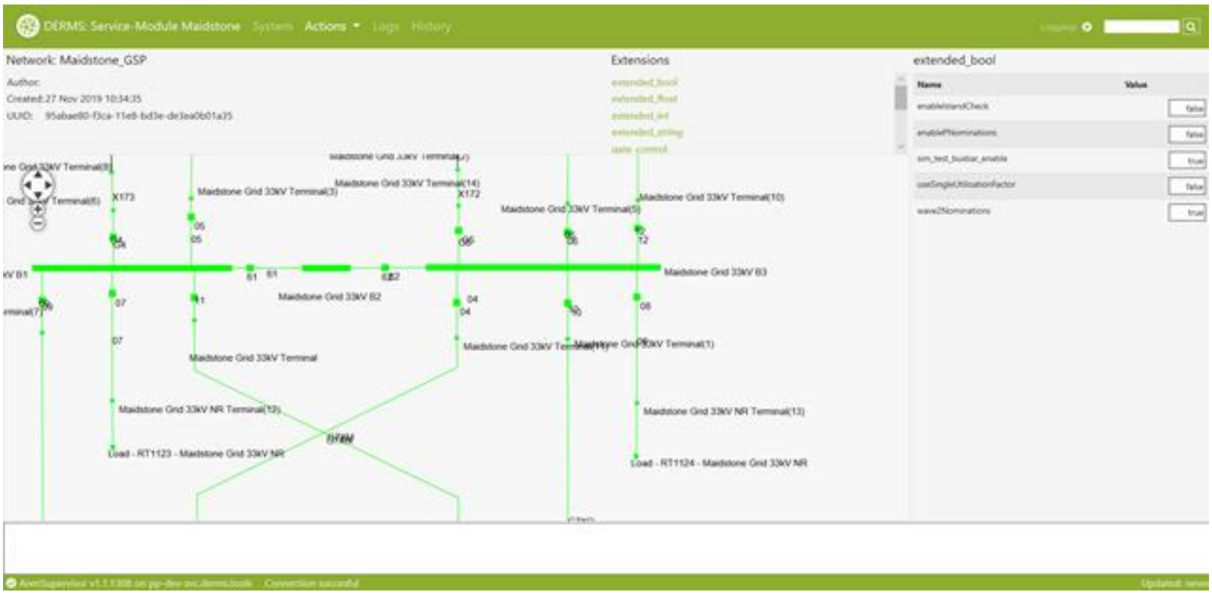
The offline system simulation can potentially analyse past data, current data, simulated data, or future forecasted data applied to a wide range of potential network scenarios.



```
Events received from SCADA system at: 01:00:00
Future3: Generator operating at 28.00MW with curtailment limit of 28.00MW
Future4: Generator operating at 6.00MW with curtailment limit of 6.00MW
Future5: Generator operating at 55.71MW with curtailment limit of 66.00MW
Events received from SCADA system at: 01:00:00
```

This Simulation module runs on the network model generated from the Chapelcross model shared by SPEN. It runs continuous loadflow and other analysis of the network and includes time-domain simulation of all active DERs and other active devices on the network.

This analysis can be based on various datasets including data generated by the Predictor Module which allows scenarios to be investigated for all dates and times during the year and under different weather conditions providing flexible but realistic test scenarios for the other analysis modules. The Predictor Module is described in detail in Section 8 of this document.



Network: Maidstone_GSP

Author:

Created:27 Nov 2019 10:34:35

UUID: 95abae80-f3ca-11e8-bd3e-de3ea0b01a35

extended_bool

Name	Value
enableIslandCheck	false
enablePNominations	false
sim_test_busbar_enable	true
useSingleUtilisationFactor	false
wave2Nominations	true

Note: The network can be broken into sub-networks and analysed in parallel with multiple Simulation Modules if required.

5 Workflow Scheduler

5.1 General Workflow Definition

A workflow model is defined by the resources being utilised and the sequence of tasks being performed. Phases are a specific set of tasks that are grouped together in a sequence to achieve a specific outcome. The Workflow Scheduler is responsible for establishing, verifying, and dispatching the workflow instructions to perform a successful re-start of a DRZ Zone.

5.1.1 Resources

Resources can comprise DERs such as

- Battery Storage Systems
- Load Banks
- Flexible Demands
- Windfarms
- Solar Farms

and other network equipment such as

- Switches
- Circuit Breakers
- Tap Changers

These are the devices upon which tasks can be performed.

5.1.2 Tasks

Tasks are the actions that can be performed on the resources such as

- Open/Close
- Ramp Up/Down
- Increase/Decrease Reactive Power Output
- Etc.

5.1.3 Phases

Phases are a specific set of tasks that must be grouped together in a sequence to achieve a specific outcome.

Examples of phases for the DRZ workflow might include the following: -

Initiation Phase - This phase would need to ensure that communications are available to the required resources. It might need to switch network circuit breakers to a pre-defined configuration for start-up and possibly switch protection setting groups as appropriate.

Stabilisation Phase - Achieving stability of the Anchor Generator may require incrementally loading the Anchor Generator using flexible demand and then possibly switching to normal feeder demand after the minimum stable generation (MSG) is met.

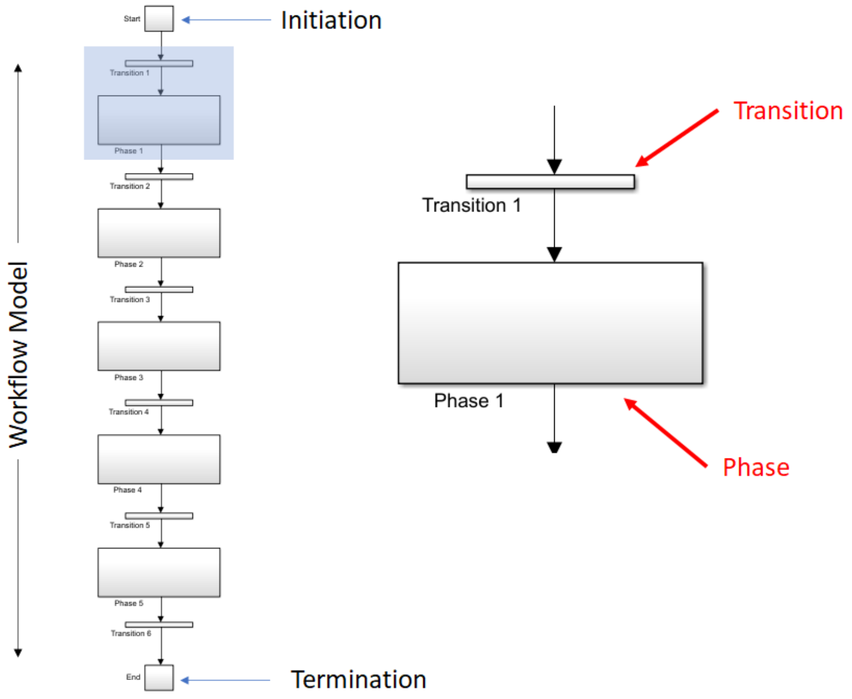
Growth Phase(s) - Once the stabilisation phase is complete then the Growthy Phase(s) can begin. This may involve successively block loading an energisation path to connect more DERs or to connect other substations. Multiple growth phases can be applied in sequence or in parallel to energise the wider distribution network and the microgrid reaches a Point of Connection with other microgrids or the transmission grid.

Transmission Energisation Phase - After subsequent Growth Phases the DRZ energises the network up to the point of a transmission grid supply point (GSP). At this point, through direct liaison with the TSO, the distribution island can begin to establish a voltage at transmission level.

Once connected to the transmission grid, the DRZ acts as a Virtual Power Plant service provider to provide support for other GSPs or Microgrids and aid wider transmission energisation.

5.2 Workflow Execution

The workflow model comprises a sequence of specific phases (groups of tasks). Tasks and phases are separated by transitions. Transitions govern when the process moves from one task/phase to the next.

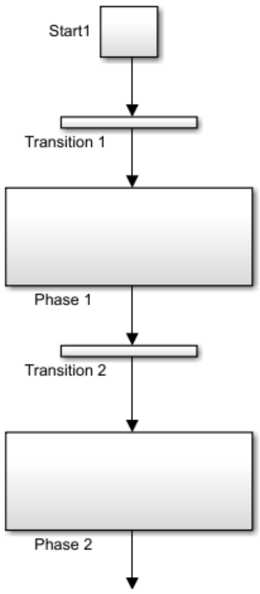


5.2.1 Phases

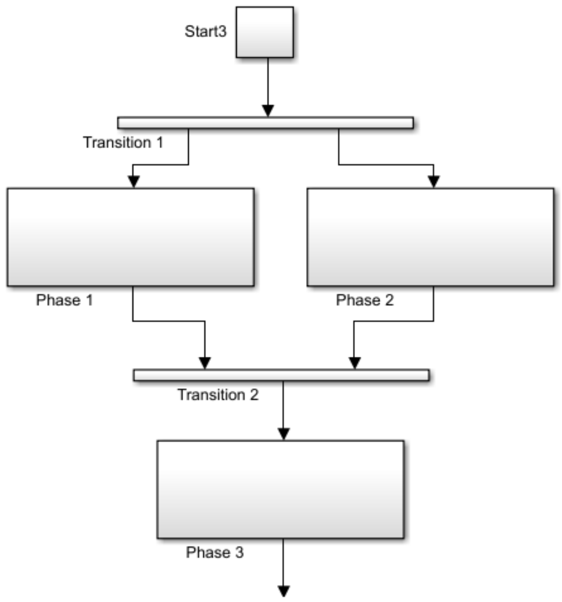
Phases define a specific objective and comprise a sequence of underlying tasks required to achieve the objective. Like the Phases, the underlying Tasks are performed in sequence, each separated by transitions, which are associated with logic conditions.

Phases can be processed in a sequence but can also be processed simultaneously in parallel, Alternatively, the transition can be set up as an EITHER/OR condition.

Sequential Operation



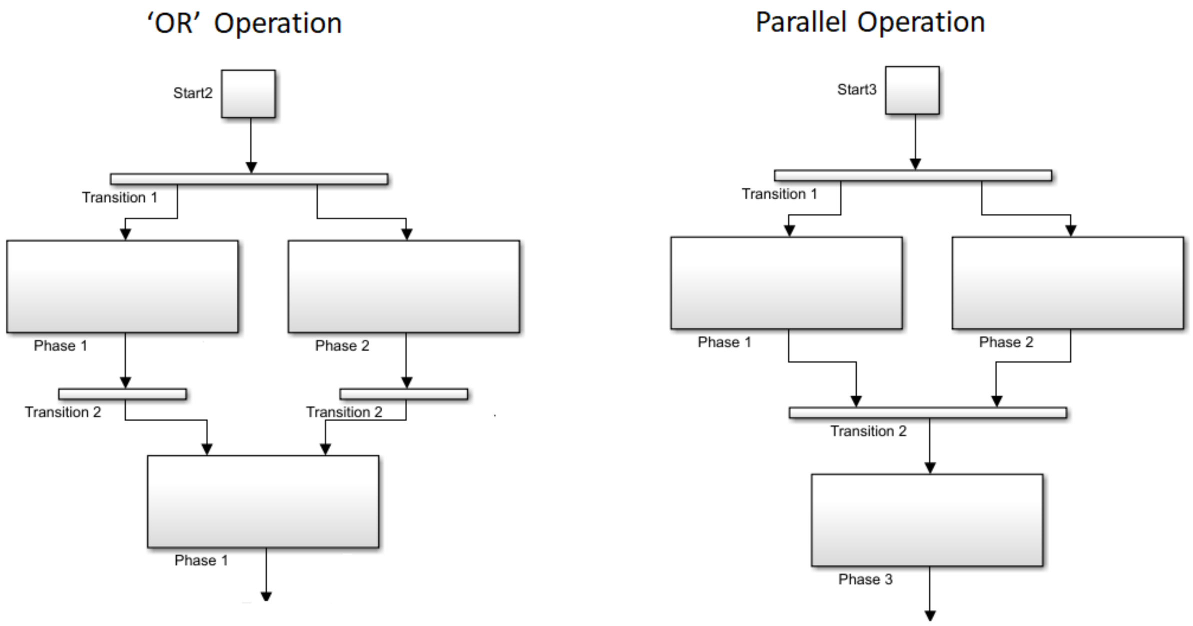
Parallel Operation



The tasks within a Phase can be manual operations such as opening a breaker via the SCADA system or calling a DER to execute dispatch. These can be carried out from the Control Room via the SCADA System or by telephone. Alternatively, a task can be an automated task carried out by the control system directly or via the SCADA network.

5.2.2 Transitions

Transitions provide discrete boundaries between Phases or between Tasks. The transition is a defined set of Logic conditions. The Logic conditions need to be fulfilled before the workflow can proceed to the next task or Phase.



Transitions can be manual, fully automatic, or either depending on the online assessment of risk.

If a transition is designated as manual, then human confirmation is required to proceed to the next phase or task.

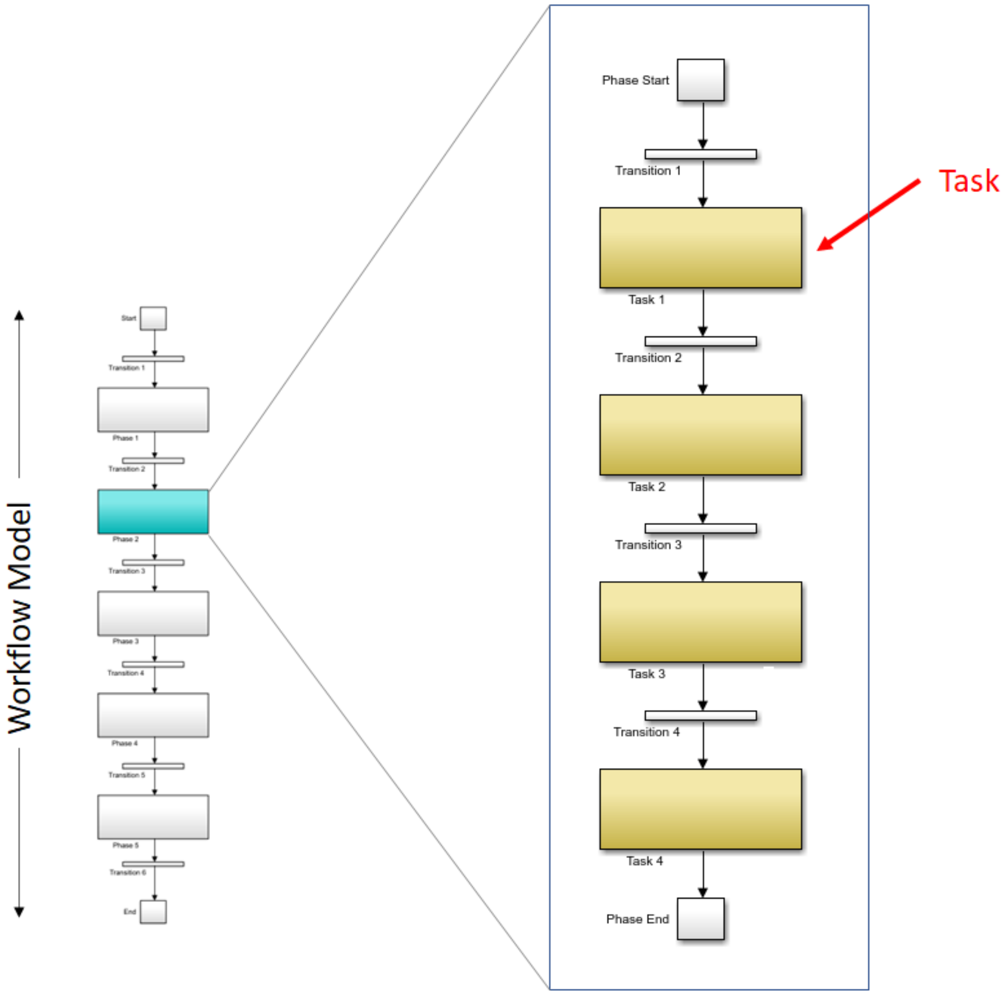
If a transition is designated as automatic then no human confirmation is required to proceed however the system can be configured to seek manual confirmation task if a block load is close to the capabilities of the microgrid to handle safely.

The Workflow Manager will perform steady state analysis and transient analysis on any proposed tasks in advance of executing the task and will determine how large the planned blockload is compared to the overall microgrid's blockload capability.

5.2.3 Tasks

Phases consist of a series of tasks. Tasks are specific actions performed within a Phase. A Phase can consist of one or more Tasks. Each Task is separated by a transition which is a set of Logic Conditions that must be fulfilled for the workflow to proceed to the next Task.

Note – Phases can operate in parallel as indicated in section 5.2.2 above. If branching is defined in a workflow then the phases of each branch are process sequentially in parallel.

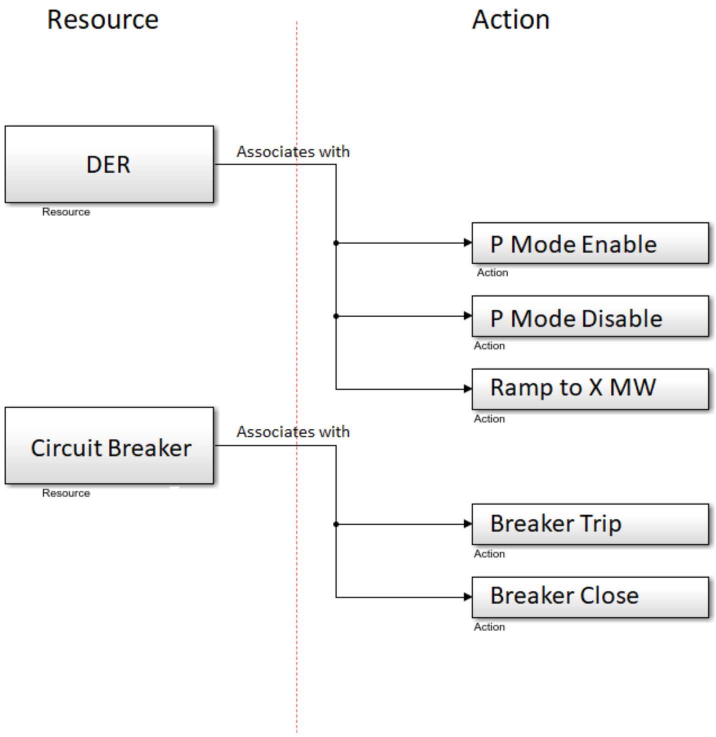


A Task is defined as one or more specific actions defined in a list known as the Action Dictionary. Actions are combined to operate on one or more resources to complete a Task.

5.2.4 Action Dictionary

The Action Dictionary is a list of defined actions that can be carried out on Resources in the workflow. Each Resource in the workflow has a defined set of associated Actions.

For example, a Circuit Breaker can be defined as a Resource and in the example below two Actions are-associated with this Resource, Circuit Breaker OPEN and Circuit Breaker CLOSE.



5.3 Automatic Generation of Workflow Models

Workflow models can be defined manually for each DRZ system. However, the Scheduler Module could be extended to generate the Workflow Models automatically for each DRZ in the future, based on agreed principles and rules defined in collaboration with the TSO and DSO. For long term support of the system, automation features such as this will be required to simplify system updates, reduce support time, and automate the validation of the Workflows

Based on defined rules the Scheduler would decide how a workflow model for a particular DRZ case should be structured. The scheduler would use standard tasks to build the workflow.

The Scheduler would group tasks into phases and order phases to optimise the DRZ workflow. Generally, the main sequences of phases will follow a standard template:

- Network Initiation
- Anchor Generator Start-up
- Multiple Growth Phases block loading to DERs and Substations

The order in which DERs are energised could be based on several different strategies optimising speed, reliability, number of customers restored etc.

The Scheduler interrogates the network model to establish what resources are available and their technical capabilities. The Scheduler loads the local network conditions such as the running arrangement, forecast demands, forecast generation and so on.

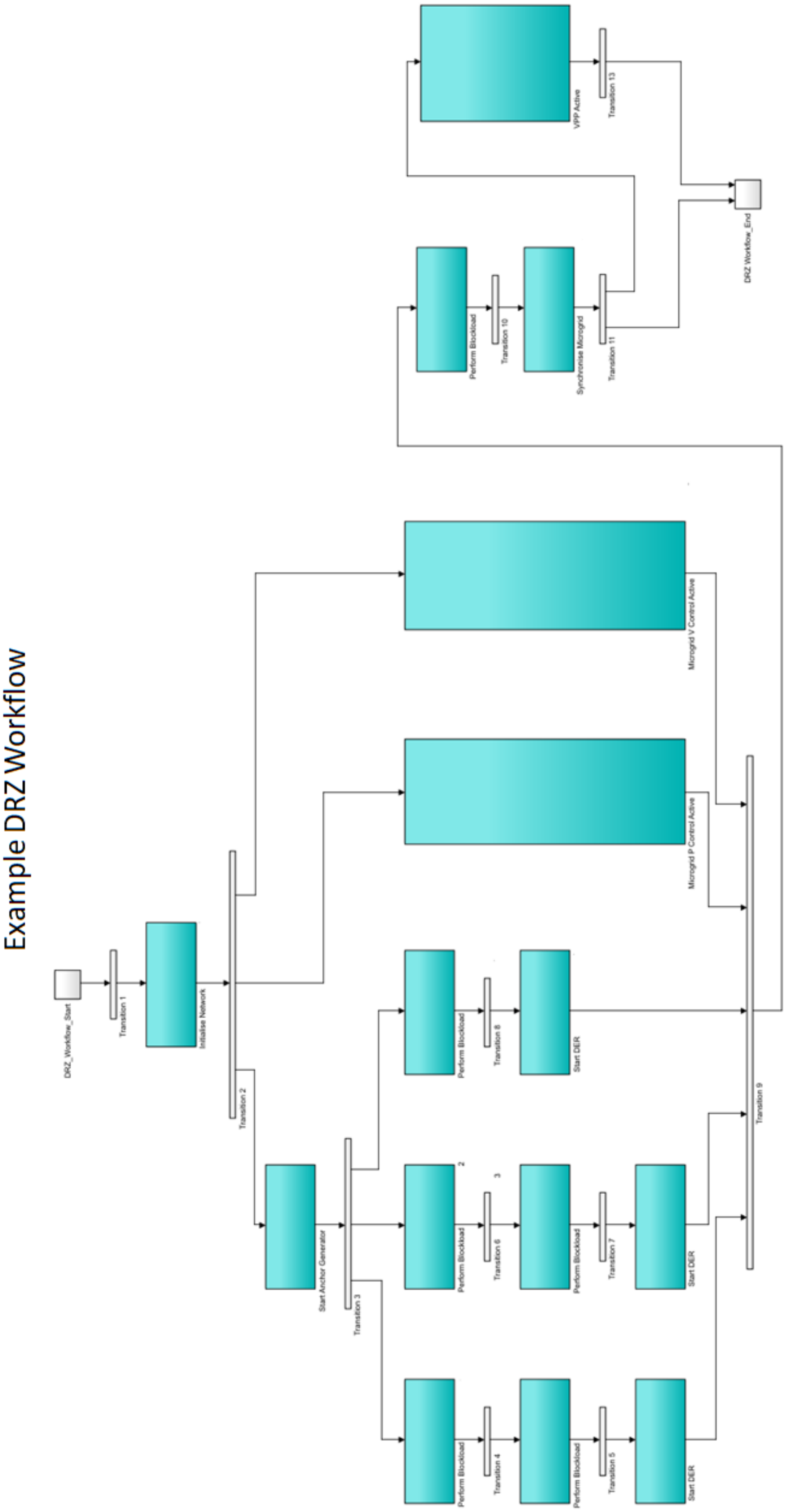
Based on the optimisation criteria, the Scheduler establishes a sequence of tasks combined into phases for sequential execution by the Sequencer to energise the DRZ.

The Scheduler validates the Workflow Model by simulating the execution for the current network and validating that it can be executed successfully without introducing any network instabilities.

The Scheduler publishes these Workflow Models for official review and validation. Once approved, the Workflow Models would be enabled for subsequent use by the Sequencer Module.

Initially all workflow models would be defined manually but once operational experience is developed sufficiently to define the principles and rules for the automatic generation of the sequences, the scheduler could be configured to generate them automatically.

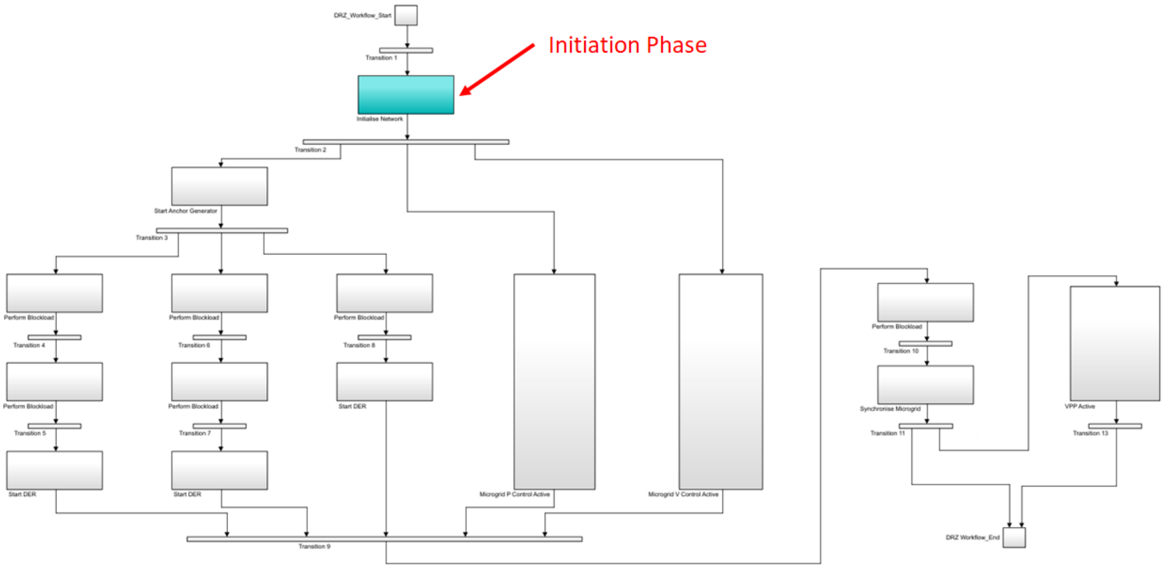
5.4 DRZ Workflow Example



The following sections outline the main phases involved in a DRZ Workflow.

5.4.1 Network Initialisation Phase

This phase ensures that communications is available to the required resources and that all other pre-conditions are met. It ensures that the Anchor Generator and Load bank are isolated from the rest of the Microgrid by switching network circuit breakers to the required configuration. This phase also sets protection setting groups as appropriate along with any tap changer positions.

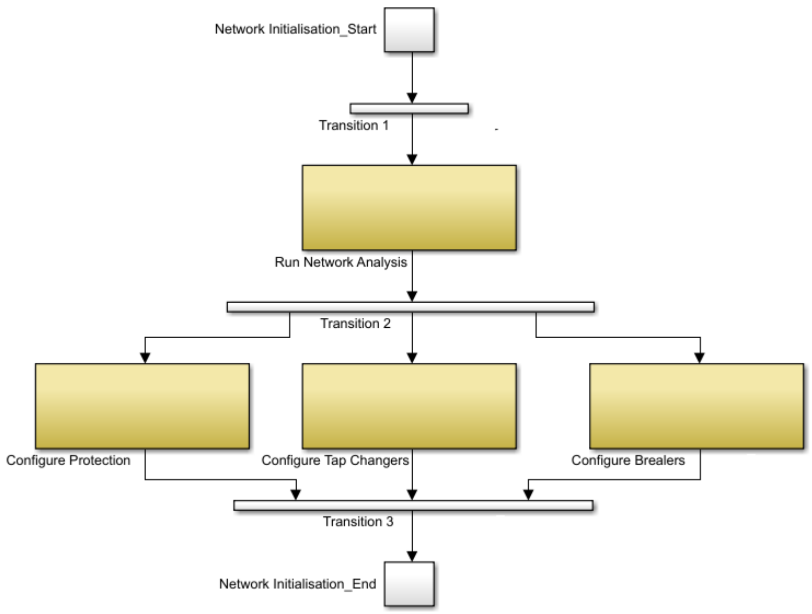


Once the phase is initiated all pre-conditions are checked. These might include:

- Anchor Generator Ready
- DRZ Subsystems Ready
- SCADA Data Available

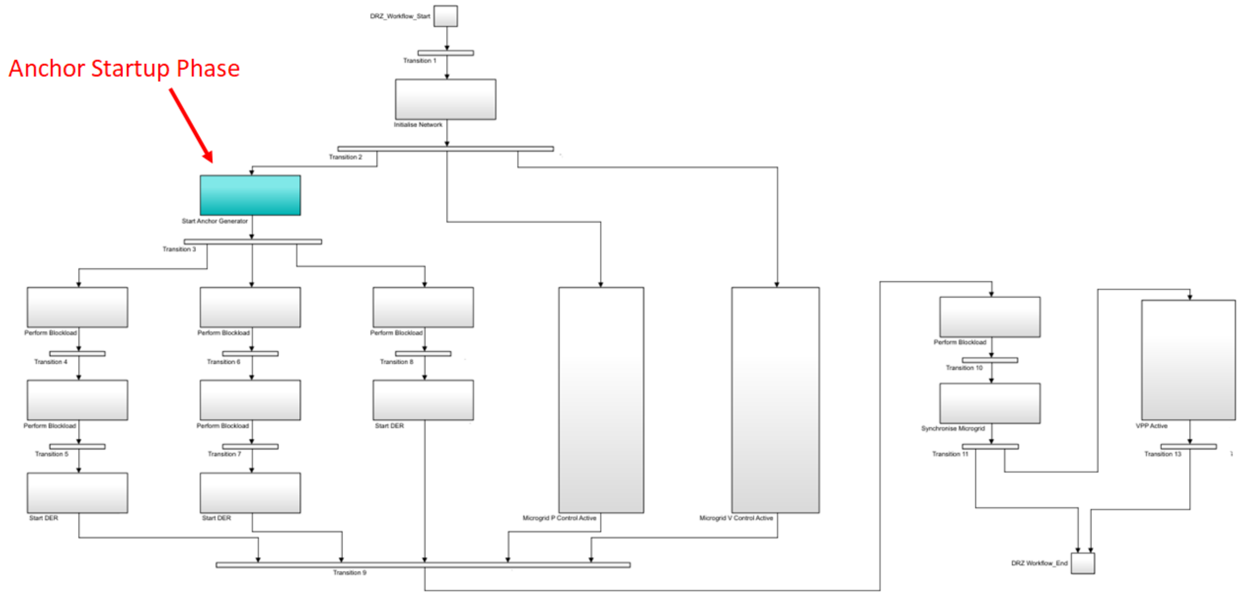
A Network Analysis is run to determine the initial conditions that need to be set for the various resources. For example, three tasks could be initiated that set the Protection Settings, Circuit Breaker positions and Tap Change Positions. Each of these processes could be manual or fully automated processes.

Microgrid Initialisation Phase



5.4.2 Start Anchor Generator

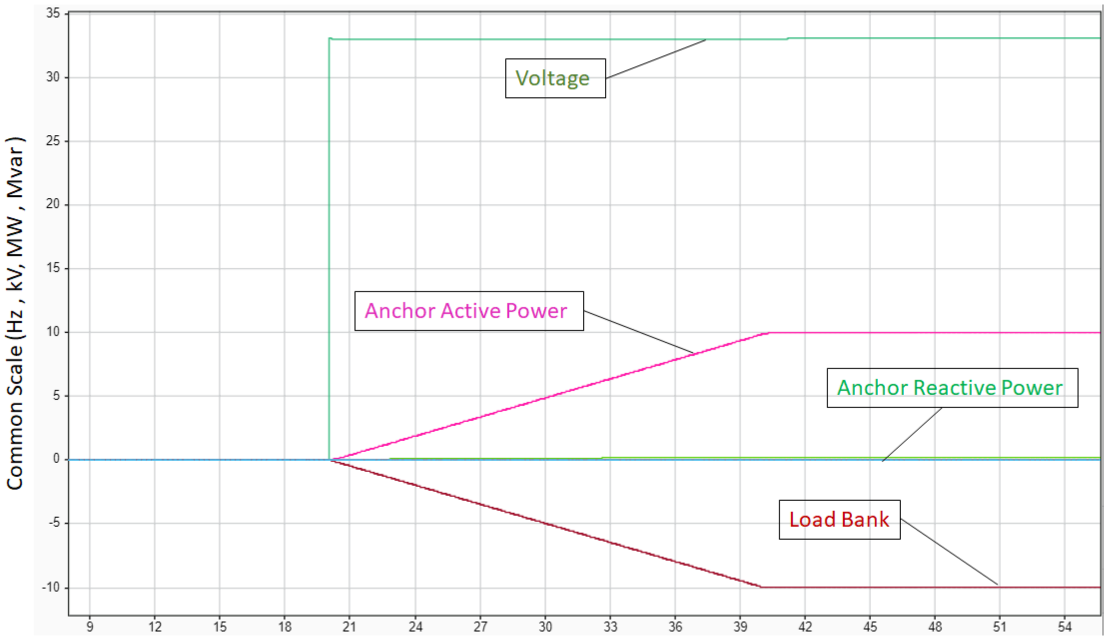
The objective of this phase is to achieve stability of the Anchor Generator by incrementally loading the Anchor Generator using flexible demand such as a load bank.



The Anchor Generator may require a load bank to start against. In this case, the load bank is ramped/stepped until the anchor generator output is at a level that will allow it to energise additional load blocks that in turn allow other supporting DERs to be energised.

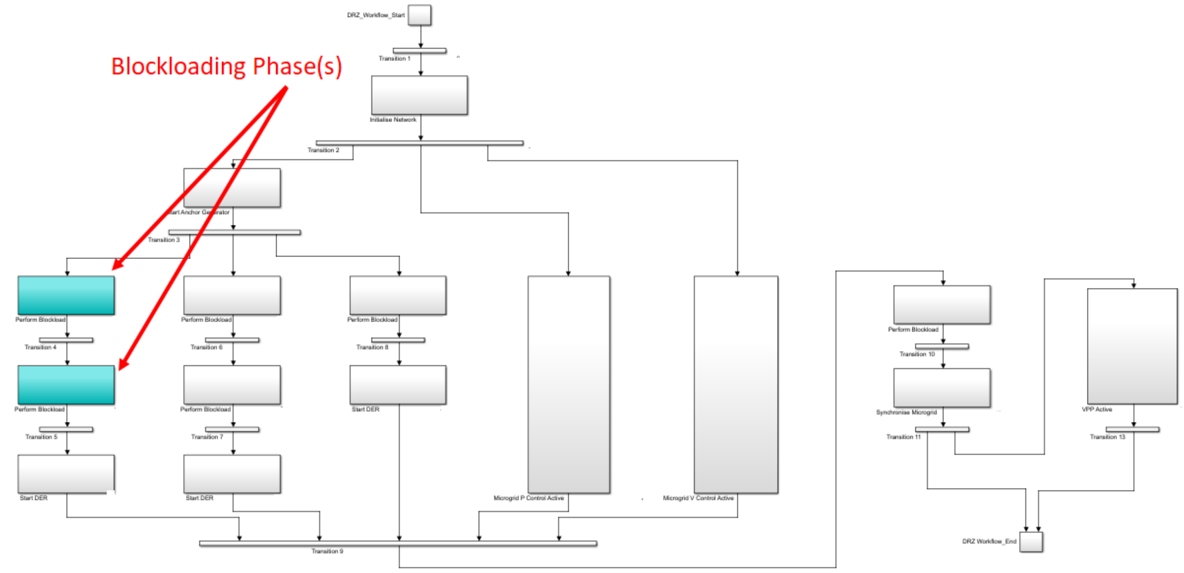
This is a controlled process where the load bank is ramped at a rate that can be followed without adverse effect by the Anchor Generator.

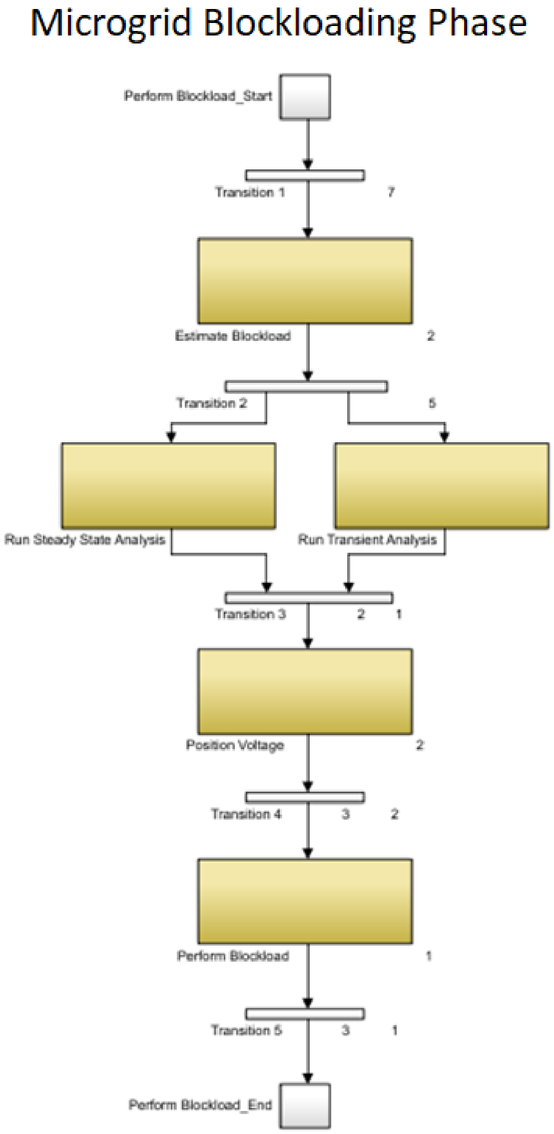
Preconditions are that the Anchor Generator and Load Bank are ready. A Network Analysis is run to determine the Anchor Generator initial operating position, the maximum safe load increment or ramp rate depending on the type of Load bank. Once the Load bank is initiated the Anchor Generator is started and loaded incrementally until the desired Anchor Active Power Output is achieved. An example of Anchor Start-up phase is shown below: -



5.4.3 Network Energisation (Block Loading)

To create an energisation path from the Anchor Generator to any available supporting DERs, sections of the network must first be energised. Control System treats the network energisation (without adding demand) and block loading in the same way where the demand or network sections are energised incrementally. Both are considered as block loading for the purposes of the Control System. Creating an energisation path is a sequence of 1 or more block loading phases. The expected energisation 'blockload' is calculated using the load flow analysis of the network analysis engine.





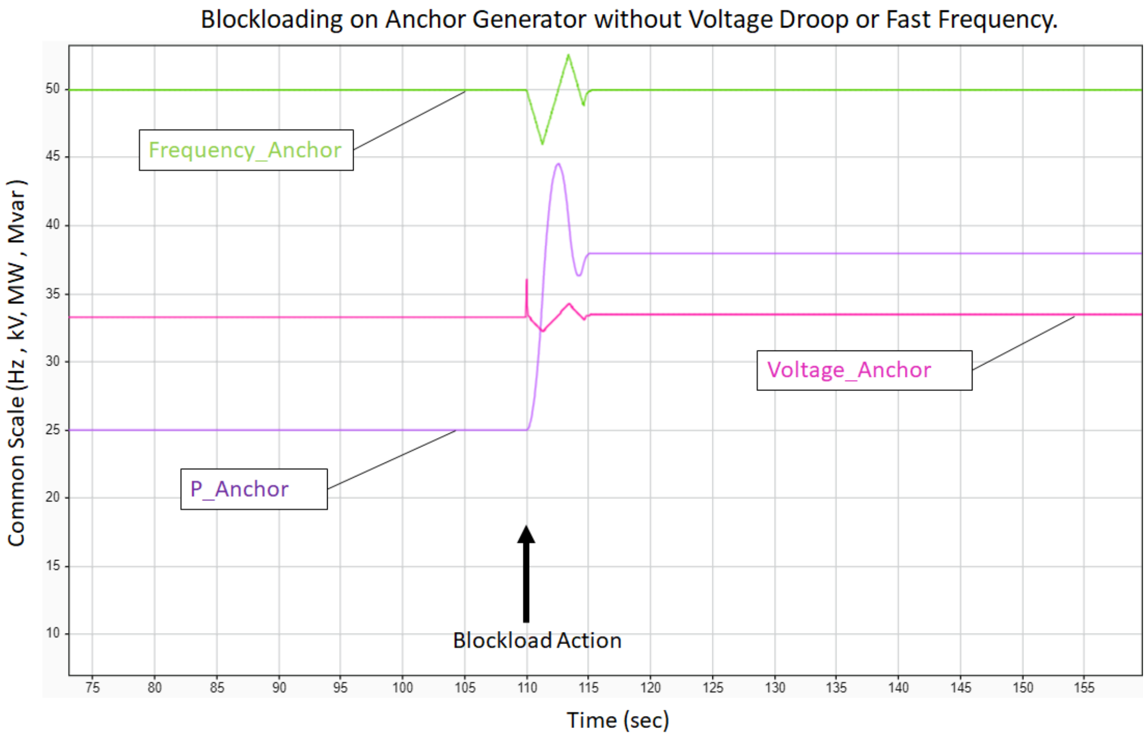
Firstly, before the block load is switched, the size of the block load must be estimated. This is done using a prediction from the Predictor Module to determine the expected magnitude of the demand under normal conditions which is then modified using an algorithm to incorporate the effect of cold-loading (transformer energisation) and load diversification (based on time since disconnection). The resulting calculated block load is then analysed using the steady state and transient analysis engines to determine if the operation will breach acceptable limits. If so, the operation is prevented.

The transient analysis engine models any available synchro-switch dispatchable loads within the model. If synchro-switch loads are not available, then they are not included in the model. If the analysis determines that the system blockload capability is too low, it can re-evaluate the process including any available synchro-switching. If the synchro-switching is required, then the synchro-switch task is armed and used in the blockload phase.

If the analysis determines that the block load is possible without breaching acceptable limits it will identify any necessary voltage adjustments to the DERs/Busbars to be implemented prior to block loading.

Finally, once the voltages are correctly set, the block load is switched in.

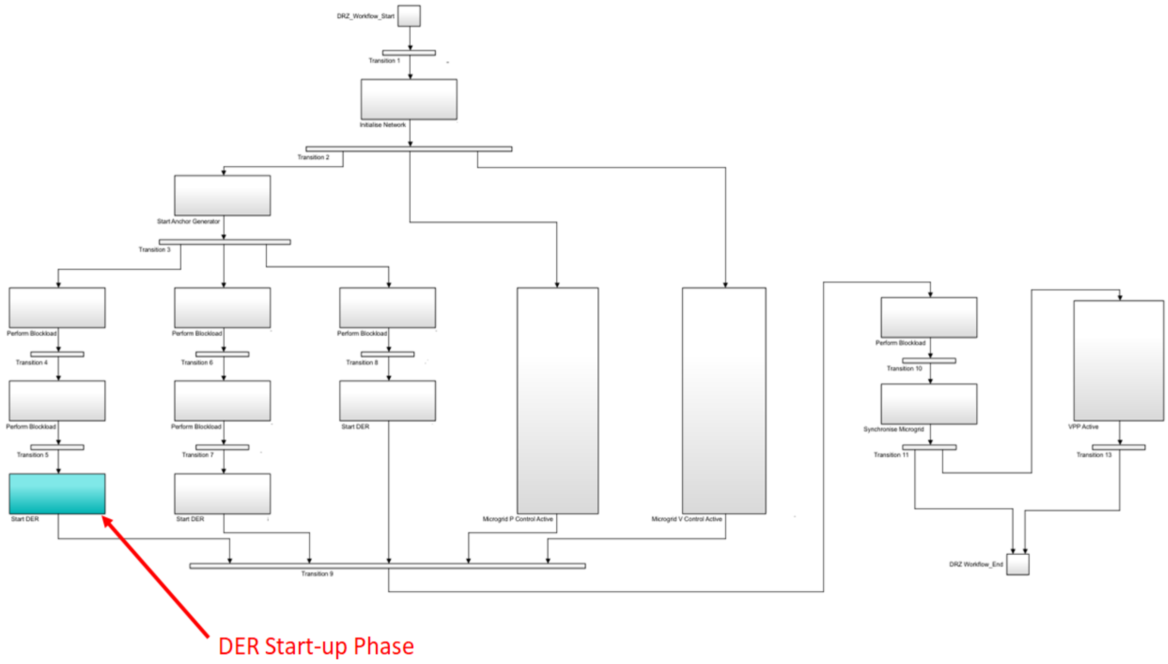
An example of block loading is shown below.



The demand in the microgrid is energised in blocks. This results in a step response to the power output at the generator and a transient response in voltage and frequency that must remain within pre-defined limits.

5.4.4 DER Start-up

Once the energisation path between the live network and a particular DER is complete, that DER can be started and used to support the Anchor Generator in stabilising the Microgrid.



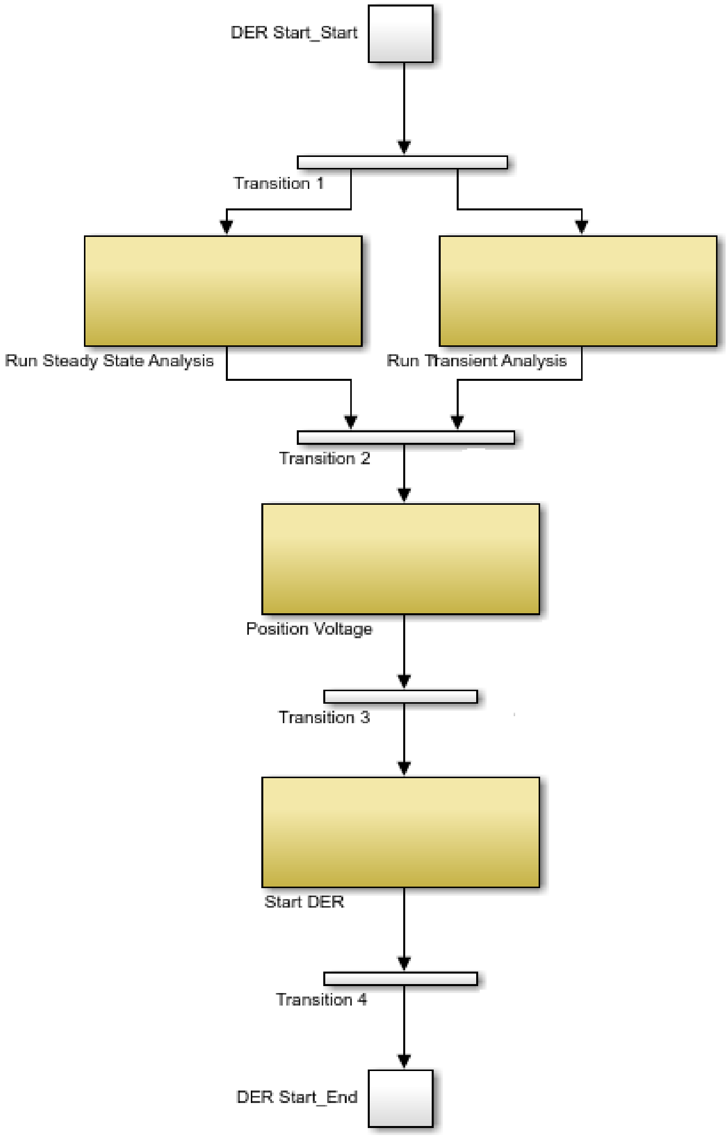
DER Start-up Phase

A steady state analysis and transient analysis is carried out to determine the appropriate operating level of the DER so that the Anchor Generator is operating in an optimum position.

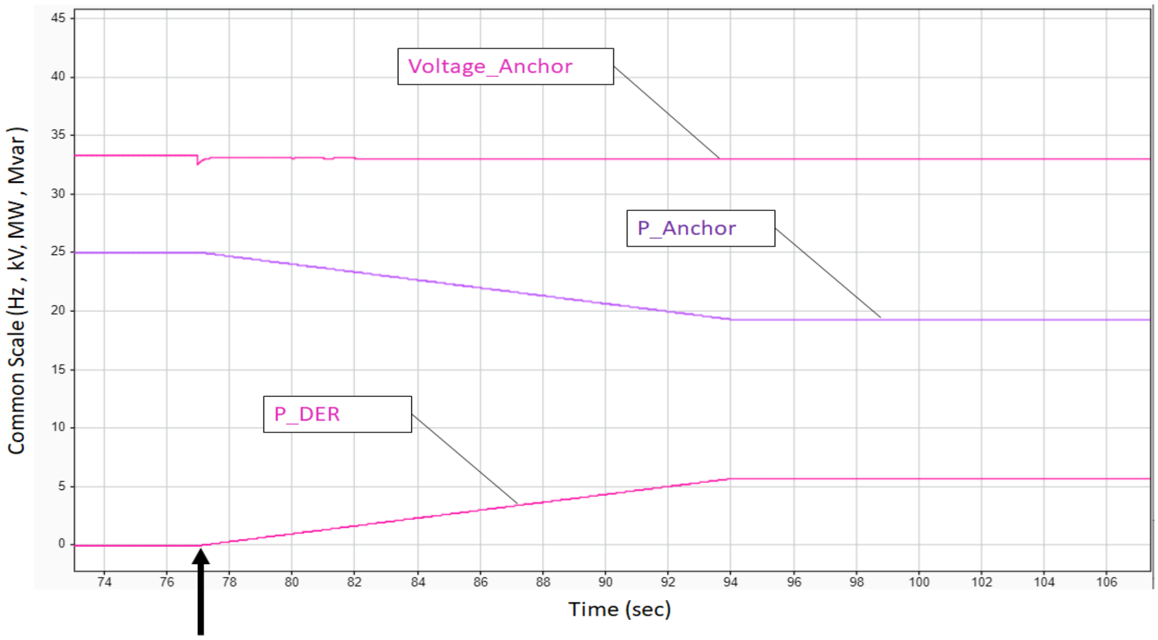
The steady state and transient analysis is determined using a standard loadflow analysis using a model of the network and the breaker states, and available realtime SCADA voltages and powerflows.

Further analysis allows the effect on the voltages to be calculated and mitigated if necessary, using the Voltage Control Function of the Microgrid Controller. Once the Voltages are optimised for DER start-up, the start-up phase is initiated.

Microgrid Start DER Phase

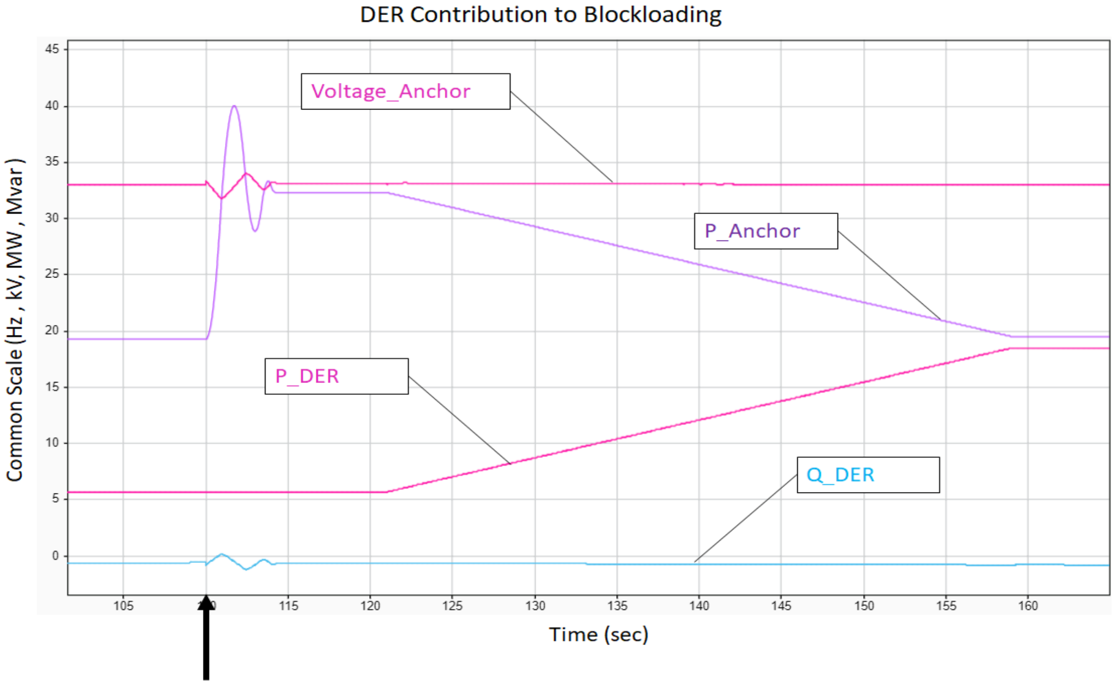


An example of the sequence is shown below where a voltage setpoint adjustment is made, and the DER active power setpoint ramped up causing the Anchor Active Power to ramp down in response.



Voltage Setpoint Change
Anchor Gen Setpoint Change

This process continues as additional Block loads are added to energise further DERs. Subsequent block loading is aided by the fact that active DERs can provide voltage support through voltage droop response. This is factored into the Network Steady State Analysis as seen below. As the block load is added the Anchor Generator responds and the Microgrid P_Controller maintains an optimum Anchor Generator P Output by transferring the load to the DER.

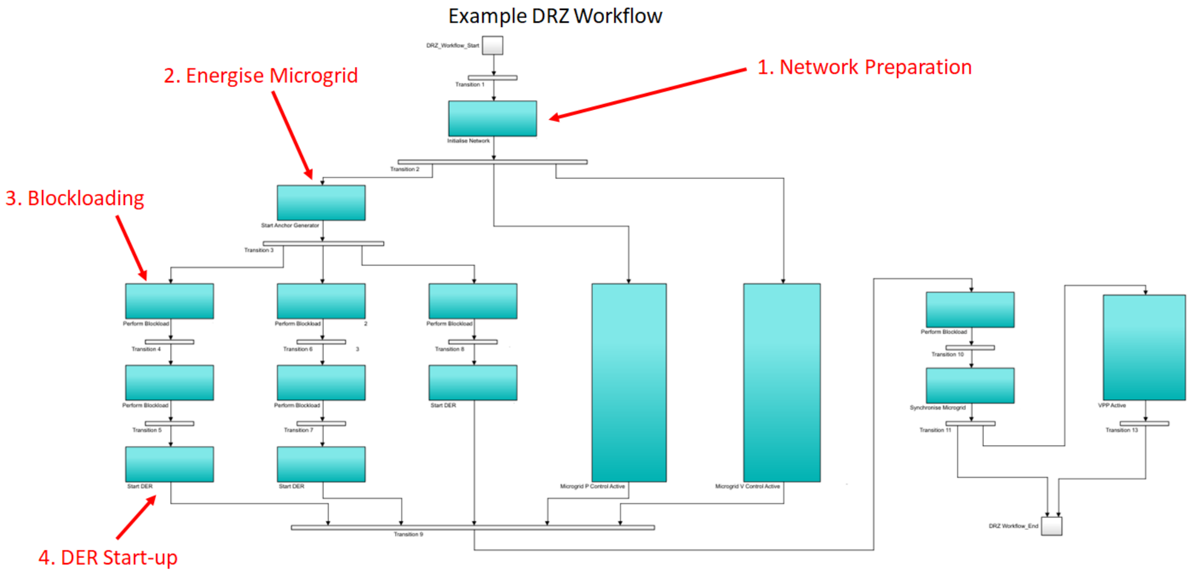


Blockload Action

5.4.5 Automation and Human Intervention

It is expected that some tasks will require human intervention and some tasks can be fully automated. The system is designed to allow a mixture of manual and automated tasks in the same workflow.

The DRZ Controller uses a workflow based on standard phases as and shown below.



The following sections outline where manual intervention may be required.

5.4.5.1 Network Preparation

There will need to be coordination of the protection and safety functions. In order to set the microgrid correctly for DRZ Control, the protection settings will have to be altered. Although this can be fully automated in time, its expected that there may be some operator intervention at this stage to change protection settings and confirm system readiness for DRZ.

In addition, the earthing arrangements will need to be re-configured. These switches and some isolators may not be motorised and therefore will have to be configured manually.

These are fundamental to the protection and safety of the network and personnel so should be under operator supervision. For important functions like this its proposed that they would be initiated manually and ideally would have some form of SCADA feedback to confirm the process steps are complete.

5.4.5.2 Energise Microgrid

a. Start Microgrid Controller

This step will need co-ordination with the various stakeholders (TSO/DSO etc.) so its expected that this step would be controlled manually once all pre-conditions are met during the previous step – network preparation.

b. Start Anchor Generator

Aspects of the Microgrid which are likely to not be automated are relating to control of the Anchor Generator as it may not feature in the regular ANM Control functions. In order to control the microgrid most effectively, the Anchor Generator setpoint dispatch will have to be automated. However, starting up the anchor generator will most likely be a manual process initially that requires contacting the operator of the Anchor Generator.

5.4.5.3 Blockloading

Generally, circuit breakers are manually operated. However, in order to minimise workload on the Control Room, de-skill the DRZ process and speed up the restoration time, the blockload energisation phases can be fully automated. The breaker operation can be automated fairly readily though the SCADA/DMS System with all breaker states fully monitored. The BLRF interlocking will inhibit any unsafe switching operations. This blockloading can then be can be configured as fully automatic of manual.

If there are situations where the automatic Blockloading sequence cannot be executed automatically then the Control Room would need to intervene in manual mode.

5.4.5.4 DER Start-up

DERs that are connected to the SCADA/DMS and ANM Systems can be automated as there is a control path and monitoring already provisioned. ANM systems use these DERs in a fully automated way so its sensible to continue to do this.

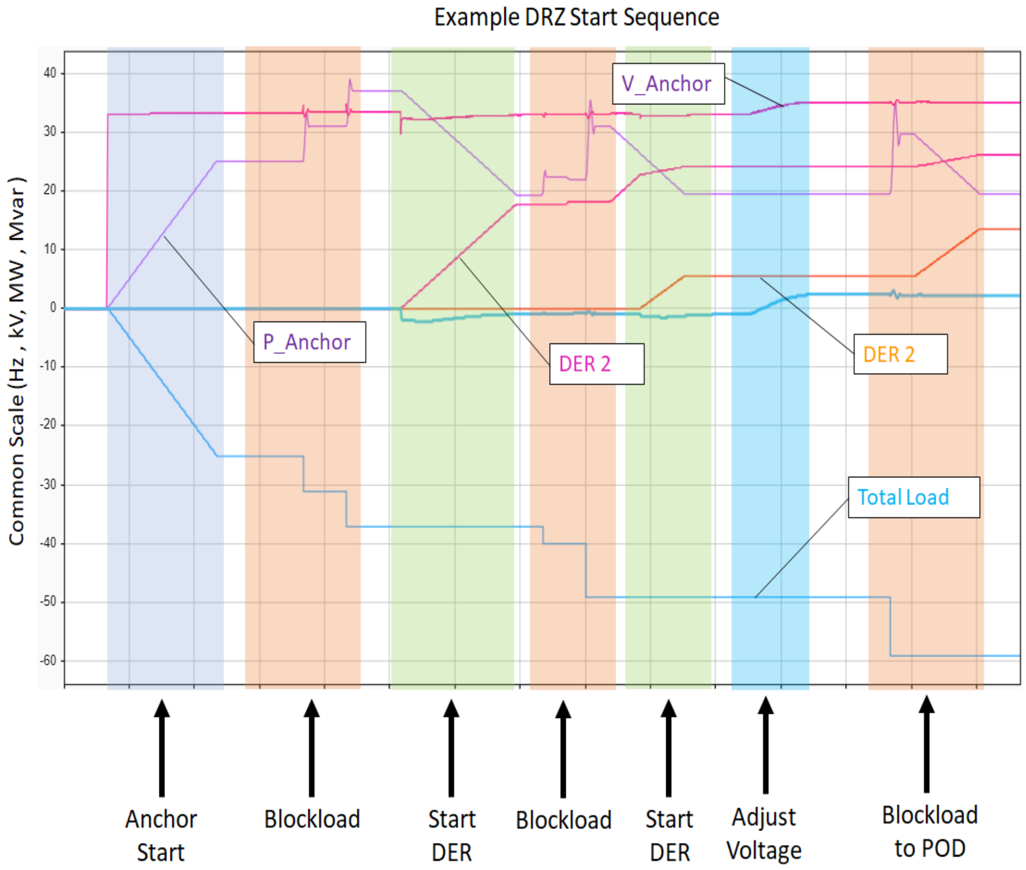
5.4.5.5 Virtual Power Plant (VPP) Operation :

Although it is expected that the process of synchronising the Anchor Generator with the transmission grid can be automated, initiating the VPP functionality will need co-ordination with the Transmission System Operator so arming and starting the VPP function and closing in the SGT breakers are likely to involve operator intervention.

5.5 DRZ (Generic) Workflow Model Example

In this example the microgrid consists of the following

- 1 Anchor Generator
- 1 Load bank (Continuous)
- 2 Asynchronous DERs providing Voltage Droop Support



In the sequence shown, once the Anchor Generator is energised, the energisation path to the first DER is block loaded. This block loading occurs without any droop support from the DERs. The first support DER is started. This DER output is used to reposition the Anchor Generator output to optimise its headroom and foot room.

Once the first DER is in operation, the energisation path to the second DER is block loaded. This block loading is supported by the droop response from the DER already in operation. Block loading and connection of any further DERs continues until the island has been energised to the point of Connection of the microgrid (i.e. the interface with the TSO or another island)

At this point the microgrid can be synchronised and re-connected to the wider grid or neighbouring island to build a larger island.

Once the microgrid re-connects to the transmission grid the Virtual Power Plant function can be initiated and the Microgrid modelled in real time as a single VPP capable of providing Active and Reactive Power Services to the transmission grid to further aid the restoration process.

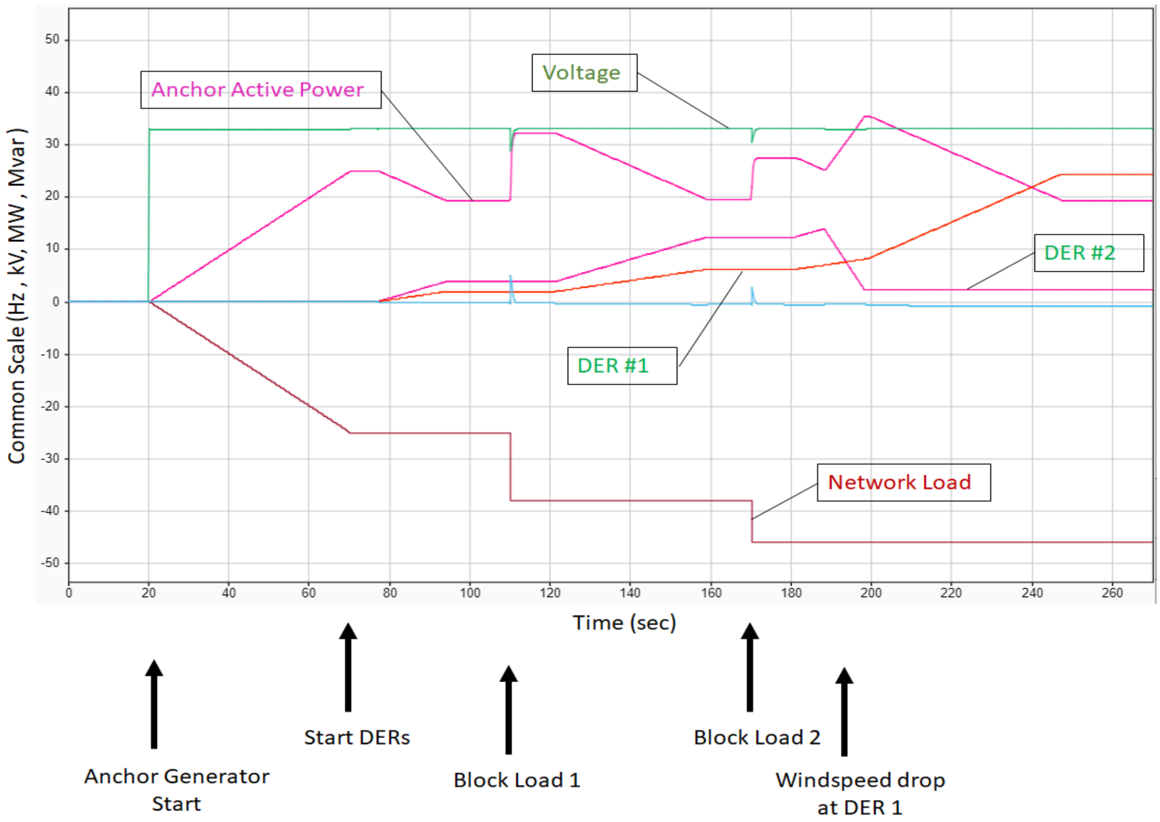
6 Microgrid Controller Module

6.1 Main Functionality

The Microgrid Controller actively manages the network in response to changing network conditions (e.g. drop/increase in generation/demand) or unplanned / unforeseen events (e.g. breaker trip). It maintains the network voltages and frequency within the network operating limits and all network assets within their safe operating range (frequency, voltage, MW and MVAr) as the power island is expanded.

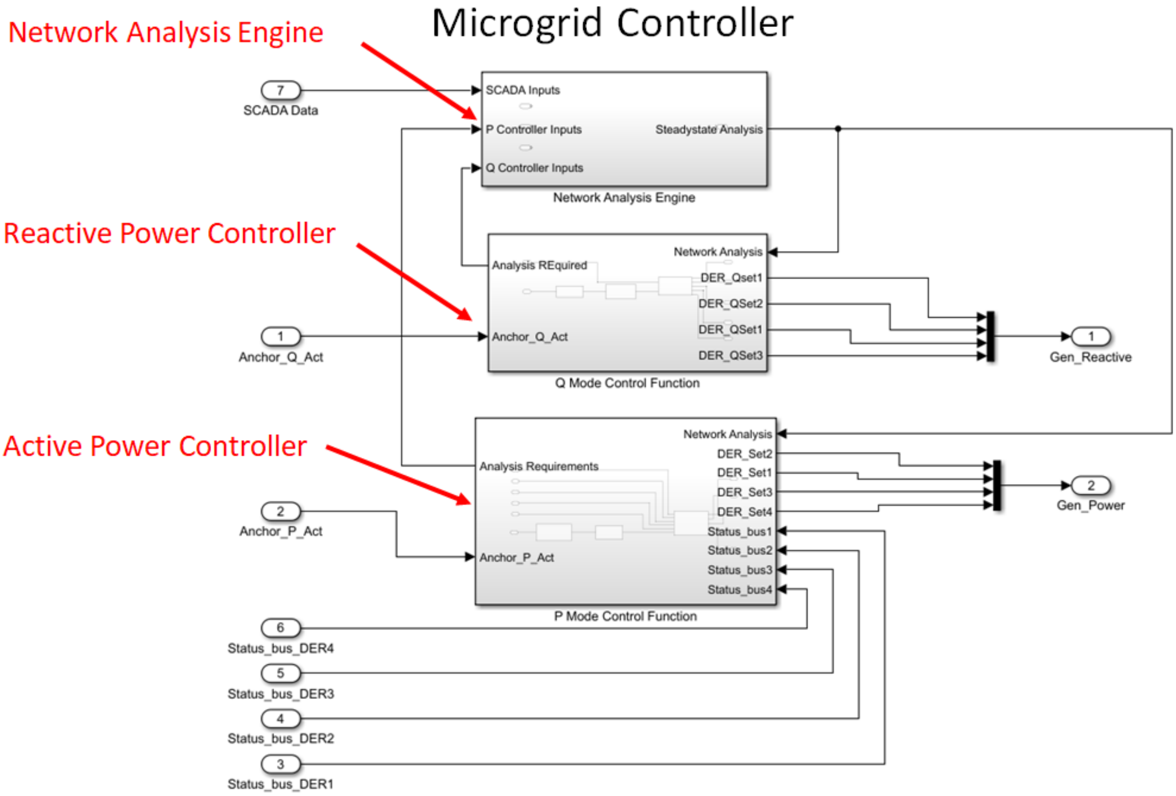
As a microgrid grows the Anchor Generator may require support from available DERs to meet the reactive power requirements. Generally DERs providing ANM services have either dispatchable or self-dispatching reactive power capabilities which can be used, if required, to manage system voltages.

Following is a diagram showing a hypothetical start-up sequence with the Microgrid Controller ramping up newly connected DERs to ensure that the Anchor Generator has enough headroom to respond to network loading when required. It also shows the system responding to a drop in Windspeed at DER #2 and how the Anchor Generator initially responds until the Microgrid Controller compensates by increasing the output of DER #1 to ensure that the anchor generator has adequate headroom and footroom.



6.2 Microgrid Controller Main Components

The objective of the Microgrid Controller is to maintain grid stability and maintain the voltage and frequency within regulatory limits. Therefore, the Anchor Generator voltage and frequency must be controlled such that these limits are not breached during steady state or transient conditions and ensure that the Active and Reactive Power Output remain within the acceptable operating range for the Generator. It will manage other DERs to ensure sufficient headroom is available on the Anchor Generator to react to any significant demand changes on the network.

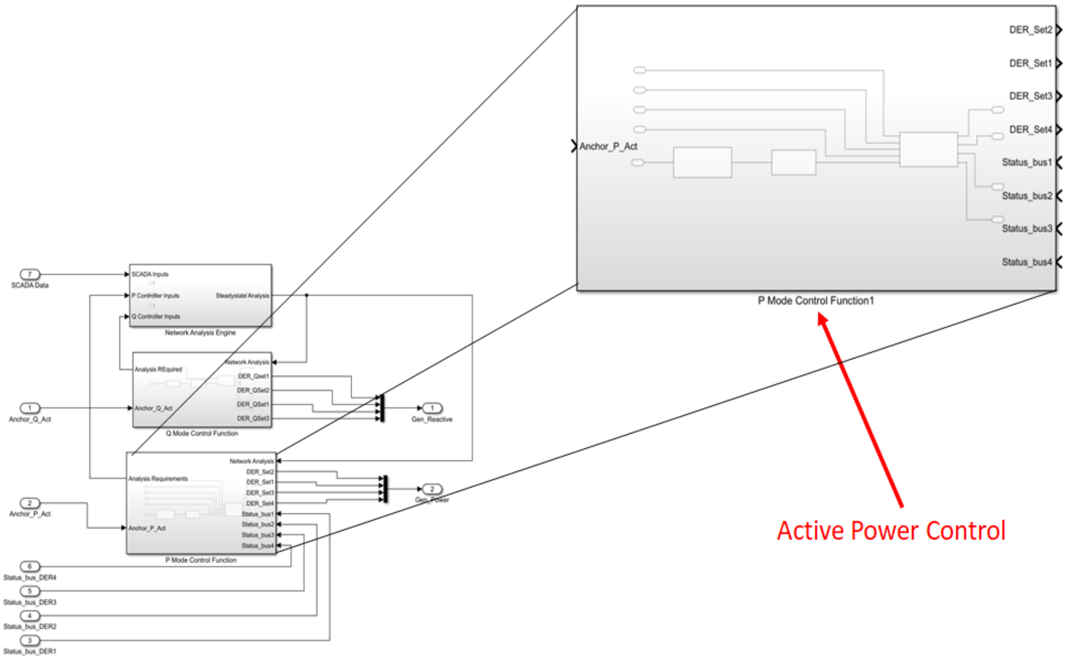


The microgrid controller consists of three main components:

- Active Power Control
- Reactive Power & Voltage Control
- Network Analysis Engine

The Active Power and Reactive Power Controllers run in parallel managing the system active power and reactive power. Although they act independently their actions affect one another and this is factored into the operation of the controllers. Both components use the underlying Network Analysis Engine as part of their calculations and to validate their results.

6.2.1 Active Power Control



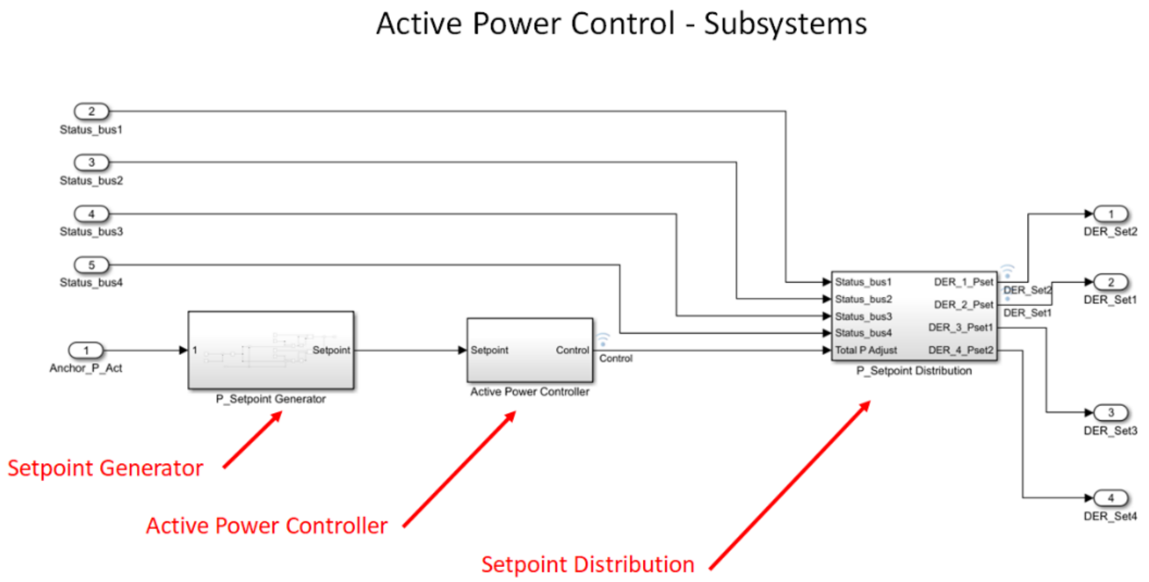
In general, the Active Power Control monitors the real time output of the Anchor Generator and compares this to a desired reference which would maintain sufficient headroom for the Anchor Generator to react to any sudden changes in demand on the network.

To ensure that the Anchor Generator active power output is maintained at the desired operating point, adjustments may be made to other controllable DERs connected to the Anchor Generator, such as: -

- DER Active Power Setpoint
- Load Bank Setpoint
- Load Shedding

The Active Power Controller comprises the following sub-components: -

- Setpoint Generator
- Active Power Controller
- P_Setpoint Distribution



The sub-module, Active Power Setpoint Distribution, is responsible for distributing the required Active Power changes among the various DERs. This allocation can be based on different Principles of Access, e.g. pro-rata, speed of response, technical best, proximity.

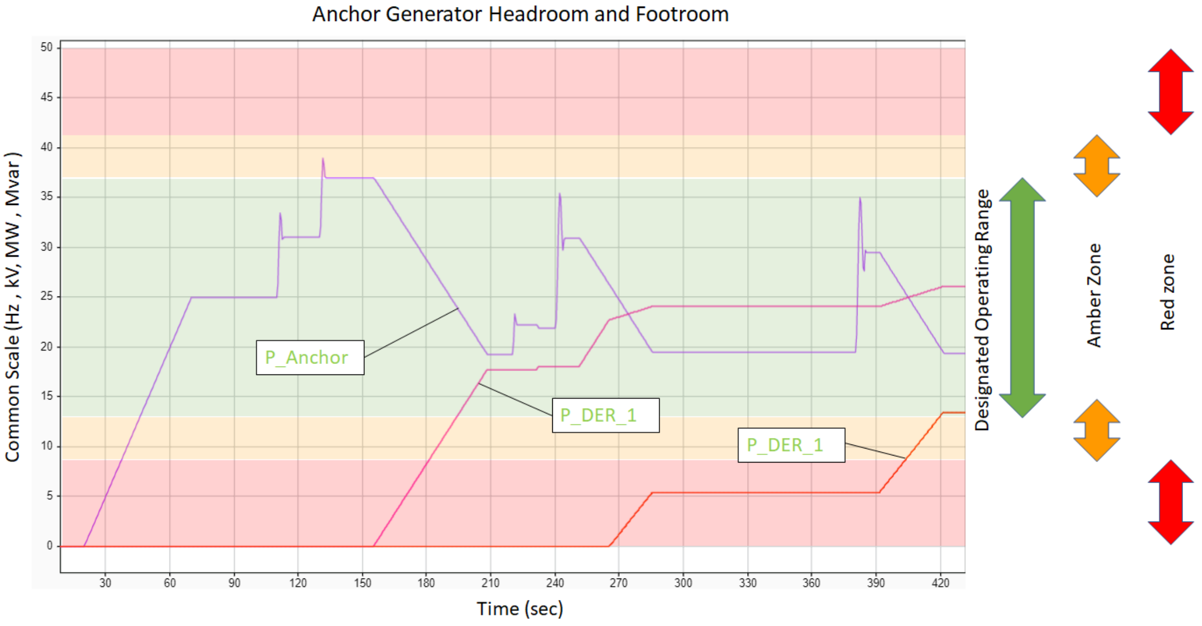
The following technical data is required to determine the Active Power Setpoint allocation across the various DERs.

- DER Total active power setpoint
- DER technical characteristics
- DER Actual real time data
    - Mode Status
    - Real time Actual P, Q, V
    - Active Power Headroom
    - Alarms and Status
- DER Forecast data
    - Forecast P, Q

Note: a forecasting function has been included in the design which predicts the expected demand and DER generation based on various inputs including calendric and weather conditions. Based on this data the system can provide a forecast of the available active and reactive power services of each DER.

The module determines the new setpoints for the various DERs. It also ensures that the overall change in DER setpoints and hence the anchor generator active power output, does not exceed the technical capabilities of the system.

It tries to maintain sufficient headroom for the Anchor Generator to react to any sudden changes in demand on the network.

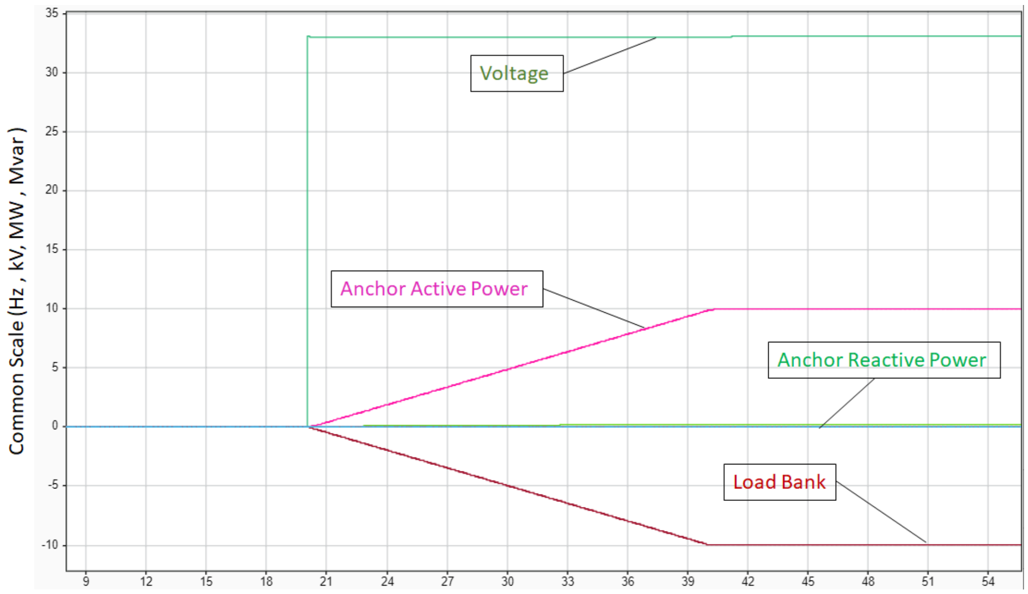


6.2.2 Active Power Responses

This section demonstrates various scenarios of Active Power response that may be experienced by the DRZ system. In all cases the Anchor Generator or self-dispatching DERs will provide the initial response to changing demand and the Active Power Controller will then adjust the DERs to ensure that the Anchor Generator active power output is maintained at the desired operating point with sufficient headroom to react to any sudden changes in demand on the network.

Note: DERs can be dispatched or have a self-dispatching capability. For example, in Q Mode a DER can be sent a direct reactive power setpoint by the DRZ Controller or in Voltage Mode the DER self-dispatches reactive power based on the connection voltage. Self-dispatching functions operate locally and rapidly. Because they are independent of the communication speed to the DRZ Controller they generally operate more quickly than dispatched services. The topic is covered in more detail in Report 3.

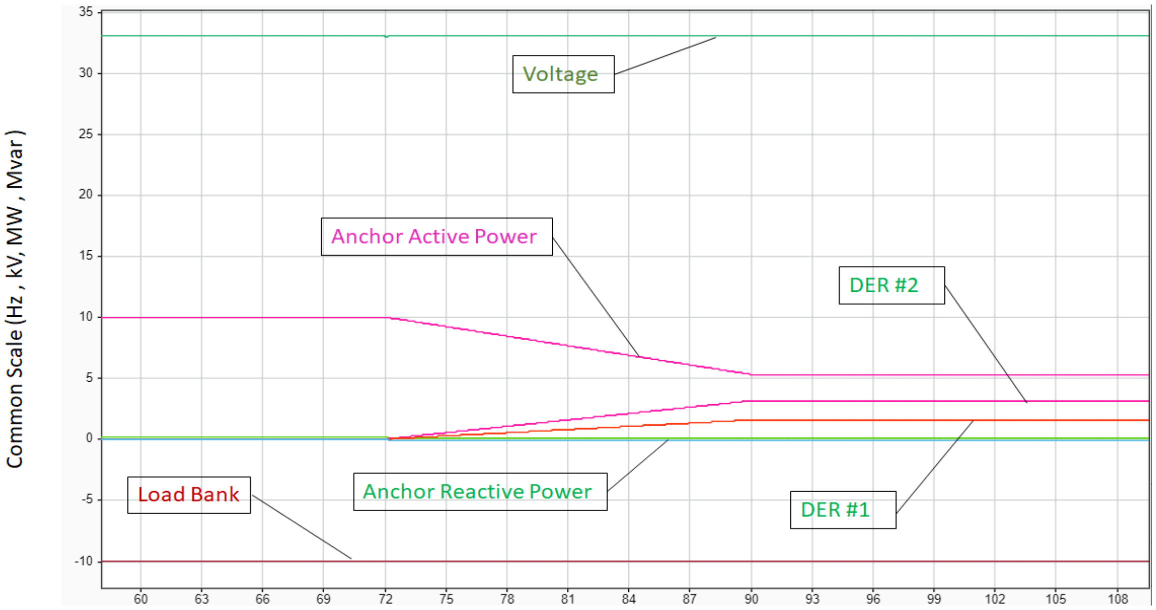
Anchor starts against a Load bank



The Anchor Generator requires a load bank to start against. In this scenario the load bank is a variable load bank that is ramped until the anchor generator output is at a level that will allow it to energise additional load blocks which in turn energise support DERs. In this case, the Active Power Controller has no DERs to control to support the Anchor Generator, so the Anchor Generator is simply reacting to the increase in ramping load.

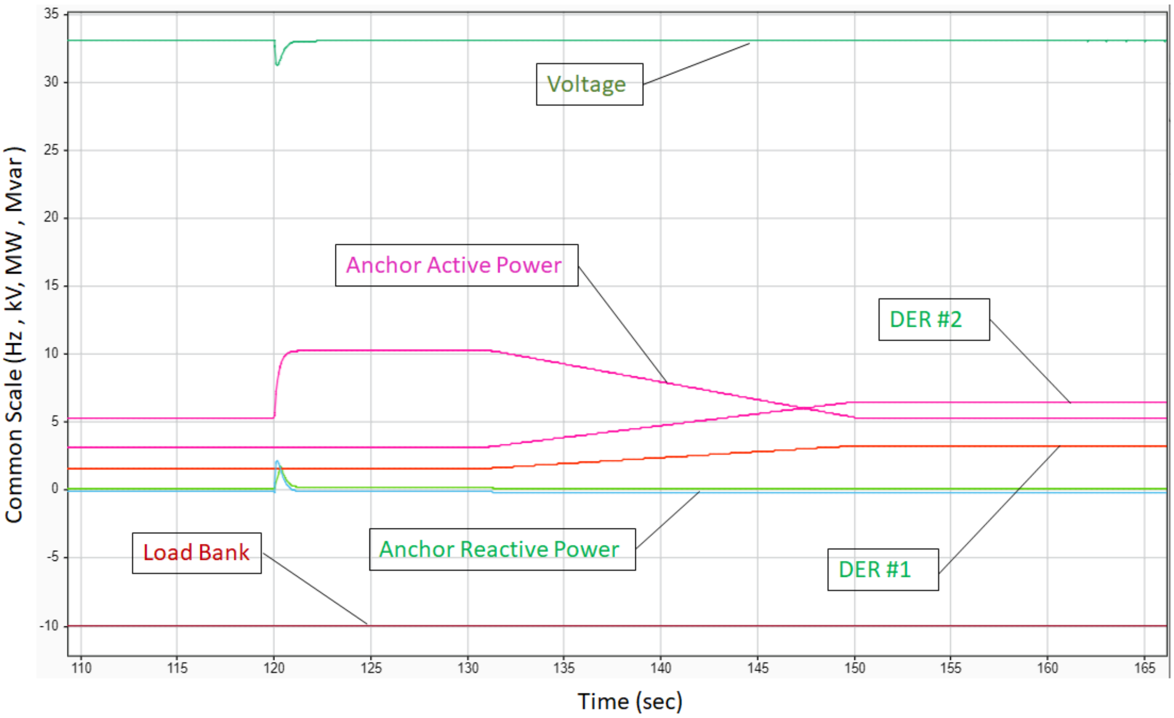
This is a controlled process where the load bank load is ramped at a rate that can be followed without adverse effect on the Anchor Generator.

Movement of Anchor P Operating Point / Starting DERs



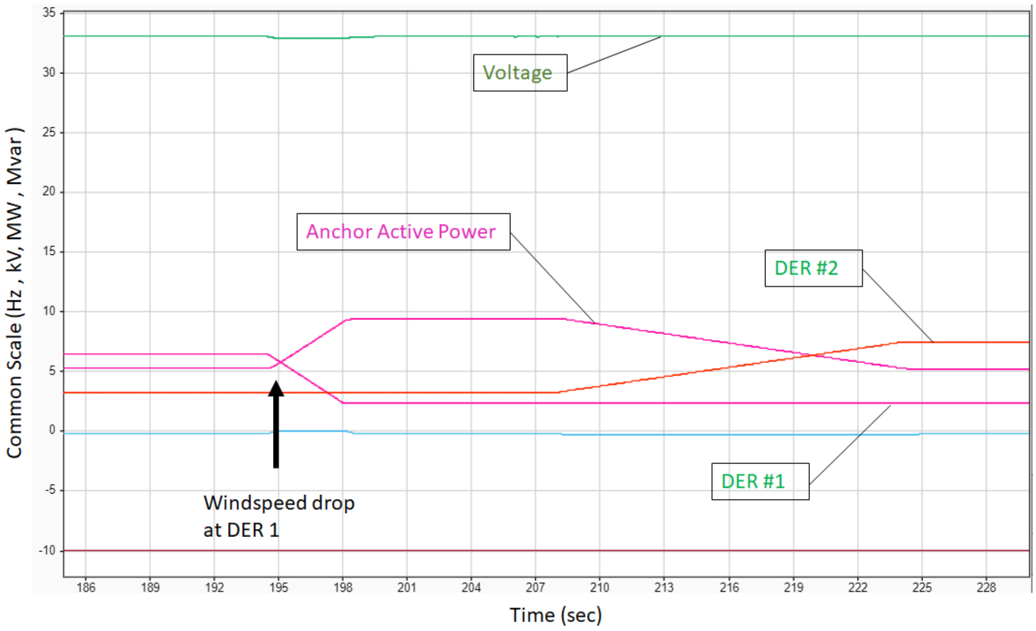
To move the operating point of Anchor Generator, the DERs that are energised and available, are ramped up or down at a rate that can be followed by the Anchor Generator. This is done to position the Anchor Generator operating point such that there is sufficient generating headroom or footroom to react to changes in network.

Energising a Load Block



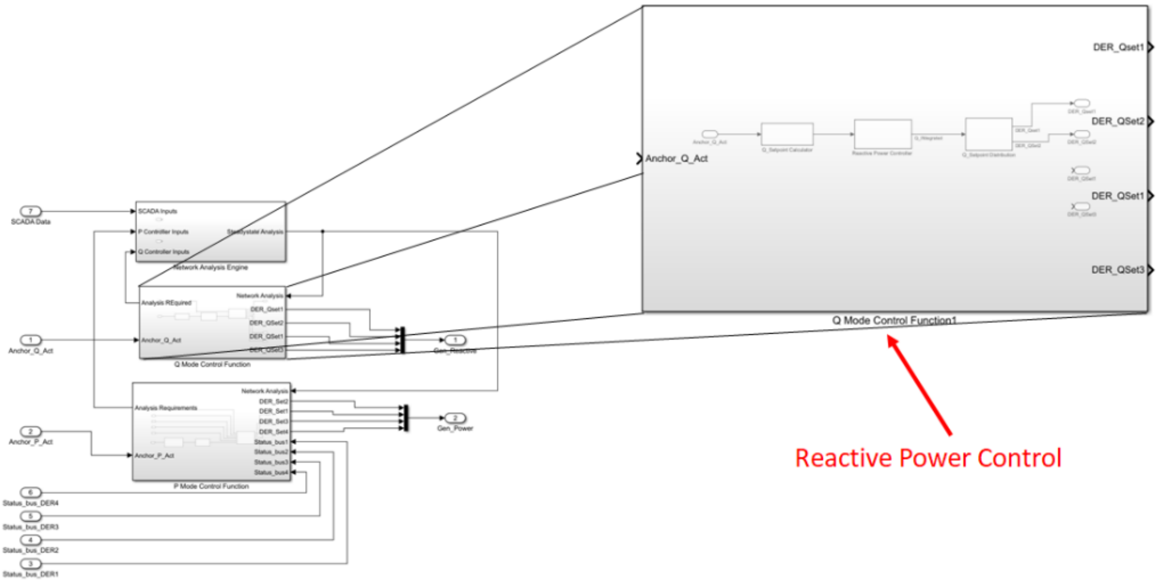
The demand in the microgrid is energised in blocks. This results in a step response to the power output at the generator and a transient response in voltage and frequency that must remain within pre-defined limits.

Drop in Wind Speed/Irradiation



This scenario shows the system reacting to a drop in windspeed/irradiation which results in a drop in output to DER #1. The resultant increase in the Anchor Generator power output is gradually transferred to another available DER bringing its operating point back to the desired position. The system would similarly compensate for circuit breaker trip or DER failure etc.

6.2.3 Reactive Power Control



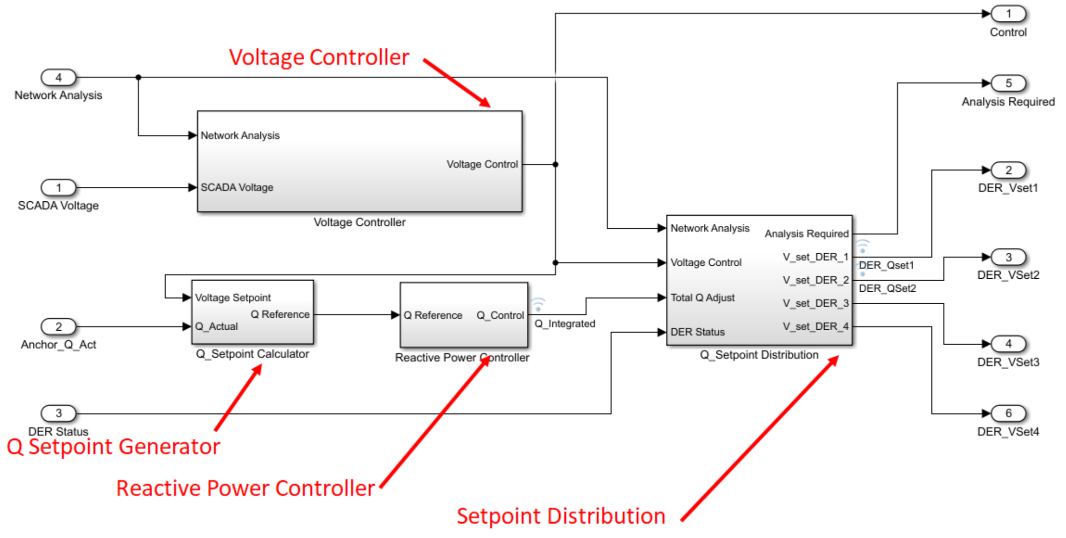
The Reactive Power Control performs two functions:

- Ensuring that the Anchor Generator has sufficient headroom to react to any sudden changes in network voltage.
- Maintaining all voltage levels throughout the microgrid within their required operating range

The Reactive Power Control comprises the following sub-components: -

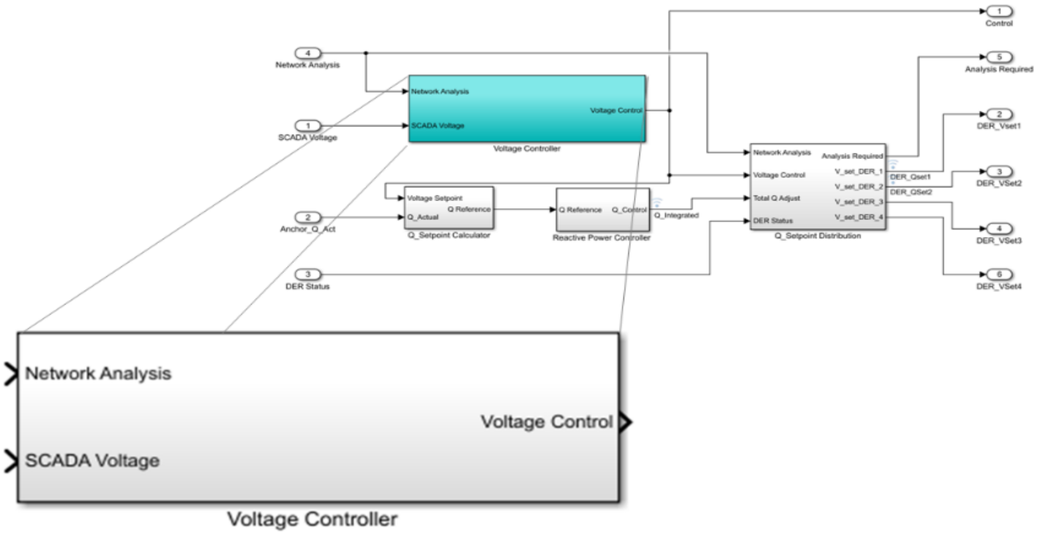
- Q Setpoint Generator -
- Reactive Power Controller
- Voltage Controller
- Q_Setpoint Distribution

Reactive Power Control - Subsystems



The sub-modules Q Setpoint Generator and Reactive Power Controller determine the reactive power required from other DERs to ensure that the Anchor Generator maintains sufficient lead and lag reactive power capability to react to any sudden changes in network demand or voltage. The controller can act using a fact acting Q signal or as self-dispatch voltage control.

Voltage Controller



The sub-module, Voltage Controller, is responsible for maintaining all voltage levels throughout the microgrid within the required operating range. The Voltage Controller inputs include Network Analysis results, Anchor Generator voltage, Busbar voltages and DER voltages and it has several options for the adjustment of the voltage levels:

a. Anchor Voltage Setpoint: adjusting the AVR Setpoint of the Anchor Generator allows all voltage levels on the system to be adjusted up or down as required.

b. DER Reactive Power Control: adjusting the total DER reactive power output to control the microgrid voltage level(s). DERs normally operate in PV mode in order to respond rapidly to network disturbances.

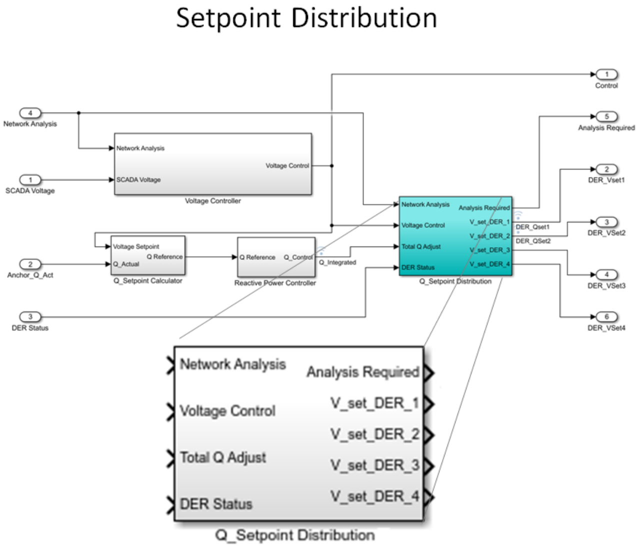
c. Individual DER Reactive Power Control: adjusting the output of individual DERs to control the voltage of specific or individual substation busbars.

d. Operation of ancillary control equipment
    i. Anchor Generator Tap-Changer
    ii. MSC / MSR Switching
    iii. Substation On-Load Tap Changers

Note : DER reactive power can be controlled by direct dispatch in Q Mode or indirectly in Voltage Mode using the self-dispatching droop response of the DER and an associated voltage setpoint. Using Voltage Mode allows reactive power to be dispatched and also supports a faster acting self-dispatch of reactive power in response to fast network voltage changes.

The fundamental control strategy is to set the voltage level at the Anchor Generator such that most bus voltages are within regulation, and adjust specific feeders using individual DERs or discrete control equipment.

The sub-module Q Setpoint Distribution distributes the total reactive power requirement between the individual DERs based on their technical capabilities, real time availability, lead/lag capability and their effectiveness / relative contribution to local voltage levels and anchor voltage level.



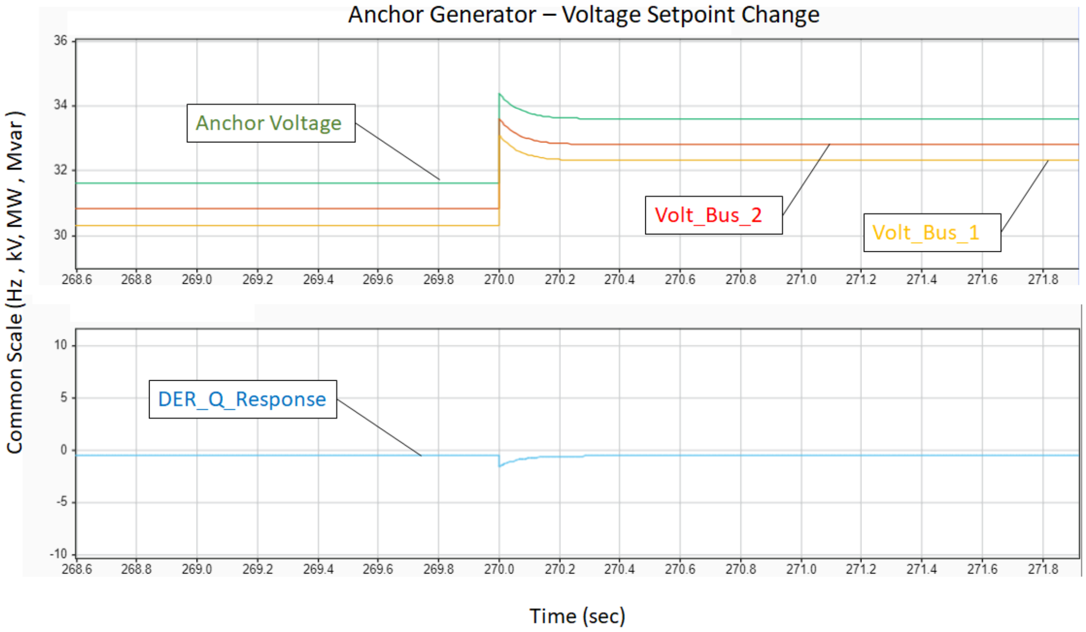
The module must account for the Q ramp rate characteristics of the DERs along with their PQ capabilities as the current P output may influence the reactive power capabilities. In addition, the lead and lag capabilities may not be symmetrical so this needs to be catered for.

6.2.4 Voltage Control Responses

This section demonstrates various scenarios of Reactive Power response that may be experienced by the DRZ system.

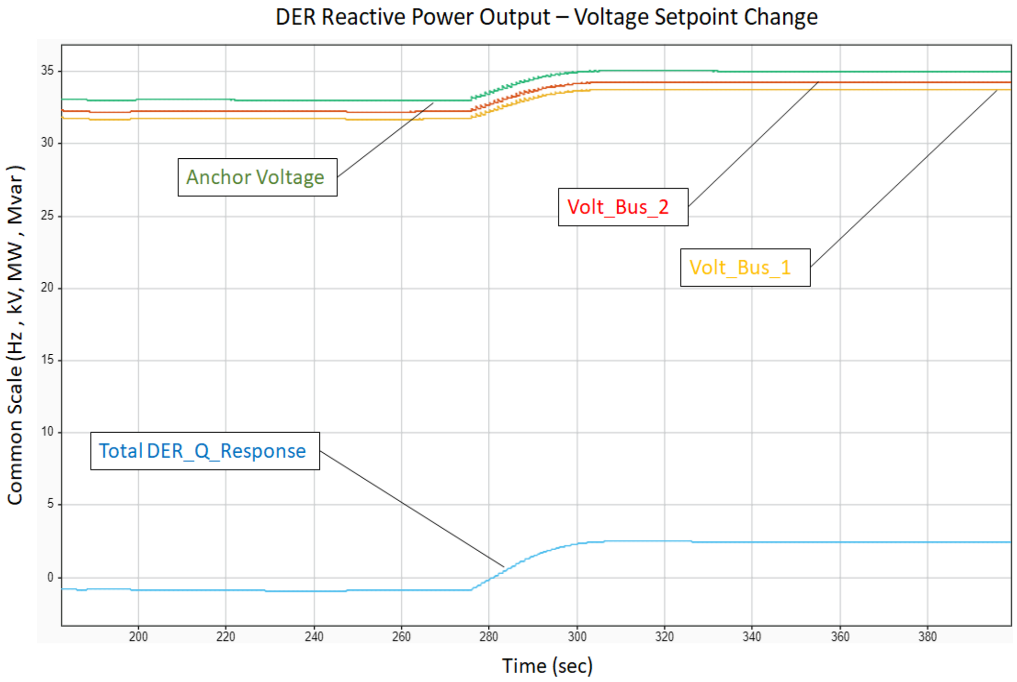
In all cases the Anchor Generator or self-dispatching DERs will provide the initial response to changing demand and the Reactive Power Controller will then adjust the DERs to ensure that the Anchor Generator reactive power output is maintained at the desired operating point with sufficient headroom and footroom.

Change to Anchor Generator Voltage Setpoint



To change the overall system voltage, the Anchor Generator setpoint can be set and the Anchor Generator AVR will manage the output accordingly. As a result, all system bus voltage is raised.

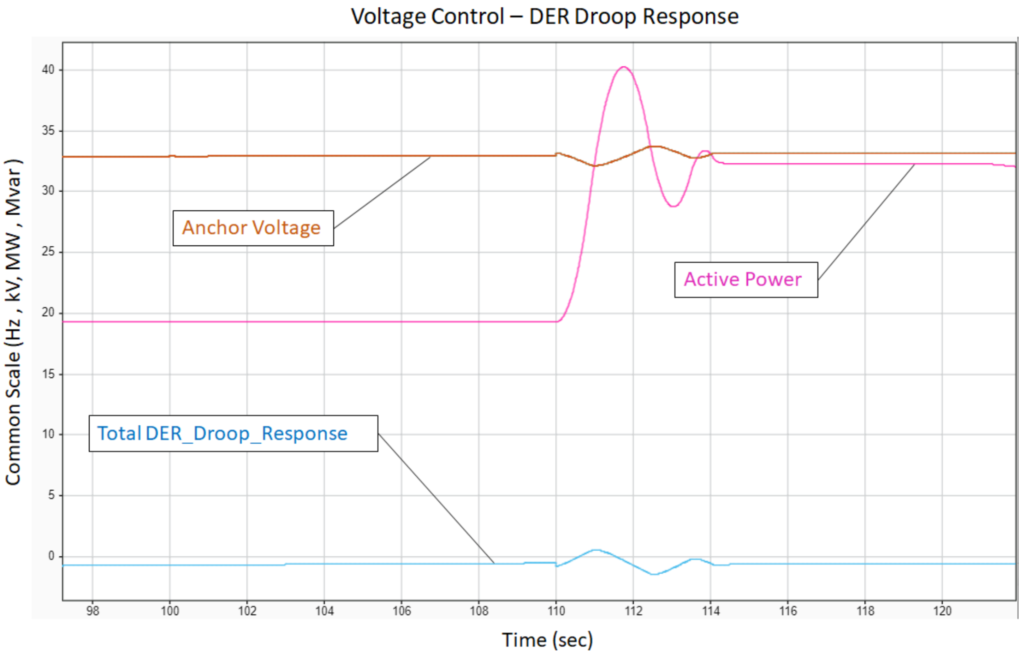
Change to DER Voltage Setpoint



To change the overall system voltage, the Reactive Power output of a DER can be changed to reposition the system voltage. This is an alternative to controlling the Anchor Voltage

Setpoint and can be used to ensure that the Anchor Generator has enough reactive power headroom to react to any network voltage changes.

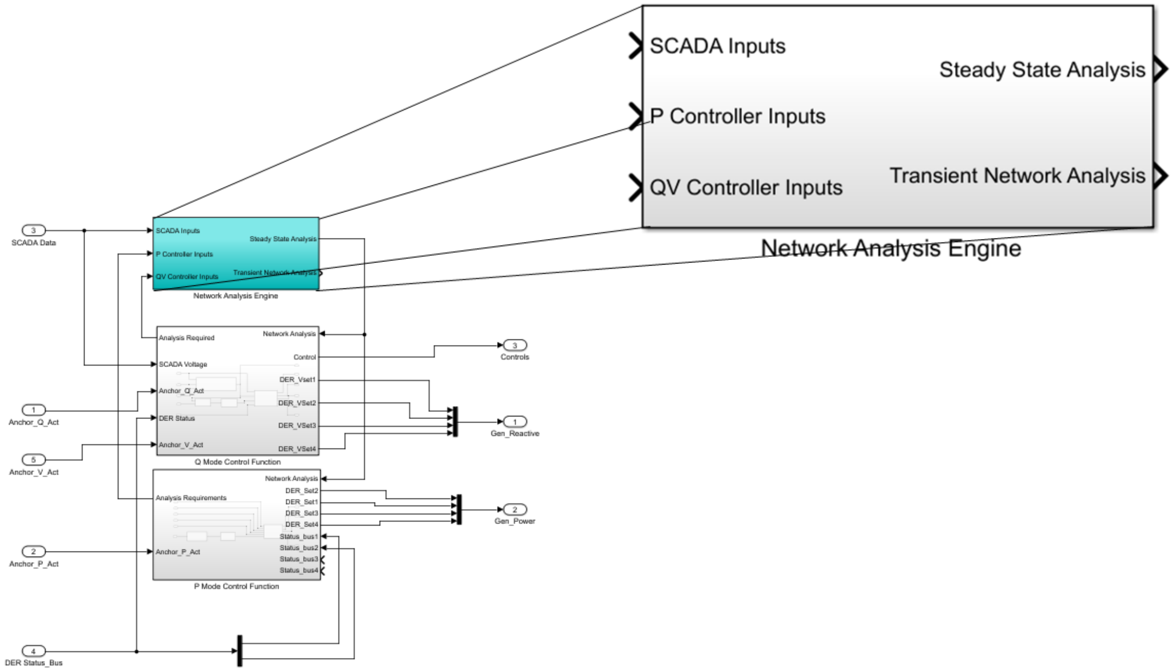
Voltage Drop on Block Load



During block loading, larger load blocks will cause more significant voltage drops. Individual Support DERs should be configured to operate in Voltage Mode (Droop Response). These DERs will respond immediately to voltage changes at their point of connection by changing their reactive power output which helps to support the voltage at the Anchor Generator.

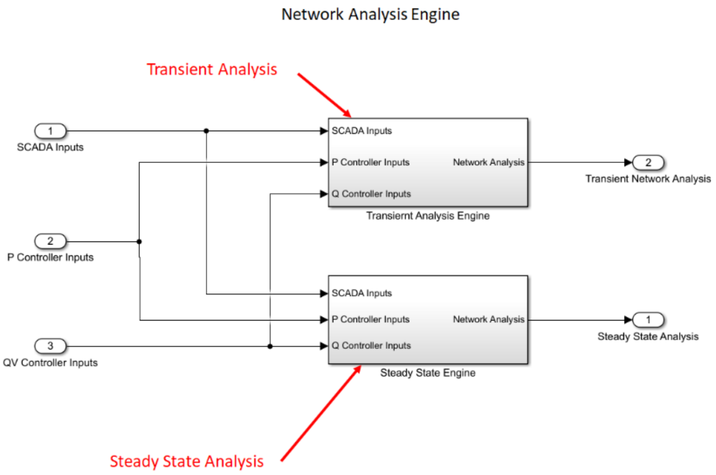
Note: This droop response is independent of the communications channel latency. Generally the self-dispatching voltage mode response is faster than Q Mode direct dispatch. If fast DER reactive power support is required to improve the overall blockloading capability or if the VPP is expected to provide fast reactive power based voltage support to the wider grid then Voltage Mode would be used.

6.2.5 Network Analysis Engine



The Network Analysis Engine performs steady state analysis and transient analysis in real time on the network in question. The results are passed back to the individual service modules in real time for use in controlling the network.

The Network Analysis Engine is used to analyse the network operation in real time to determine if any action needs to be taken to ensure it operates within safe operating limits or to determine if any proposed actions will cause steady state or transient instability on the network and to identify alternative actions to avoid problems.



6.2.5.1 Steady State Load Flow and Fault Level Analysis Module

The Steady State Analysis performs a set of steady state power flow analysis calculations on a power system network model incorporating asset data and power flow data. The network model and the power flow analysis may use historical, forecasted, simulated or real-time data depending on how the Steady State Analysis is being used.

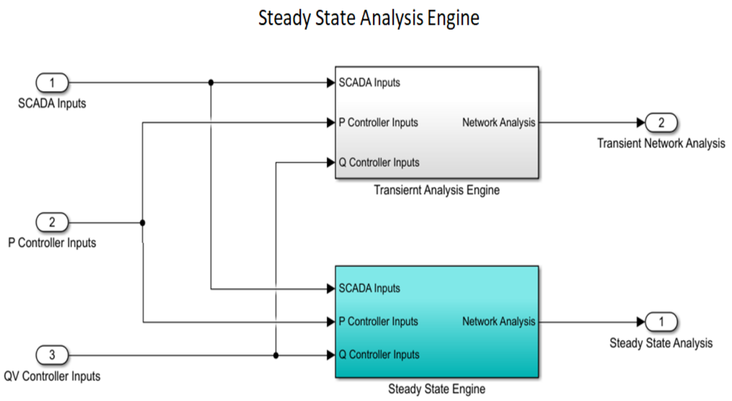
Realtime data is used for Microgrid and VPP Control functions. Simulated data is used for self-test and validation functions. Historical data is used to train the neural models in the Predictor which can then be used to plan for future states of the microgrid.

For continuous analysis of the current network operation it uses current real time data for its analysis. For any switching operations it analyses the network configuration with the proposed switching states and any expected additional generation or demand.

- Steady State Module uses
    - Current network model
    - Network data, including power flows and switch statuses (including inferred switch status), obtained from the Remote devices.
    - Real-time SCADA signals from the control devices

The network model is the static representation of the physical power system with a sufficient level of detail to allow control of the system.

The static network model must be supplemented with dynamic data to represent different operating conditions such as generation and demand values and alternative running arrangements. The dynamic data required to achieve this will be obtained, or derived from, the real-time data from the SCADA system and/or directly from the remote control and monitoring devices. All such data is stored in the DRZ Controller so that the analysis can access the appropriate data as required.



The analysis software includes a variety of user configurable settings which can be defined and saved along with the static network model.

The Steady State Analysis Engine runs on demand when new dynamic data is received. It performs a set of calculations based on that dynamic data and produces a set of analysis outputs. When complete the Steady State Engine is then ready to perform subsequent calculation based on alternative data scenarios.

The Analysis Engine maintains an internal file of historical data which is used for a variety of purposes including the monitoring of DER responses to setpoint changes over time.

The static network model and dynamic data updates allow load flow and fault level calculations to be undertaken based on the current operating state of the network. Load flow calculations identify all thermal overloads, reverse power flows and voltage violations.

Thermal overloads are identified based on seasonal ratings for lines and transformers (monthly ratings can be defined). The appropriate rating is selected automatically based on the current date and time. Shared ratings between circuits and transformers and transformer reverse power flows can also be monitored.

Voltage violations are identified from the defined voltage limits for each nominal voltage level. These voltage limits default to the statutory limits but users can add nominal voltage levels and adjust the default voltage limits.

The Steady State Analysis Module includes several functions that may be executed depending on the specific request of the client application.

These may include:

- Data validation and data quality checks
  - To determine if the calculated load flow results are within tolerance
- Sensitivity calculations
  - To determine the sensitivity of power flows and voltages to changes in DER outputs
- Violation checks and generator curtailment
  - To identify and resolve thermal and voltage constraints using real and reactive generator control
- Contingency analysis calculations
  - To identify worst case operating conditions (e.g. N-1) and use these as the basis for other control modules
- Reactive capability calculations
  - To determine the reactive capability of generators which have voltage or active power dependant characteristics
- Fault level calculations are undertaken to:
  - Ensure the fault level ratings of equipment are not exceeded.
  - Ensure that there is adequate short circuit current to operate protection correctly, including correct operation of fault passage indicators (FPIs).
  - Ensure that Earth Loop Impedance does not exceed limits, to ensure sufficient fault current to operate protection correctly and to prevent flicker.

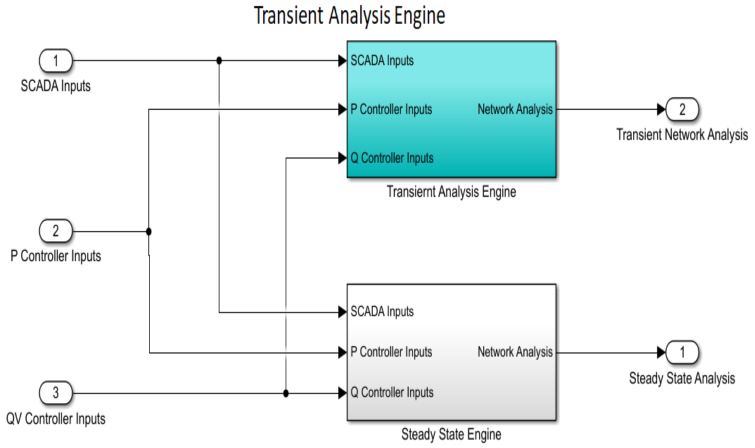
Each of the above modules may be run in sequence or in parallel depending on the application and response time requirements.

6.2.5.2 Transient Analysis Engine

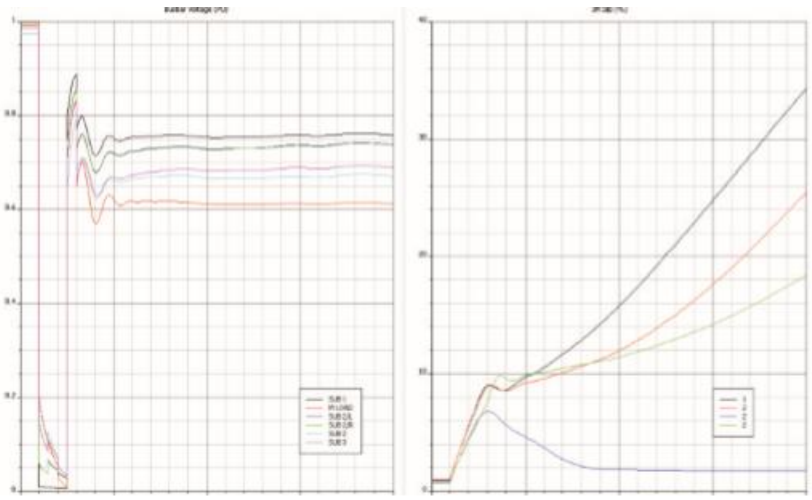
The Transient Analysis Engine performs a set of calculations using a model of the power system network and power flow data.

Transient Analysis is used to calculate the realtime blockload capability of the microgrid by modelling the response of the anchor generator and supporting DERs. The dynamic capability of each DER type is modelled along with the Anchor Generator's AVR and Governor. This Blockload capability is used to determine whether any particular blockload action during microgrid energisation is safe to perform.

The Transient Analysis module enables the system to analyse the dynamic response of the electrical power system to faults and switching operations (e.g. line/feeder, transformer, capacitive/reactive supports). This analysis will determine the effects that these disturbances may have on the system stability and therefore whether they should be undertaken in the first place. This analysis can be used to automatically avoid such actions or advise an operator of the risk level associated with such actions.



The analysis can determine critical clearing times and fault ride through compliance, as well as governor and AVR response and tuning data.



All network support devices and dynamic smart grid controllers can be fully modelled and included in the analysis to reflect the actual system as closely as possible for any decision-making process. Custom 'black box' models can be developed for complex controllers.

7 Virtual Power Plant

7.1 Main Functionality

After subsequent Growth Phases the DRZ is energised to a Point of Connection at a transmission Grid Supply Point (GSP) or another microgrid. At this point, the distribution island can begin to provide support services beyond the Point of Connection.

Instructions issued to increase or decrease DRZ output through demand and generation management are provided to facilitate this wider network growth. Demand for Active Power and Reactive Power services are provided by the Virtual Power Plant (VPP) Module.

Once the Power Island has re-connected to the main grid it can operate as a Virtual Power Plant providing Active and Reactive Power Services to the main grid at the Point of Connection to support the expansion of the main grid. The DRZ Controller calculates in realtime the available capacity of the DRZ zone to provide dispatchable active and reactive power without compromising is own stability. Only this available capacity is offered in realtime as dispatchable. It may be that although the VPP is enabled the available capacity is zero for 1 or both services.

The VPP manages the output of the individual DERs within the DRZ to deliver the required service levels at the Point of Connection. The VPP Module will calculate the sensitivity of each DER to deliver the service at the Point of Connection and provide and aggregated service to the TSO.

The DRZ network is modelled as a Virtual Power Plant which can provide Active Power dispatch and/or Reactive Power which can be provided as a direct dispatch or as a self-dispatching voltage support service.

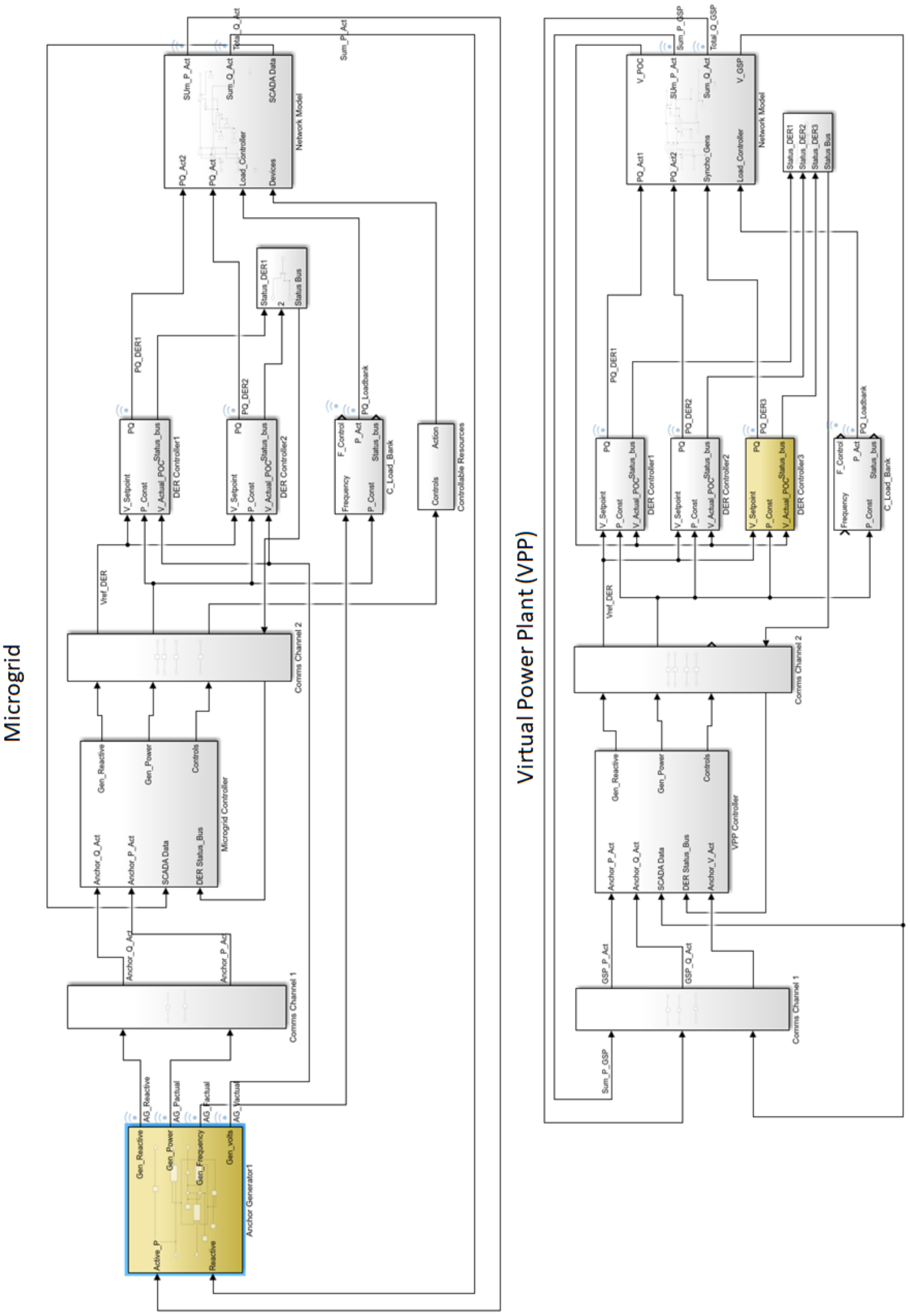
The overall algorithm consists of two separate sub-modules for the different service provisions at the Point of Connection (Grid Supply Point) :

- P_Mode - Provides Real-time Active Power Service
- V_Mode - Provides Real-time Reactive Power Service.

The VPP Module can provide both services (Active Power and Reactive Power) simultaneously. Therefore, separate service requests can be sent for each service.

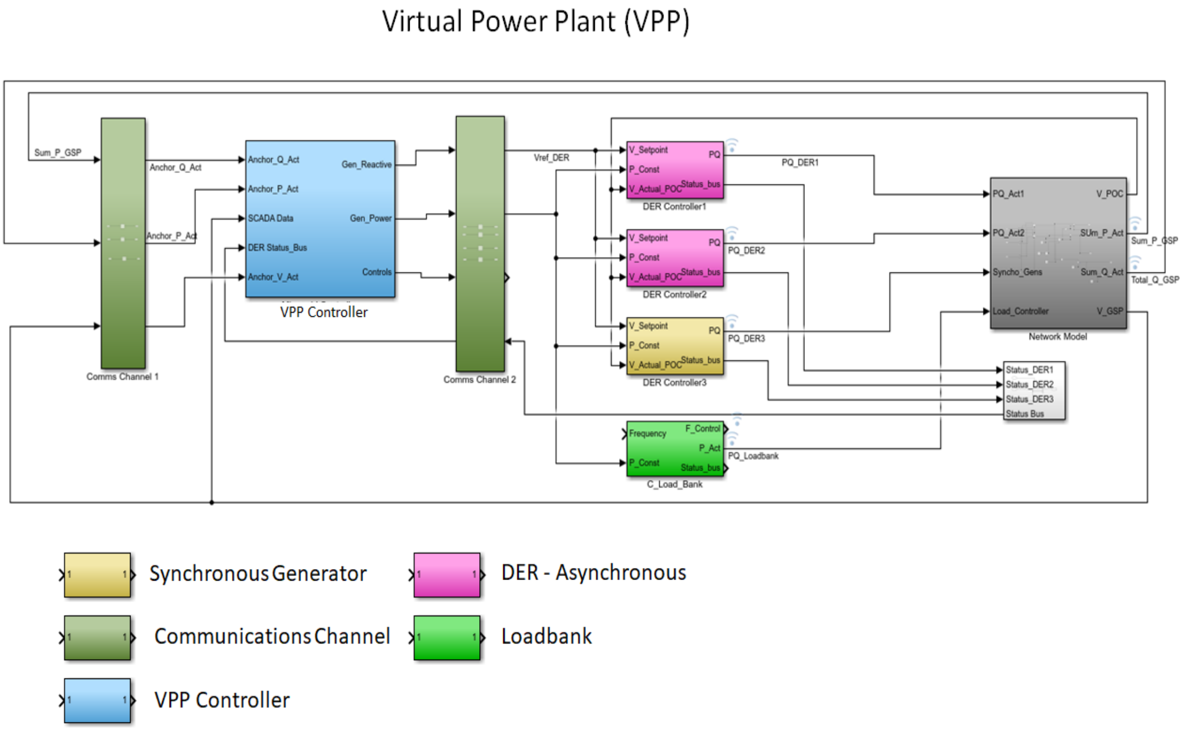
When the Microgrid has merged with the wider Grid the Anchor Generator is synchronised with the Grid and transferred to Droop Mode operation. It can then be used as one of the synchronous DERs contributing to the active and reactive power services.

Note: The DRZ Controller calculates in real-time the capability of the DRZ zone to provide active and reactive power services to the wider network at the point of connection. This is done by the VPP function. This function calculates what excess service capacity can be made available without compromising the stability of the DRZ zone.



With the Microgrid re-connected to the main network the Anchor Generator can either be switched off or switched out of isochronous mode and operated as another supporting DER.

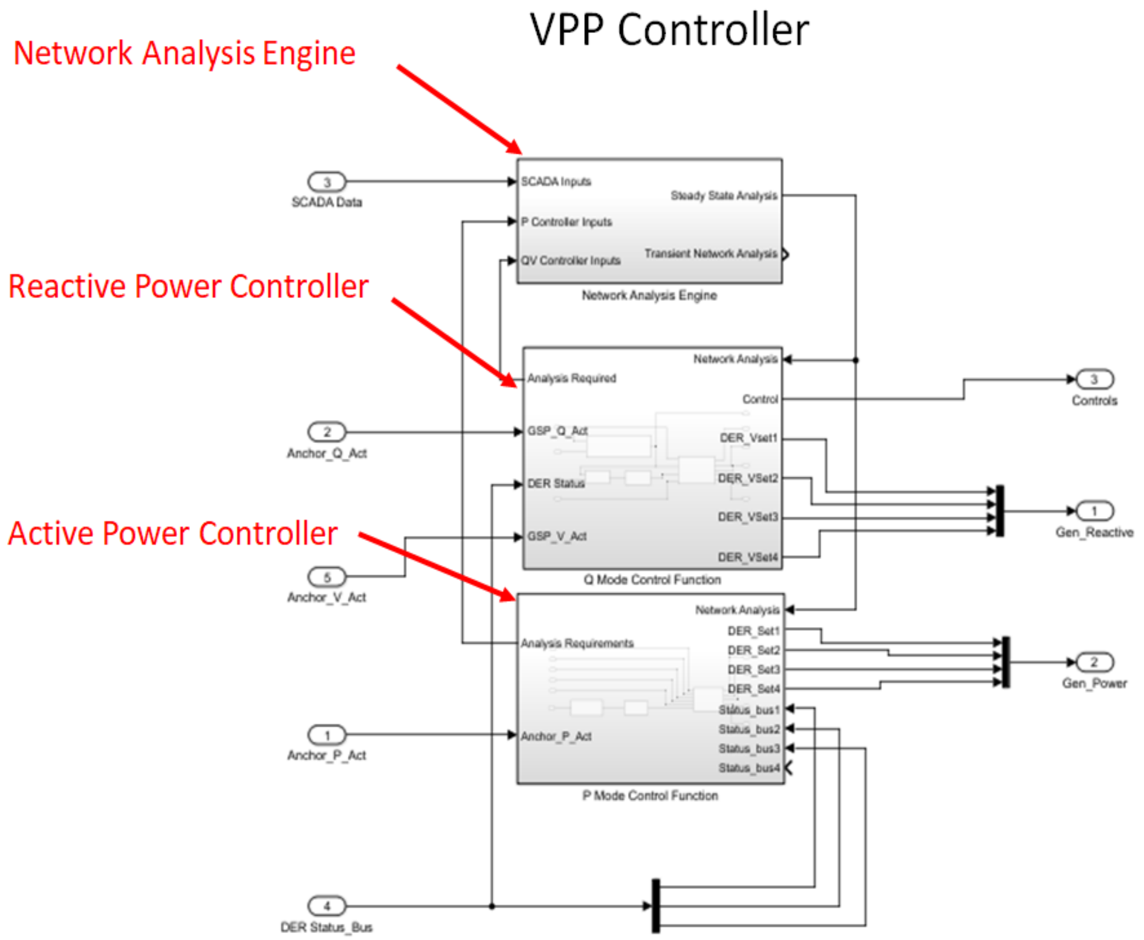
7.2 VPP Controller Main Components



The VPP Control scheme consists of Synchronous and Asynchronous DERs, controlled by a VPP Controller shown in the diagram below. DERs may be based on different technologies and include generation, demand, and support equipment, e.g. batteries, solar / wind farms, load banks, capacitive/reactive devices, demand response etc.). Each DER will be capable of delivering Active and/or Reactive Power independently of each other.

The main component of the VPP Controller are like the Microgrid Controller but the objectives are very different as are the use of resources. In the Microgrid Controller, the general objective is to balance the microgrid and ensure that the Anchor Generator has sufficient headroom/footroom to react to any significant changes. Whereas the objective of the VPP Controller is to aggregate the capabilities of the individual DERs and represent the overall capability as a single ‘virtual’ DER with both Active and Reactive Power capabilities at the Point of Connection.

The VPP Controller manages the active and reactive power outputs of the participating DERs.

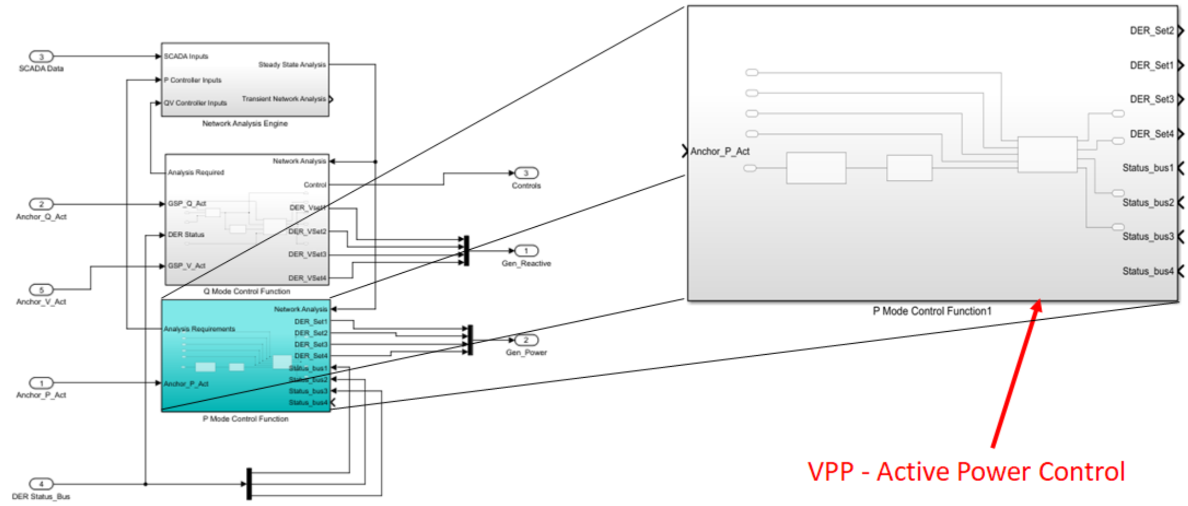


The VPP Controller consists of three main components:

- Active Power Control
- Reactive Power & Voltage Control
- Network Analysis Engine

The Active Power Control and Reactive Power Control operate in parallel managing the system active power and reactive power. While they act independently, their actions affect one another, and this is factored into the operation of the controllers. Both components use the underlying Network Analysis Engine as part of their calculations and to validate their results.

7.2.1 Active Power Control



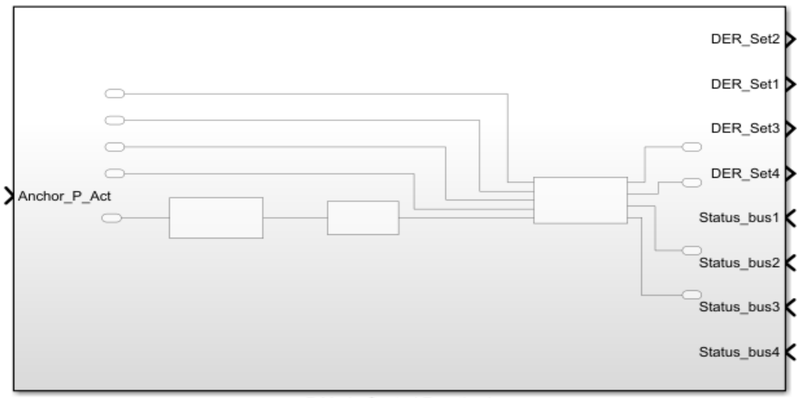
Using the real-time demand, generation and network running arrangement and Network Analysis Engine, the Active Power Controller calculates the available dispatchable Real Power (P) at the Point of Connection. This is a maximum Real Power available to be dispatched and is calculated in real-time. As the DER outputs may change in real time (wind and PV generation), this value is constantly being re-calculated in real time.

Note: a forecasting function has been included in the design which predicts the expected demand and DER generation based on various inputs including calendric and weather conditions. Based on this data the system can provide a forecast of the available active and reactive power services at the point of connection.

As well as providing the max instantaneous dispatchable Real Power (P) available at the Point of Connection the Controller also calculates the delivery time for dispatching it by aggregating the ramp rates of the DERs that would be used for that specific amount of Real Power.

In general, the Active Power Controller monitors the aggregated active power output of the participating DERs at the Point of Connection and compares this to the desired setpoint. To ensure that the POC active power output is maintained at the desired operating point; adjustments are made to the following control plant: -

- DER Generator Active Power Setpoint
- Demand Response Active Power Setpoint

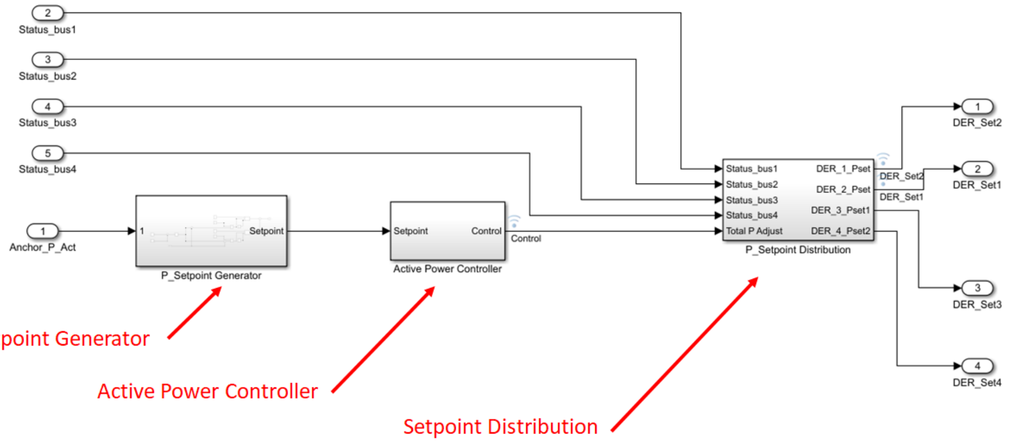


P Mode Control Function1

The Active Power Controller comprises the following sub-components: -

- Setpoint Generator
- Active Power Controller
- P_Setpoint Distribution

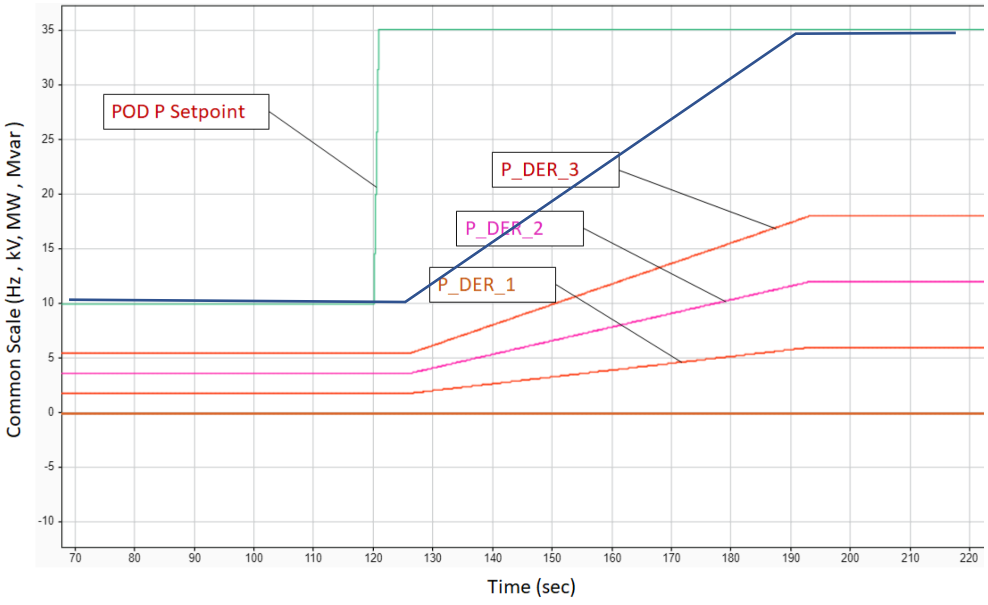
Active Power Control - Subsystems



7.2.2 Active Power Response

This section demonstrates various scenarios of Active Power response to meet the setpoint at the Point of Connection.

Active Power Dispatch

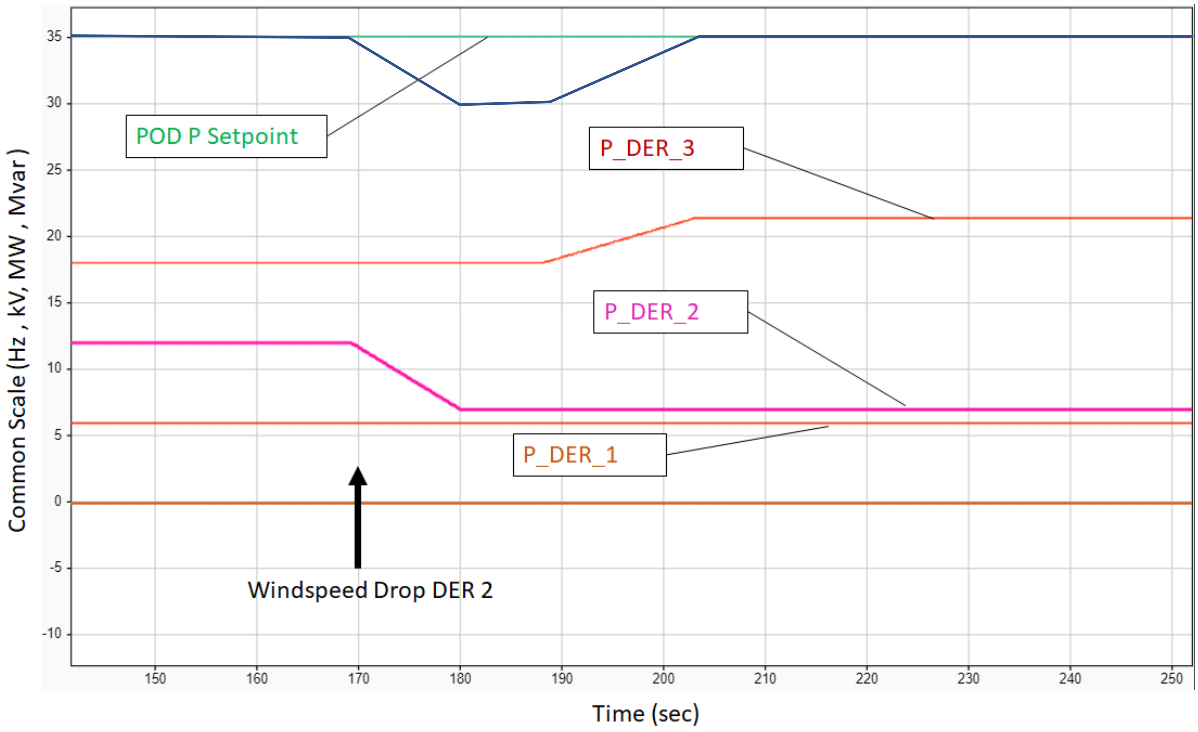


A change in the POD Active Power setpoint results in DER output levels being modified to achieve the target.

7.2.2.1 Drop in Wind Speed/Irradiation

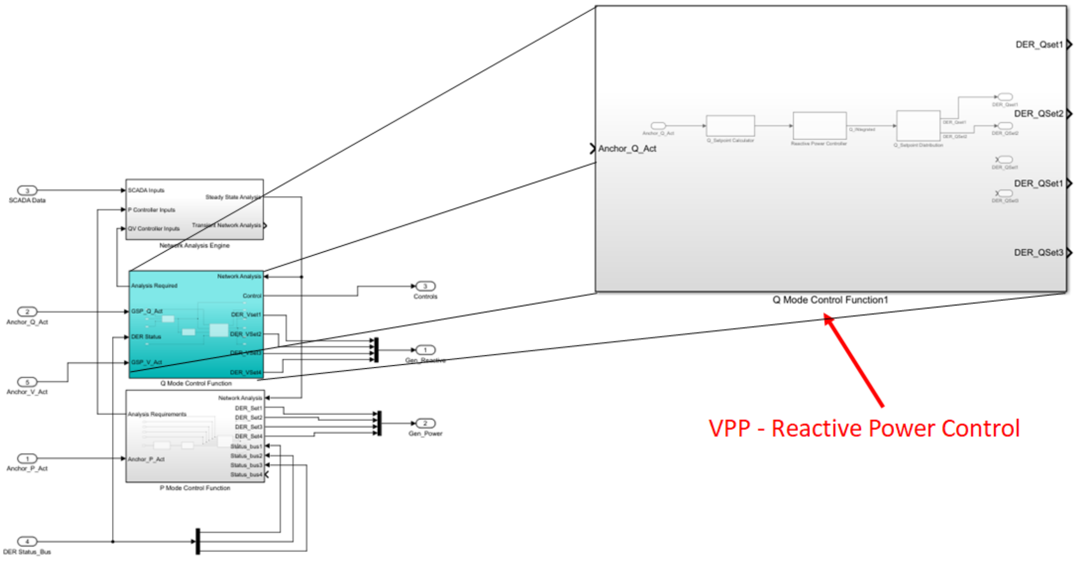
When operating as a VPP, the system is continuously monitoring and adjusting DER outputs to maintain the required Active Power output at the POD. The system is continuously monitoring and compensating in response to changing network conditions (e.g. drop/increase in generation/demand) or unplanned / unforeseen events (e.g. breaker trip).

Following is an example of the system response to a drop in Wind Speed/Irradiation



A drop in windspeed/irradiation results in a drop in output to DER #2. The resultant change in the total power output is gradually transferred to other available DERs bringing its operating point back to the desired position.

7.2.3 Reactive Power Control

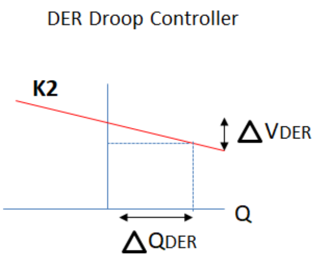


In general, the Reactive Power Controller monitors the aggregated reactive power output of the participating DERs at the Point of Connection and compares this to the desired setpoint. To ensure that the POC reactive power output is maintained at the desired operating point; adjustments are made to the following control plant: -

- DER Reactive Power Setpoint

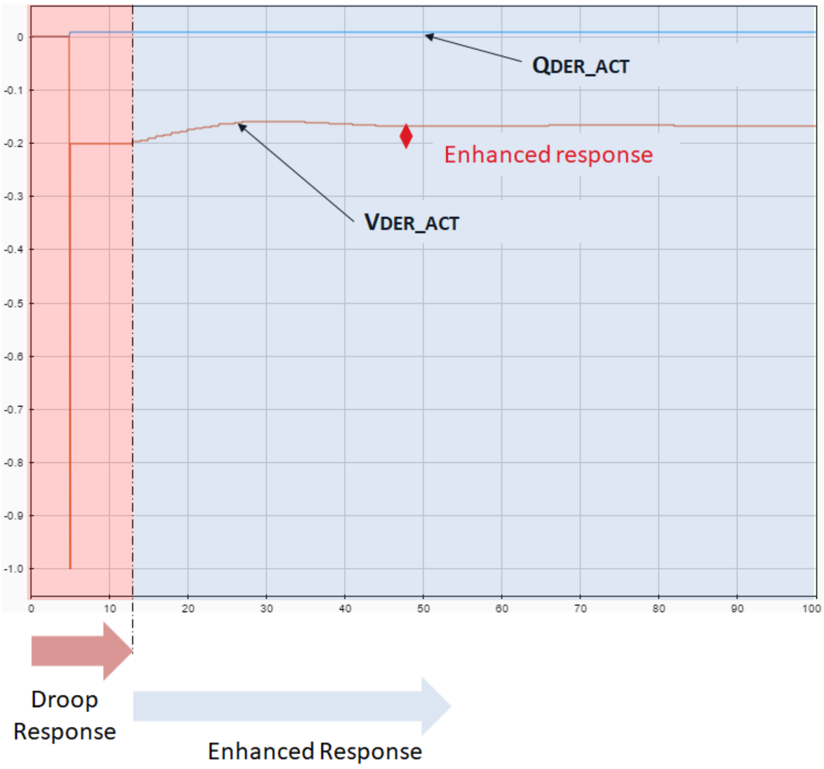
The VPP Controller provides Reactive Power (Q) Service using a combination of Droop Response and Enhanced Response.

Droop Response is the Reactive Power (Q) response of a DER to a change in its measured voltage at its connection point. A change in the connection voltage results in an immediate production of Reactive Power. The amount of Reactive Power produced is directly related to the voltage change at the connection point of each DER and the droop slope of that DER. It bears no relation to the desired amount of Reactive Power that should be produced at the Point of Delivery.



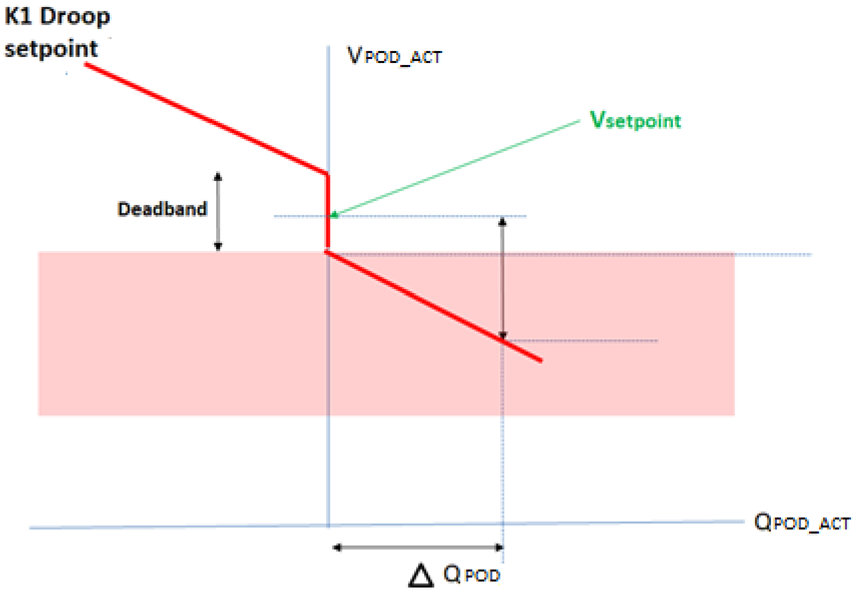
Enhanced Response is the closed loop control algorithm of the Reactive Power Controller. It monitors the difference between the POD Voltage and the POD Voltage Setpoint and adjusts the reactive power required from each DER to deliver the service at the POD (allowing for sensitivity of each DER to deliver the service at the POD). It does this in a closed loop allowing for the different response times from each DER until the Voltage at the POD is within the POD Voltage Setpoint deadband.

The high-speed self-dispatching droop function is performed by the DERs themselves, and the slower acting enhanced response is controlled by the Reactive Power Controller to ensured that the reactive power setpoint is maintained.



The Reactive Power Controller monitors the actual combined reactive power response from all DERs that is being received at the Point of Delivery and seeks to control it so that it lies on the defined droop slope.

When the voltage measured at the GSP is less than the Voltage Setpoint and deadband range then the DERs that are currently armed and in droop mode must generate the required Reactive Power QPOD_REQ at the Point of Delivery. Note: K1 is the Droop setpoint.



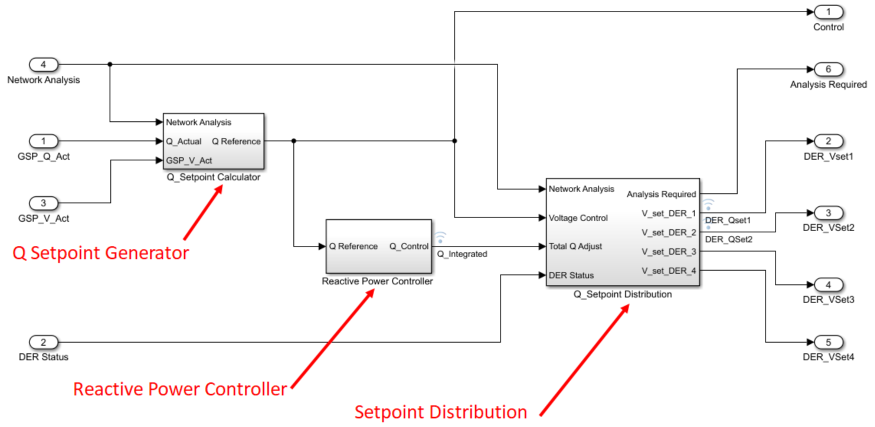
The control module continually monitors the actual voltage at the Point of Delivery. When low voltage is detected the algorithm will continually recalculate new voltage setpoints for available DERs, so that the expected Q is delivered at the POD. Once the voltage re-enters the deadband range then the Reactive Power DELTA QPOD_REQ will be reset to 0 MVAr and the DER voltage setpoint VDER_REQ set accordingly.

The same process occurs when the voltage measured at the GSP is greater than the Voltage Setpoint and deadband range.

The Active Power Control comprises the following sub-components: -

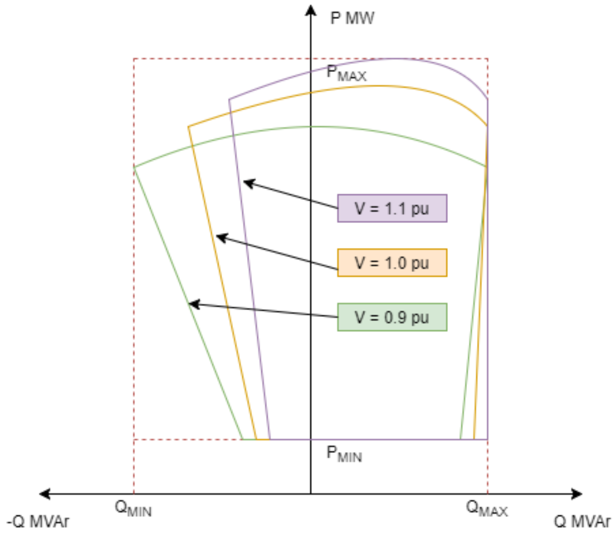
- Q Setpoint Generator -
- Reactive Power Controller
- Q_Setpoint Distribution

VPP Reactive Power Control - Subsystems



The sub-modules Q Setpoint Generator and Reactive Power Controller determine the aggregated reactive power required from the DERs based on the voltage difference at the POD and the droop slope at the POD.

The sub-module, Q_Setpoint Distribution, is responsible for determining how the required Reactive Power support is to be distributed and delivered by the DERs that are currently contracted to provide Reactive Power Services. To do this it first determines the current reactive power capability of each DER based on the PQ curves for the various DERs. There may be different PQ curves based on the DER terminal voltage.

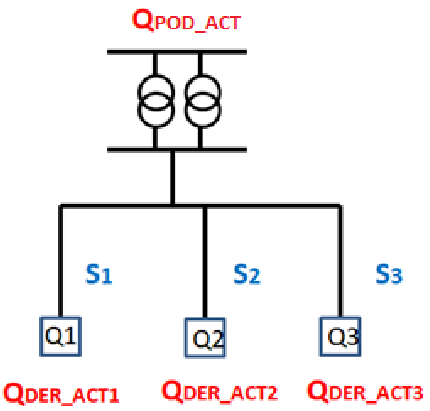


Once the reactive power capability of each DER has been determined the system determines the percentage of this that is seen at the Point of Connection (sensitivity of each DER to the Point of Connection). This is calculated by the Network Analysis Engine.

The module then proceeds to allocate the required POD Reactive Power Support across the individual DERs starting at the lowest ranking DER.

The system supports different ranking mechanisms or principles of access (PoA). These can be LIFO, technical best, Cost, Pro-rata, Speed of operation etc. The PoA mechanism can be selected based on policy and may vary depending on whether the system is operating as an intact network or during a blackstart situation.

It utilises the available capacity of the DER or a reduced capacity to avoid thermal or voltage violations determined by the Network Analysis Engine. Heuristically the algorithm utilises each DER in turn until the required quantity of Reactive Power is fully allocated based on the rules defined by the principles of access.



$$Q_{POD\_ACT} = S1 \, . \, Q_{DER\_ACT1} + S2 \, . \, Q_{DER\_ACT2} + S3 \, . \, Q_{DER\_ACT3}$$

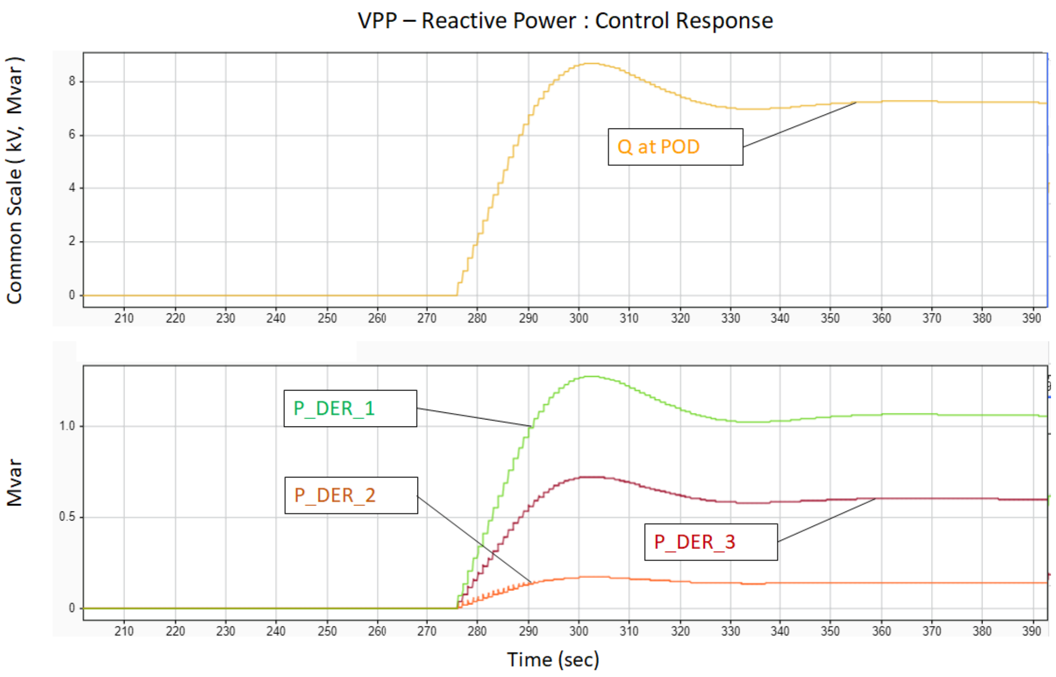
This solution is checked by the load flow for validity to determine that there will be no resulting thermal or voltage violations. Each Mvar assignment is then converted to a Voltage offset for that DER using the droop factor of that specific DER.

7.2.4 Reactive Power Response

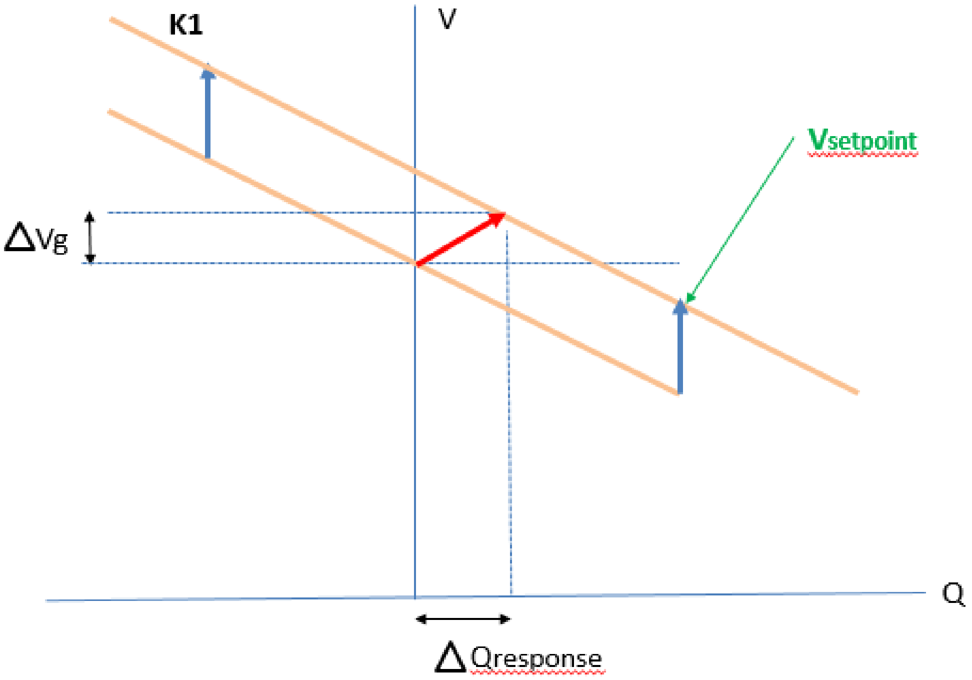
This section demonstrates various scenarios of Reactive Power response to meet the setpoint at the POD

Reactive Power Dispatch – Voltage Setpoint Change

A change in the POD Reactive Power setpoint results in DER output levels being modified to achieve the target.



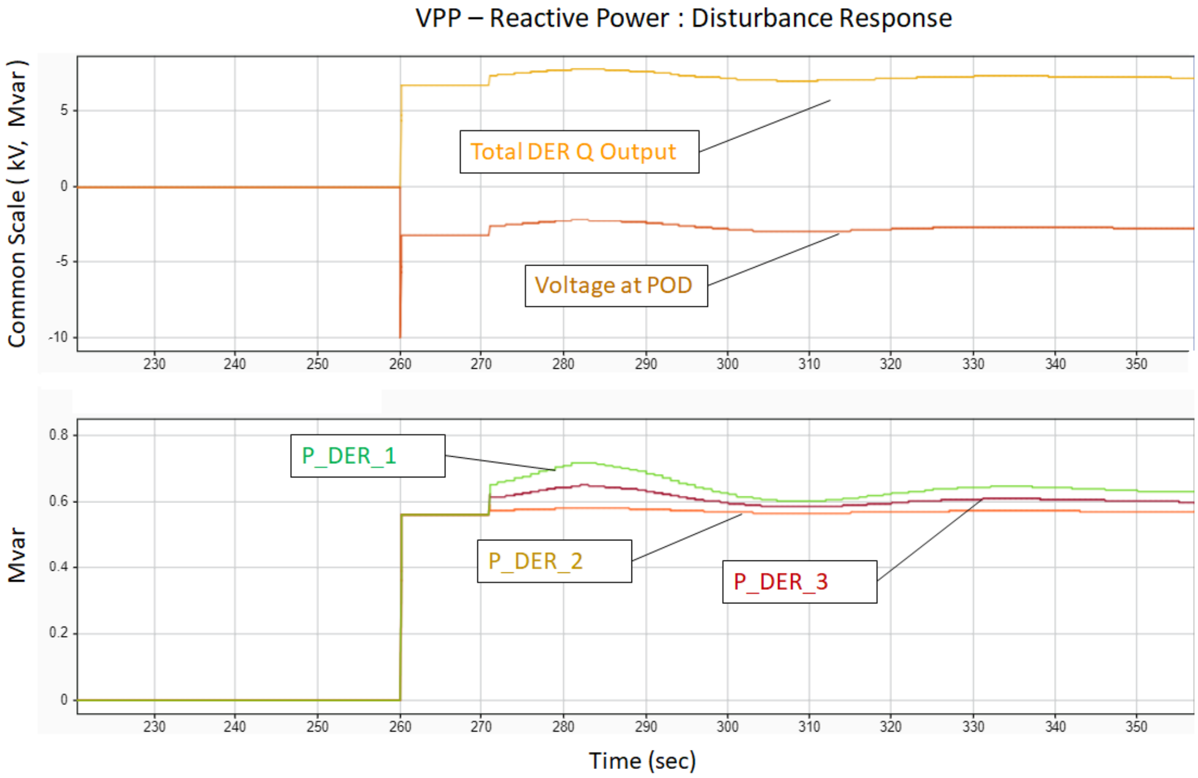
Changing the voltage setpoint at the POD VPOD_REQ results in the calculation of a new reactive power setpoint QPOD_REQ setpoint for the control scheme. The VPP controller calculates new DER voltage setpoint VDER_REQ and the droop controllers produce the required QDER_ACT response. This results in a voltage response at the POD and an ongoing re-calculation of the DER voltage setpoints until the V-Q response settles once more on the POD Droop line as per the diagram below.



Reactive Power Dispatch – Voltage drop at Point of Delivery

When operating as a VPP, the system is continuously monitoring and adjusting DER setpoints to maintain the required Reactive Power output at the POD. The system is continuously monitoring and compensating in response to changing network conditions (e.g. change in voltage at POD, change in DER output resulting in the change in reactive output).

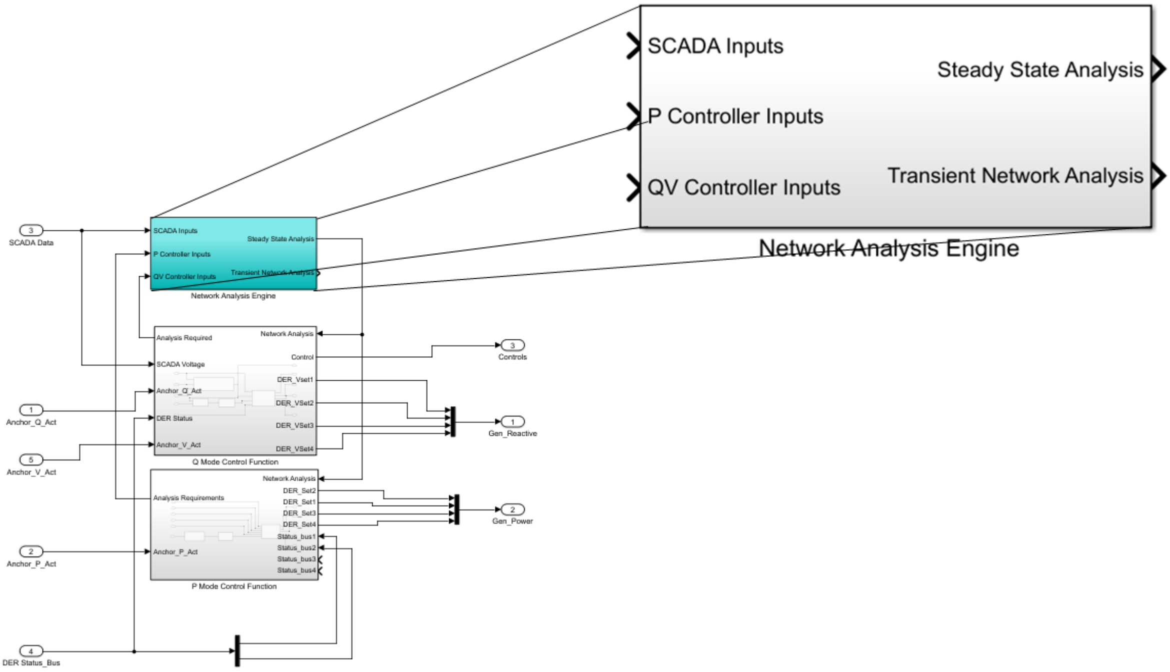
Following is an example of the system response to a Drop in Voltage at POD



A drop in the voltage at the Point of Delivery results in a drop in the Voltage at each DER's Point of Connection which triggers the Droop Response in each DER which in turn neutralises the voltage drop through reactive power voltage support at the POD. This is self-dispatch.

Once the controller detects that the POD Voltage and Reactive Power Flow are lying off the defined droop slope for the POD, the controller adjusts the total DER reactive power output (by adjusting the Voltage setpoint to each DER) until the correct ratio between voltage and reactive power has been achieved. This is the enhanced response.

7.2.5 Network Analysis Engine



The Network Analysis Engine performs steady state analysis in real time on the network in question. The results are passed back to the individual service modules in real time for use in controlling the network. The Network Analysis Engine is described in more detail in Section 6.2.5

8 Predictor Module

8.1 Main Functionality

The Predictor Module takes data including historical demand and generation data, historical and forecast weather data (including temperature, wind and irradiance data), and tidal data (local to each generator) to generate a prediction for all generators (Wind/Solar etc.) and loads/demands on the system. The prediction is updated periodically and stored by the system for use by other modules.

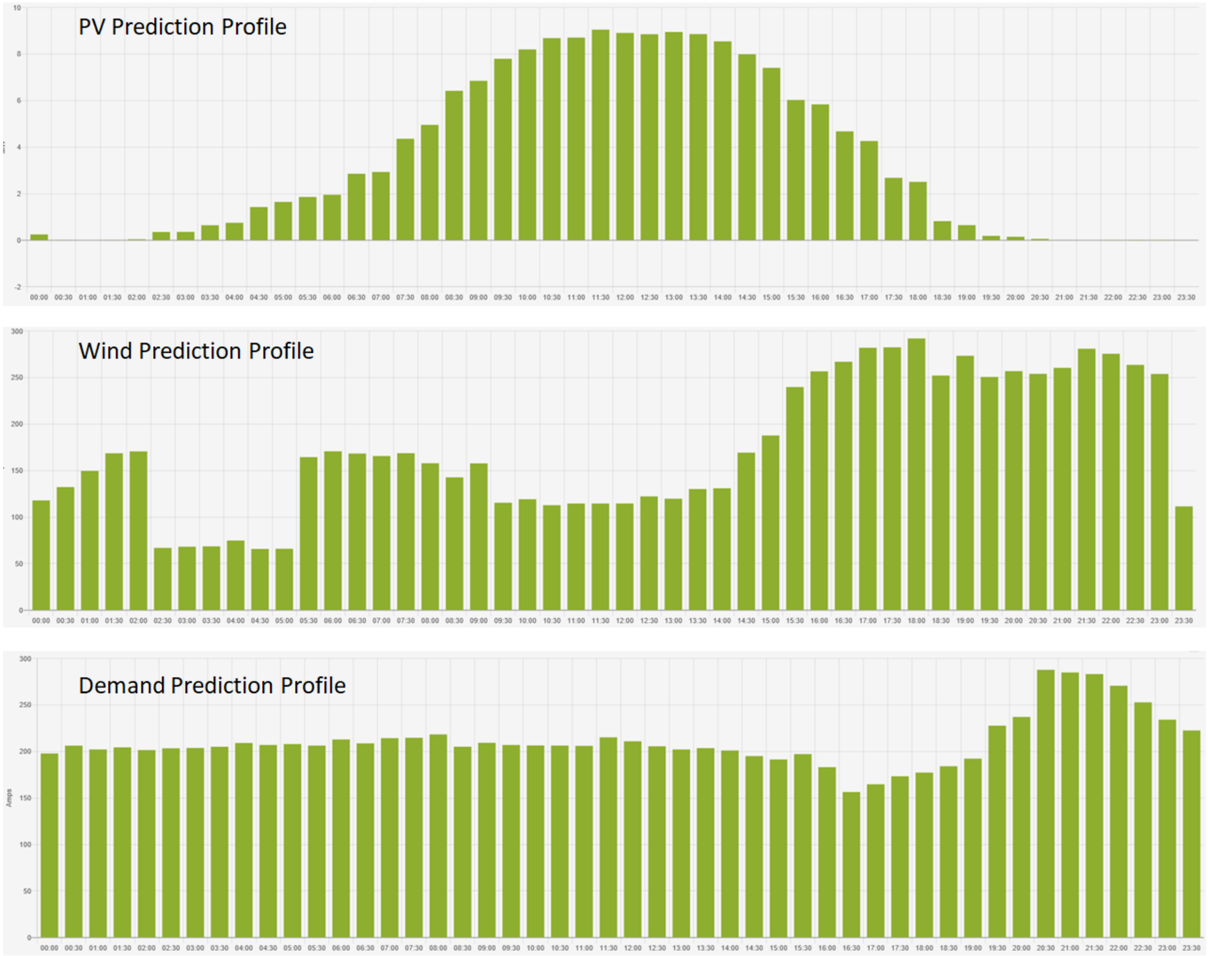
The predictor module uses historical data in a training phase, during which time it is trained to build a predictive model based on a wide range of historical input parameters. Initially this historical data can be provided from archived data and input into the system to train the predictive model.

Once trained, the predictor module can integrate real-time weather and weather forecast updates, date and time information, and current network data to predict the behaviour of each generator and load in the network model.

For new loads and generators, the system is configured with initial values which are used by default until real-time data becomes available. As real-time data is collected over time and stored in the core database, the default values are updated, and the solution becomes more and more accurate. As the dataset is extended over time it will provide more learning data, supporting more accurate predictions.

If the Predictor is provided with input data in real-time (e.g. live weather forecasts, date/time), it can provide real-time predictions for the system.

Typical Prediction Profiles



8.2 Predictor Inputs

The Predictor uses a combination of historical data and forecast data to produce forecast results for both Demands and DER output.

The forecaster module bases its forecasts for demands and generation predominantly on forecast weather data and calendric data. Historical data is used for training the forecast models.

8.2.1 Weather Forecast Inputs

The weather forecast data can be received directly from an external weather service provider or the forecast data can be exposed by the System Owner via the standard Weather API and stored in the central core database.

The following (typical) weather forecast data is available per forecast location. The weather data is (typically) provided on a 4 Hourly basis in 1 hourly intervals, looking ahead 24 Hours.

- Temperature (degrees Celsius)
- Wind direction (16 point compass)
- Wind speed (mph)
- Wind gust (mph)
- Dew Point (degrees Celsius)
- Screen Relative Humidity (%)
- Weather Type
- Visibility (m)
- Pressure (hPa)
- Pressure Tendency (Pa/s)
- Screen relative humidity (%)
- Wind gust (mph)
- Feels like temperature (degrees Celsius)
- UV Index
- Precipitation Probability (%)

Weather for each forecast location is requested specifically. The forecast locations will be selected to ensure that forecast coverage is provided for all Demand and DER sites. Forecast data for each location will be stored in the system database for retrieval by the Predictor Module when required.

8.2.2 Calendric Inputs

Calendric variables have a significant impact on the forecast profile of demands and of solar / Wind DERs

- Month
- Date (Day of Month)
- Daytype (Monday, Tuesday…, Sunday)
- Time of Day
- Holiday calendar: public holiday (with bridge day, after/before holiday) and school holiday

This data will be stored in the central core database for retrieval by the Predictor Module when required.

8.2.3 Historical Demand / DER Data

The Predictor models are trained using historical data which is correlated with historical outputs from the DERs and historical Demands.

The following data is typically received as Half hourly metered data from the DMS System for training purposes.

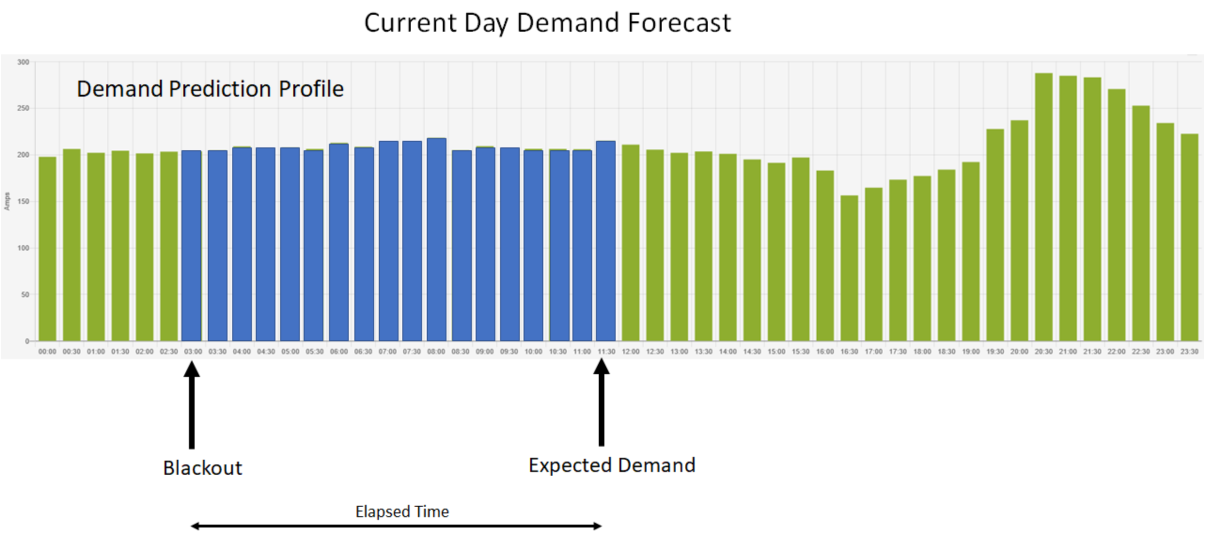
- Demand (Active Power) – half hourly
- Demand (Reactive Power) – half hourly
- DER (Active Power) – half hourly
- DER (Reactive Power) – half hourly
- DER Availability (%)

8.3 Use Case 1 - Blockload Estimation

During a DRZ restoration process the network is energised in sequential steps. These blockload steps must be small enough that the microgrid controller, which includes the Anchor Generator and its supporting DERs, can handle the transient after the sudden increase in load on the microgrid voltage and frequency.

Based on the current running conditions and available resources, the Network Analysis Engine runs a transient analysis to determine if a given blockloading action can be performed without compromising the Microgrid's stability

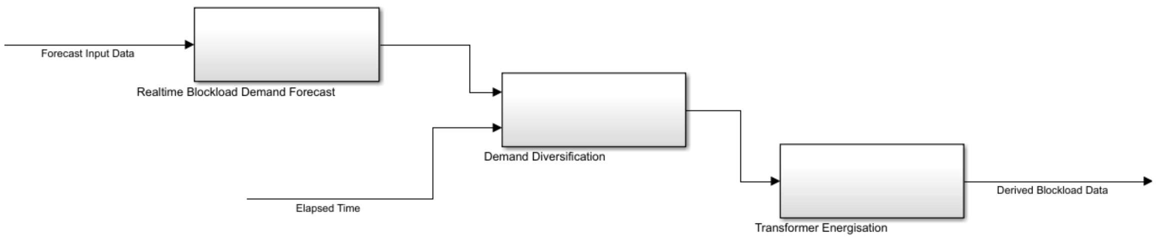
In order to perform the analysis, the size of the blockload must be known.



This is done in a three-step process:

1. Forecast Normal Blockload Size based on the expected demand under normal conditions.
2. Apply an aging function to the Blockload based on the time elapsed since blackout occurred, to allow for diversification.
3. Apply an energisation factor to account for transformer energisation.

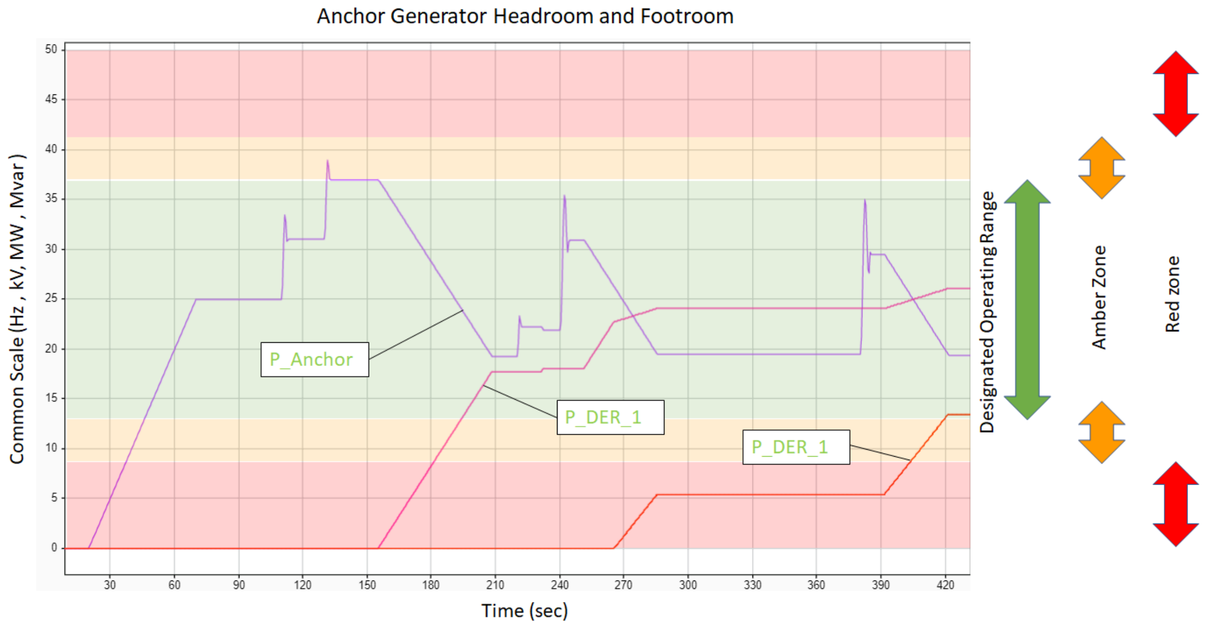
This derived value is used in the network analysis to determine the transient effect.



Note: Cold load energisation increases the blockload size so it's important to ensure that the Anchor Generator and supporting DERs are capable of handling the transient effect.

8.4 Use Case 2 - Anchor Generator Load Forecast

During Microgrid operation the Microgrid Controller manages the supporting DERs' output to maintain the Anchor Generator within a defined operating range to maintain acceptable headroom and footroom.



The microgrid is expected to operate for up to a week duration. During this time there will be constant variation in the demands and also variability in some of the supporting DER generation capability based on changing weather conditions.

By combining the forecast for generation and demands the Microgrid Controller can determine the required output of the Anchor Generator and whether action needs to be scheduled to perform load-shedding or utilise support from Battery Systems etc to protect the Anchor Generator.

This forecasted requirement can then be used to raise a warning for any expected load loss. Additionally, forward knowledge of the excess generation capacity can be used to plan any windows where a battery or other storage systems can be charged to ensure availability when needed.

8.5 Use Case 3 - Virtual Power Plant Availability Declaration

When re-connected to the transmission grid the VPP Controller manages the DERs in the DRZ area to provide an aggregated P & Q service to the transmission grid while maintaining the Anchor Generator within a defined operating range to maintain headroom and footroom to react to any network events.

The VPP is expected to operate for up to a week duration. During this period the VPP may be called on to provide active and reactive power support to the transmission grid or a neighbouring microgrid. During this time there will be constant variation in the demands and also variability in some of the supporting DER generation capability based on changing weather conditions. This ultimately affects the available capacity of the VPP to support external grids.

By combining the forecast for Generation and Demands, the VPP Controller can predict the support capacity available to external grids at the point of connection over the forthcoming period, typically 0-24 hrs.

Appendix 1 – Power System Studies

Generally, the stability of the microgrid will be determined by the Anchor Generator, specifically the performance of the Governor and the AVR.

The Governor is a controller used to measure and regulate the speed of the generator and hence the frequency.

The AVR is an automatic voltage regulator designed to automatically maintain a constant voltage level by the generator.

Disturbances to the grid provoke a response from the anchor generator. The greater the disturbance the greater the deviation in voltage (Undervoltage / Overvoltage) or frequency. (Underfrequency / Overfrequency / ROCOF).

When either the voltage deviation exceeds defined or acceptable limits, or the frequency deviation exceeds acceptable limits the anchor generator protection my trip or damage may be caused to network plant that is energised on the microgrid.

The most common disturbance will be blockloading demand caused by closing in Circuit Breakers onto demand.

For increasing levels of blockloading i.e. increasing MVA, the anchor generator reaches a point where it cannot maintain the microgrid within the defined limits. This is explored in Evaluation 1 below.

Note: The conclusion is that there may be Circuit Breakers on any given microgrid which cannot be switched in because the blockload exceeds the Anchor Generator capacity.

When there are other active components on the microgrid such as asynchronous DERs, Battery System, SVCs or loadbanks then the overall blockloading capability of the Anchor Generator increases.

In order to evaluate if a blockload operation is safe the DRZ controller compares the size of the expected blockload with the current microgrid’s blockload capability. In order to do this the DRZ controller calculates the current blockload capability by modelling the network and including effect of any supporting devices on the network such as Battery Systems, Statcoms etc. The evaluations below demonstrate the relative effects of different technologies.

Note: some technologies such as synchro-switching require direct DRZ Controller operation, and some technologies such as DER reactive power or frequency response can be self-dispatching.

Generally the DRZ Controller energisation strategy is to prioritise blockloading to DERs that can provide support (controlled or self-dispatching) to the Anchor Generator to improve the overall blockloading capability and hence stability.

Evaluation 2 below studies how synchronised switching of loadbanks with the blockload event can reduce the voltage and frequency deviations.

Evaluation 3 below studies the impact of using DER reactive power support on the overall blockload capability.

Evaluation 4 evaluates the effect of DERs providing synthetic inertia via a frequency response function on blockload capability.

Evaluation 5 evaluates the effect of SVC/Statcom devices on blockload capability.

Evaluation 6 evaluates the effect that battery systems can have on blockloading performance by providing both active and reactive power support.

Note: the studies have been carried out to compare the relative effectiveness of different technologies on blockloading. The voltage limits referenced are not fixed and the overall evaluation of voltage and frequency response is configurable. Regulatory limits may be different during a black start event.

Evaluation 1 – Block Loading Anchor Generator with increasing demand.

A range of blockload events are analysed with increasing MVA capacity, demonstrating that with increasing demand, loading each generator eventually reached a limit known as its Block Load Limit.

This is the maximum blockload capacity (MVA) that can be applied to the microgrid that the Anchor Generators can absorb without exceeding the defined voltage and frequency limits.

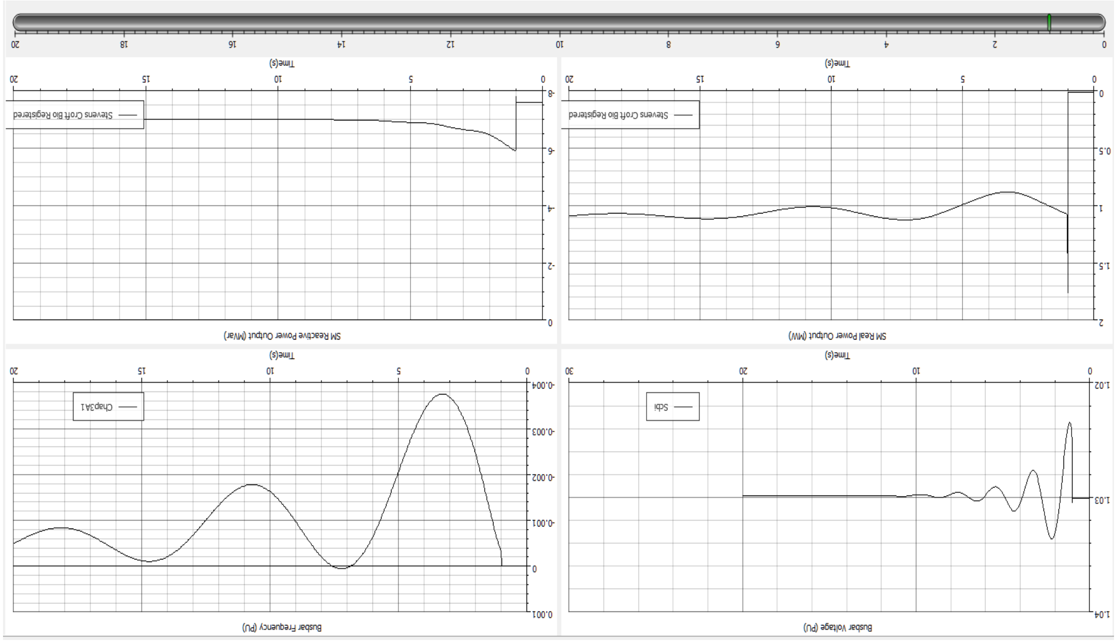
Note: in the following studies only the anchor generator is supporting demand switching.

All studies use a transformer inrush model with 2pu peak inrush on rating. The initial generator voltage is 1.03pu. The model includes a significant cable which results in the initial negative MVAr value.

Note: The transformer inrush can be configurable and this will be set based on policy.

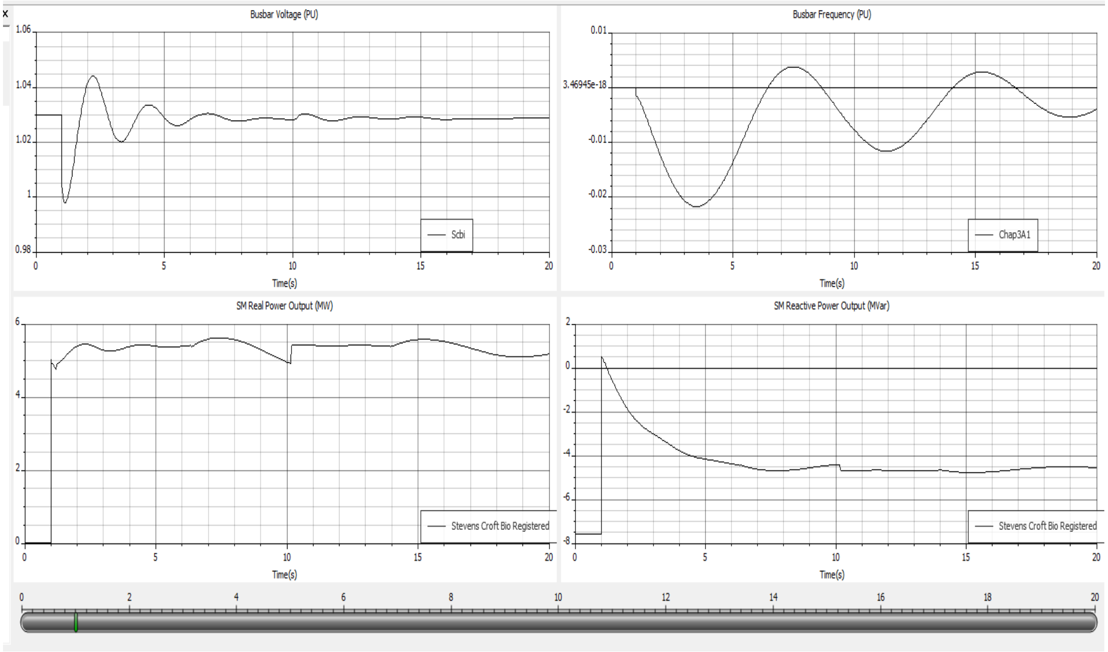
Test Conditions: 1MVA Transformer Energisation with 1MW, 0.5MVAr LV Load:

Result: 0.4% frequency dip, 0.7% voltage dip



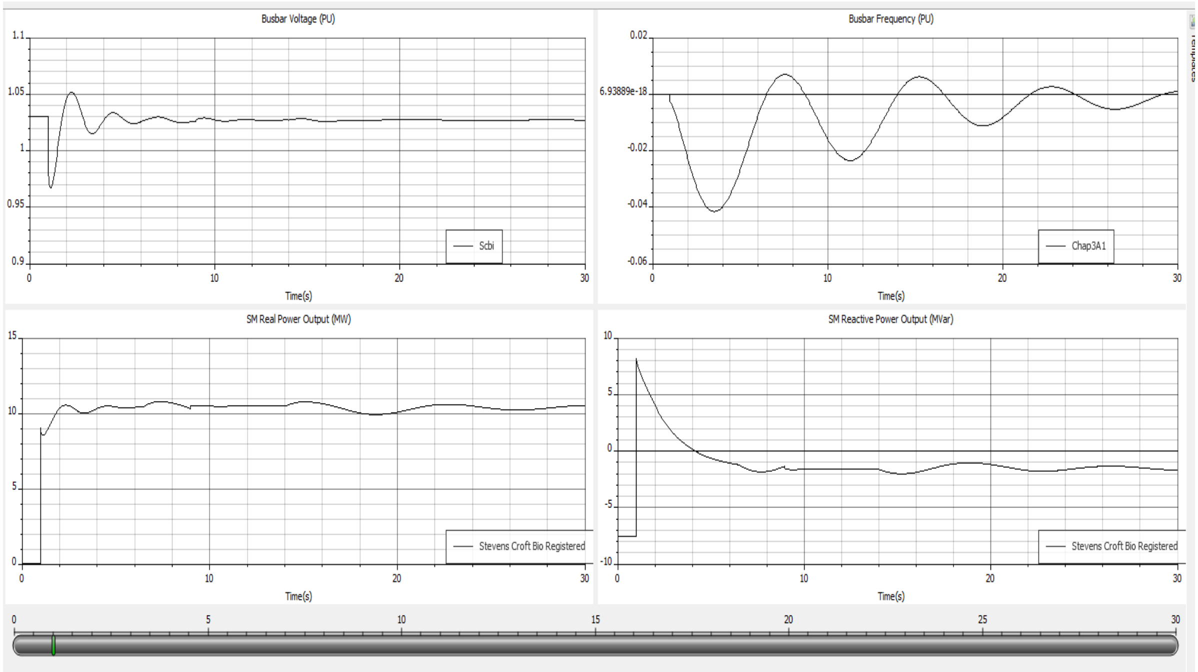
Test Conditions: 5MVA Transformer Energisation with 5MW, 2.5MVAr LV Load

Result: 3% frequency dip, 3% voltage dip



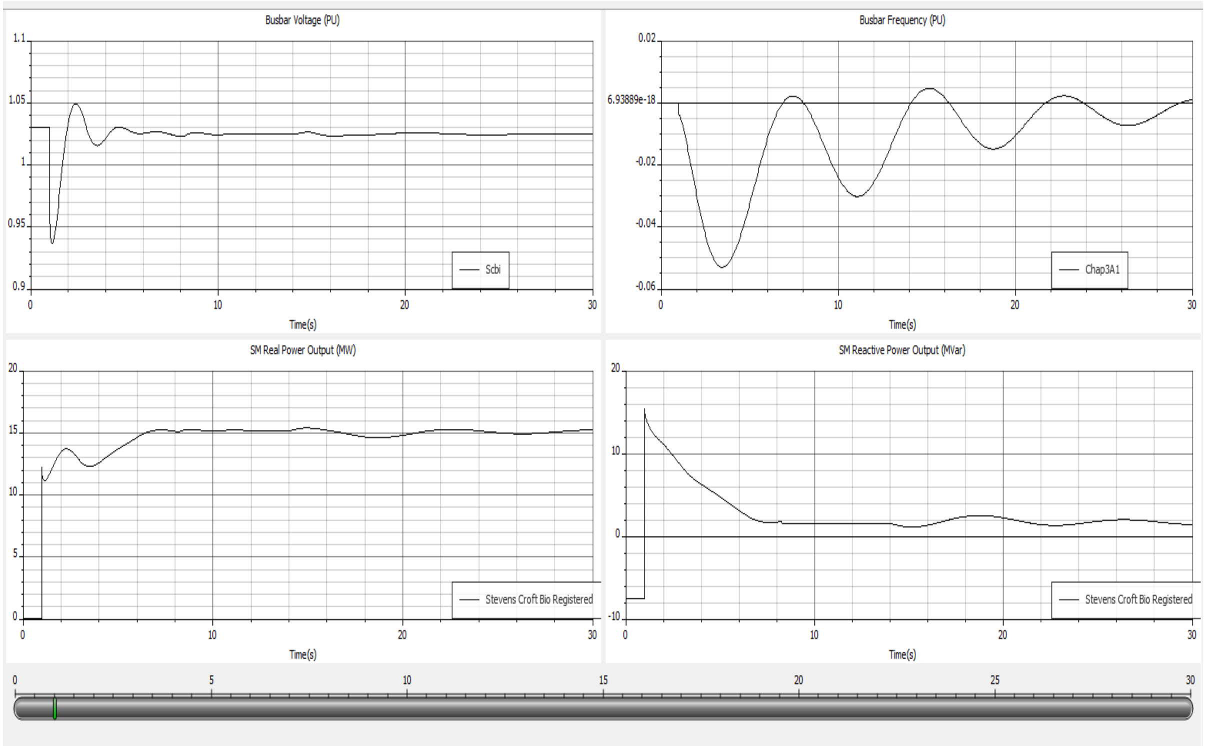
Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load

Result: 4% frequency dip, 6% voltage dip



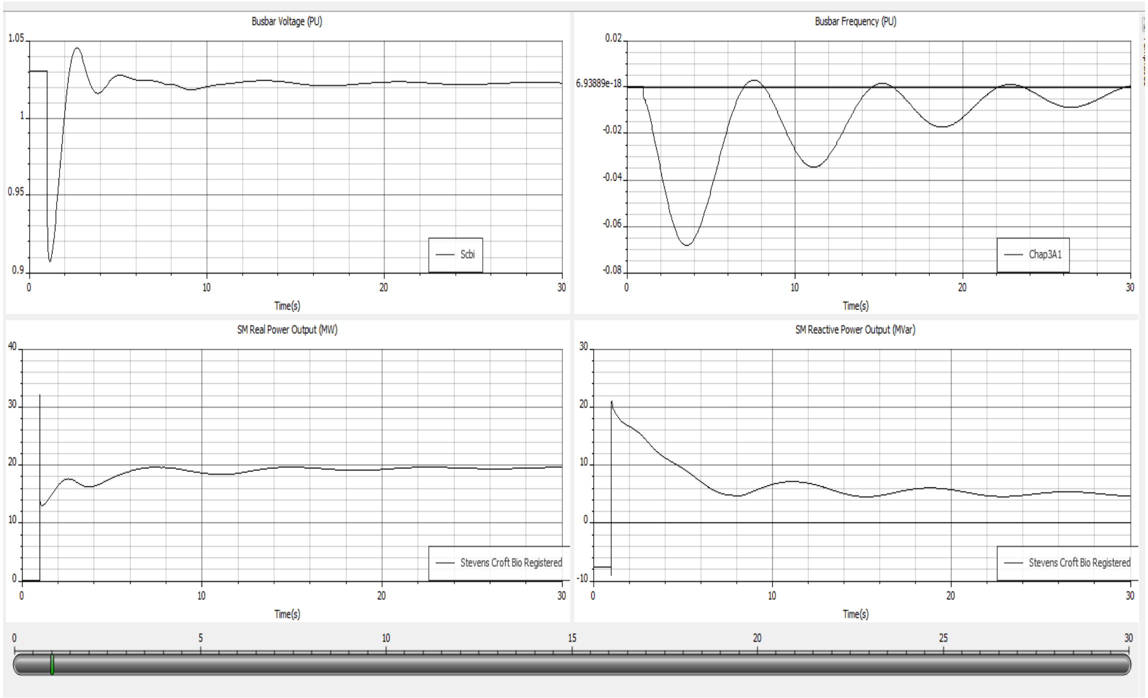
Test Condition: 15MVA Transformer Energisation with 15MW, 7.55MVAr LV Load

Results: 5.5% frequency dip, 9% voltage dip



Test Condition: 20MVA Transformer Energisation with 20MW, 10MVAr LV Load

Result: 7% frequency dip, 12% voltage dip



For the above studies, the maximum block load capability of the system is 10MVA, based on a maximum frequency deviation of 4% and voltage limits of +/-6%.

Note: The frequency and voltage limits used in the study are just example values but these are configurable and can be modified to suit policy.

Evaluation 2 – Block Loading Syncro-Switching

Generally, a Loadbank is included in each Microgrid. This is used to provide a load for the Anchor Generator to start against.

Performing a synchronised switching of a Loadbank and a Blockload can reduce the impact of a blockload event on the Anchor Generator performance. The study below evaluates synchro-switching using a Loadbank with a series of different time offsets to represent a range of time offsets.

The evaluation shows the improvement of the synchro switch and the effect an increasing delay has on the result.

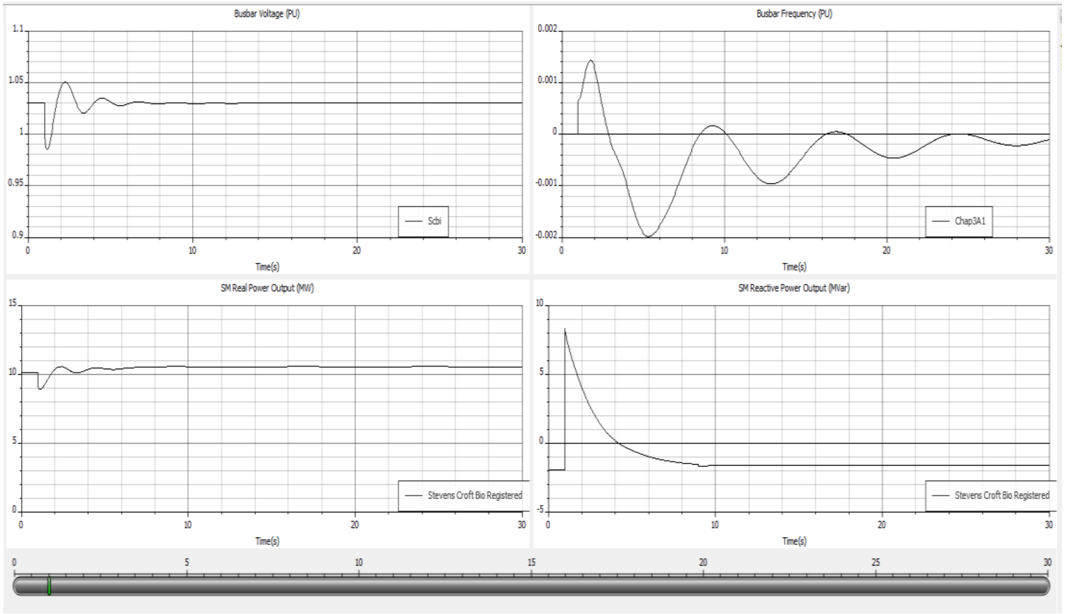
Using the 10MVA study as a basis, the following results have been obtained for load bank synchro switching. The load bank has been set equal to the load switched in, i.e. 10MW and 5MVAr. As this exactly cancels out the demand load most of the transient is the transformer inrush. This method reduces the frequency deviation down to less than 0.5% from 4%. The worst-case voltage response is largely unaffected with the maximum dip of 6% due to the reactive power inrush.

Note : It is not expected that the load bank and block load MVA values will match exactly and this will impact the result , but the conclusion is that this approach significantly improves the resilience of the microgrid from a frequency perspective, with the result being best when the offset in the synchronisation between the two switching operations can be minimised.

Therefore, the block load capability of the system remains at 10MVA due to the voltage limits.

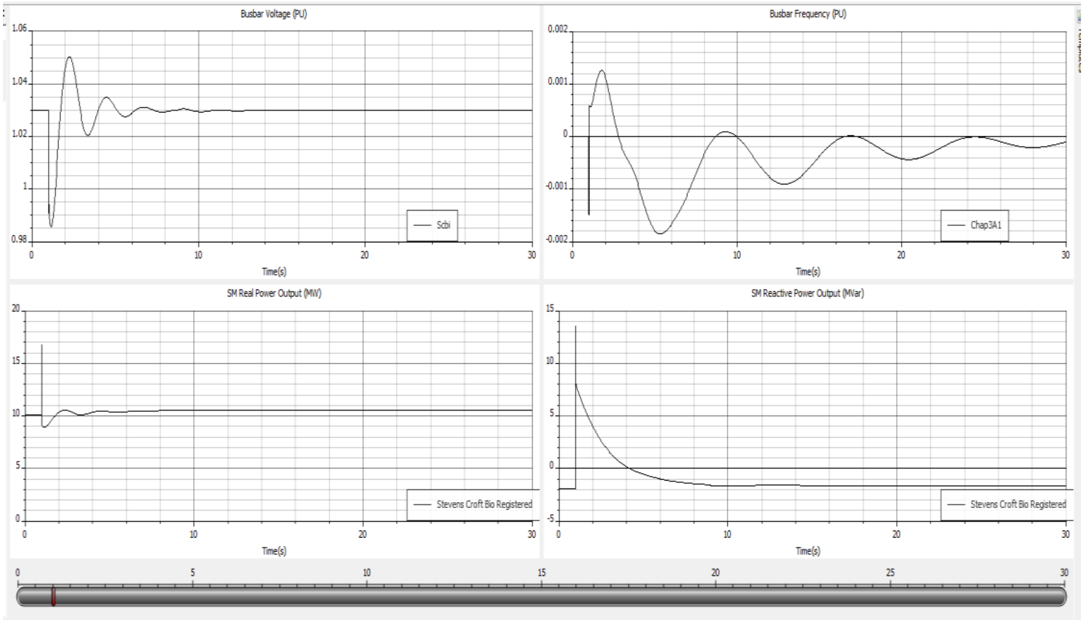
Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load, 0ms Load Bank switching

Result: 0.2% frequency dip, 4.5% voltage dip



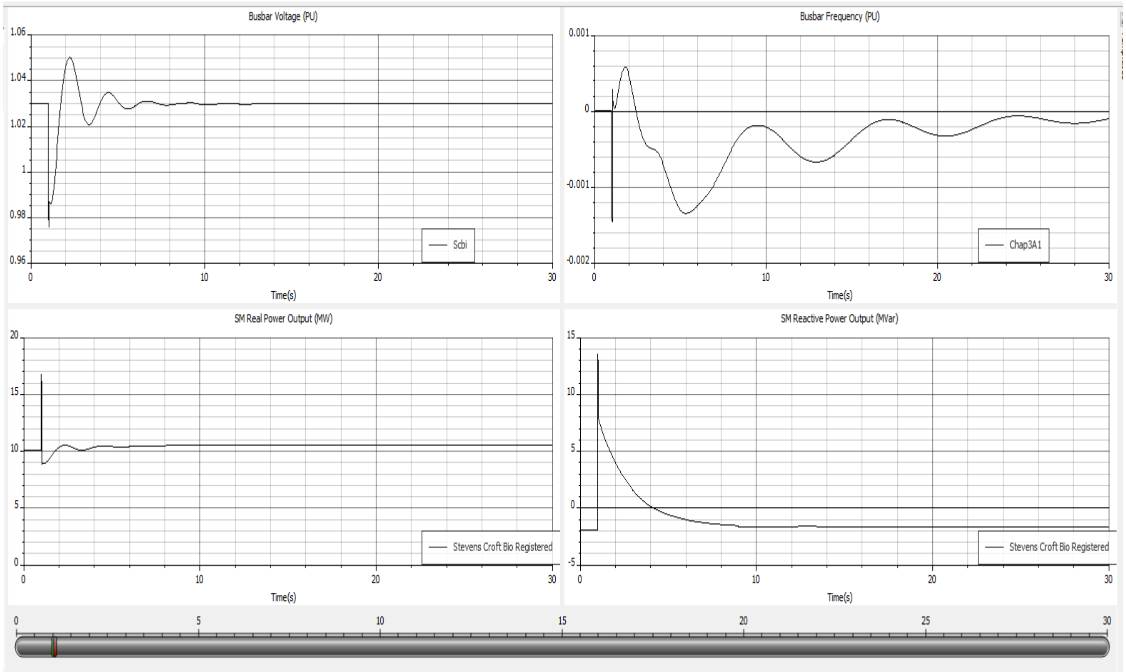
Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load, 10ms Load Bank switching

Result: 0.2% frequency dip, 4.5% voltage dip



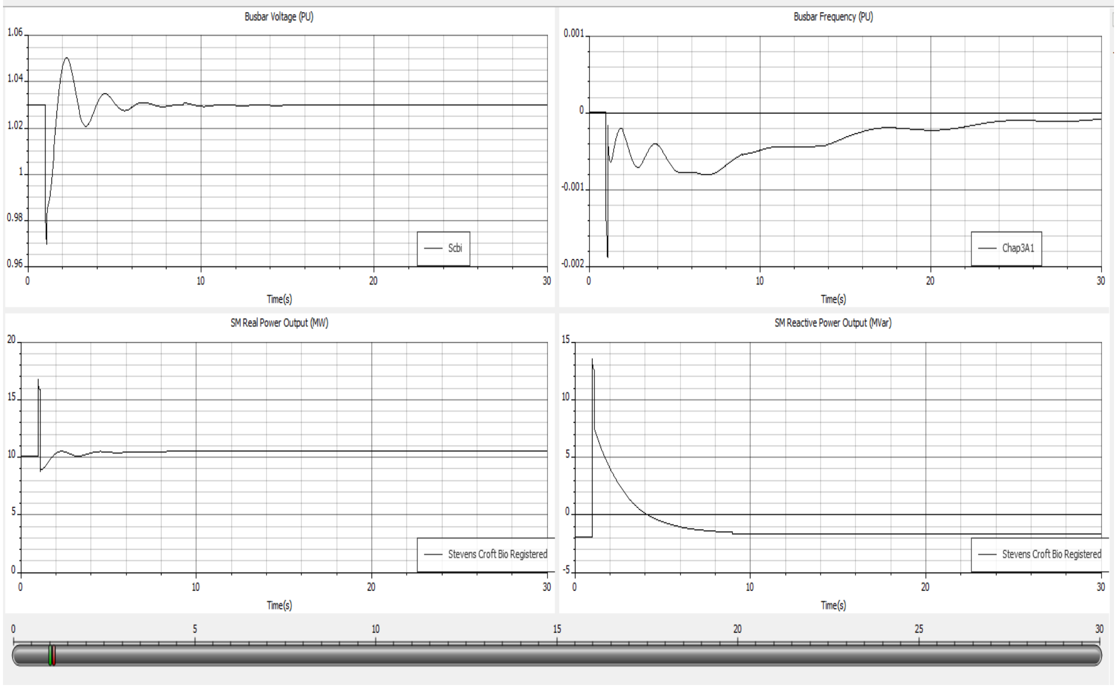
Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load, 50ms Load Bank switching

Result: 0.15% frequency dip, 4.5% voltage dip



Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load, 100ms Load Bank switching

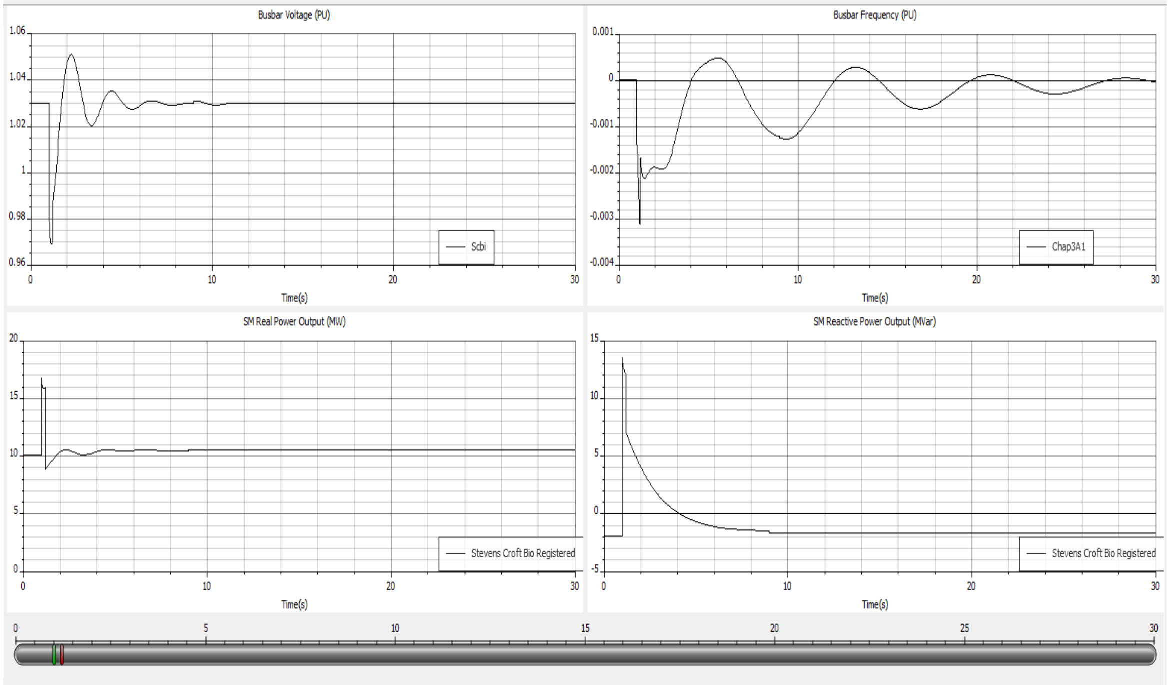
Result: 0.2% frequency dip, 6% voltage dip



Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load, 200ms Load Bank switching

Note: The switching delay was varied to investigate the effect of communications delays and operating delays in the overall microgrid blockload capability.

Result: 0.3% frequency dip, 6% voltage dip



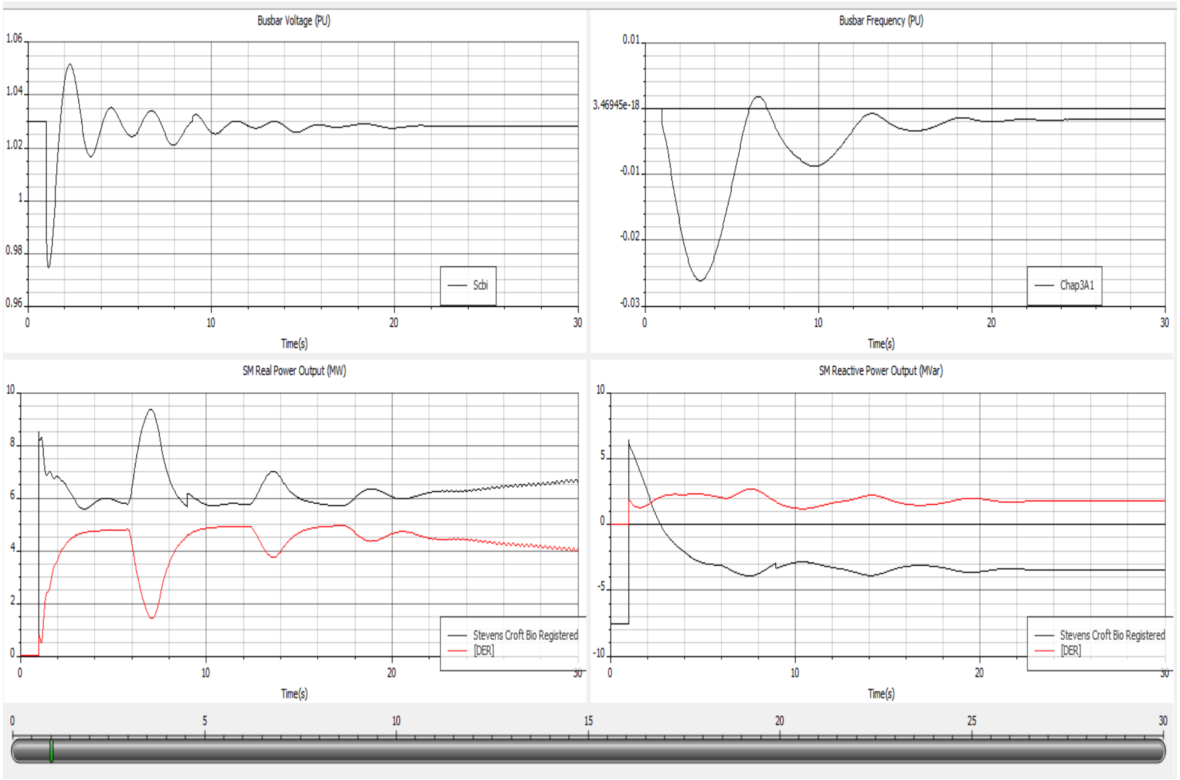
Evaluation 3 – Block Loading with DER Voltage Support

There will be scenarios on a Microgrid where the Anchor Generator is supported by other DERs of varying technologies that can provide support to the Anchor in the form of reactive power.

In this evaluation a second generator has been added with AVR and governor including 4% droop response representing a small wind farm etc. The generator is 5MVA and initially at zero output. It is connected to the system by a 33/11kV 10MVA transformer. In this evaluation the load bank response has been disabled to study the effectiveness of the DER support.

The load switched in is the original 10MVA transformer plus 10MW, 5MVAr demand. There is a 2.5% frequency dip, reduced from 4% for the case with only the anchor generator. The voltage dip has reduced from 6% to 5.5%. The first peak of the voltage dip is therefore unaffected by the presence of the anchor generator AVR. Power swings do occur between the anchor and the DER which may require a PSS (Power System Stabiliser) in some cases.

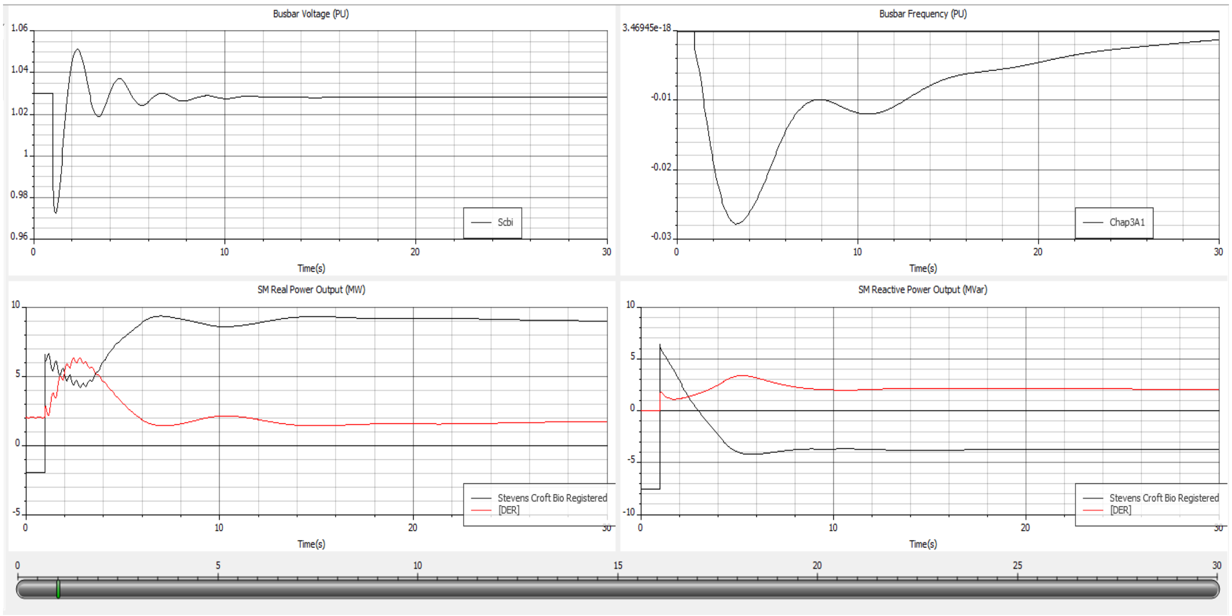
Therefore, the block load capability of the system remains at 10MVA due to the voltage limits.



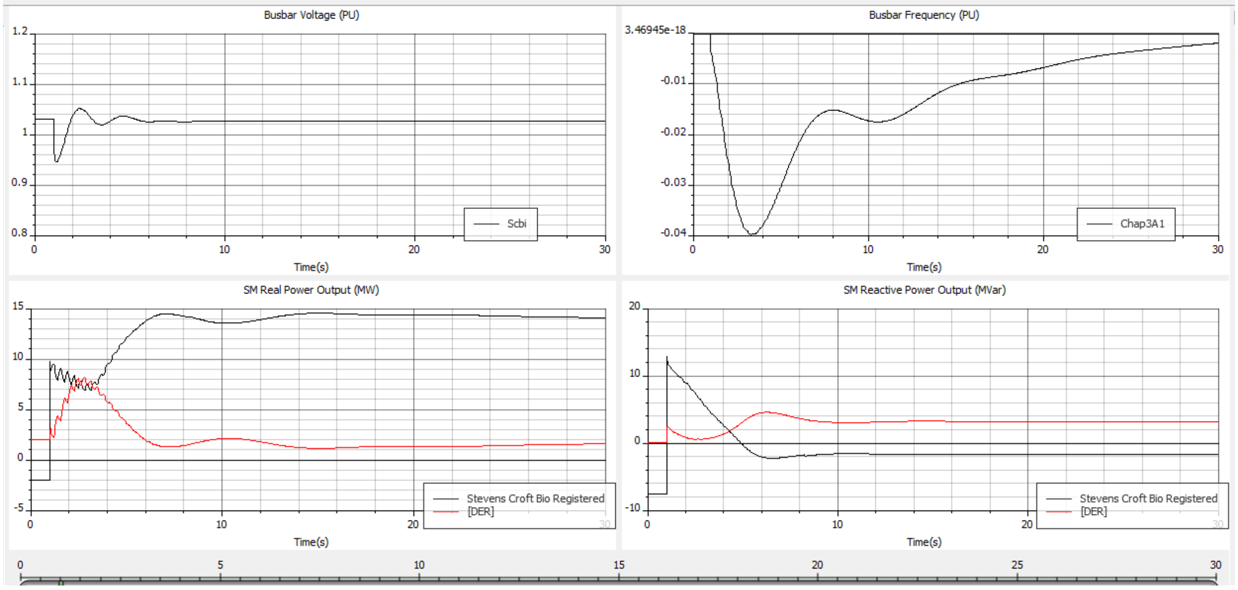
Evaluation 4 – Block Loading with DER Synthetic Inertia (Frequency Resp.)

There will be scenarios on a Microgrid where the Anchor Generator is supported by other DERs of varying technologies that can provide support to the Anchor in the form of active power based on frequency response.

Synthetic inertia model is added to the 5MW DER. The DER in the model operates at 2MW. With the same 10MVA demand switching as for previous baseline evaluations the results are as follows:



With a 15MVA demand the frequency dip reaches 4% and therefore the study below represents the maximum block load capability of the system:



The study shows that the initial voltage and frequency transients are largely unchanged, but the frequency recovery is however smoother. The effect of the synthetic inertia can be seen in the DER MW response. It increases during the initial frequency dip then falls off as the frequency starts to recover. This increases the block load capability from 10MVA to 15MVA.

With faster communications infrastructure an additional control loop could be deployed to improve the overall droop response of the DER.

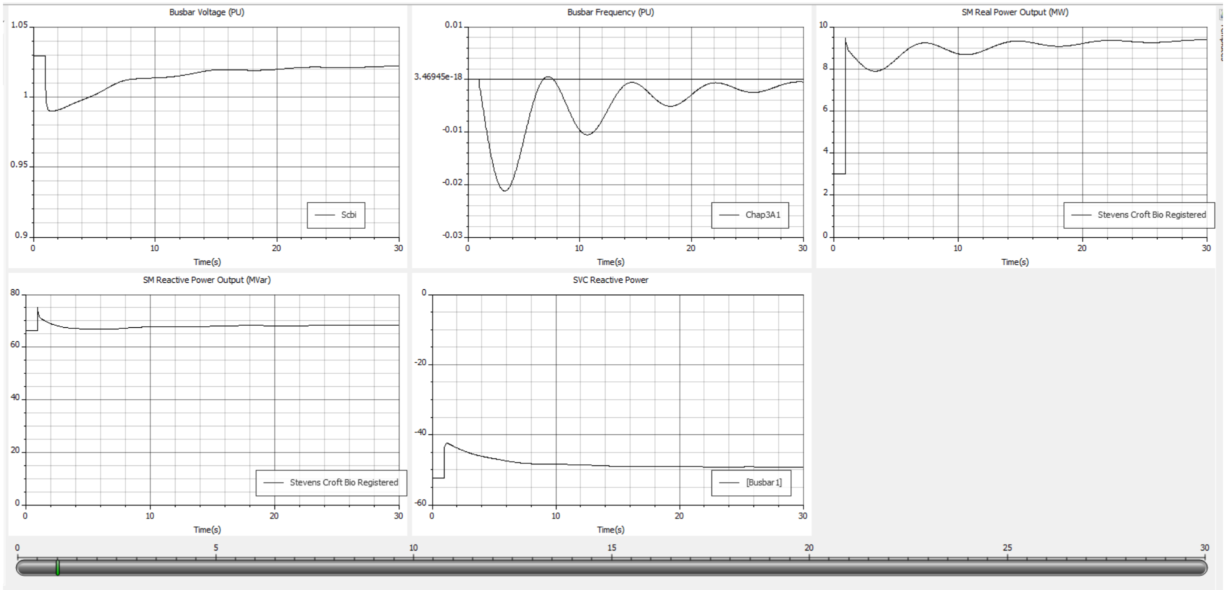
Evaluation 5 – Block Loading with SVC/Statcom

There will be scenarios on a Microgrid where the Anchor Generator is supported by other DERs of varying technologies that can provide support to the Anchor in the form of reactive power, such as an SVC or Statcom.

The study used a transformer inrush model with 2pu peak inrush on rating. The initial generator voltage is 1.03pu but 33kV voltage is controlled to 1.00pu to reduce the SVC steady state load. This has been configured to provide a 10MVAr swing in response to the block load switching.

Test Condition: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load:

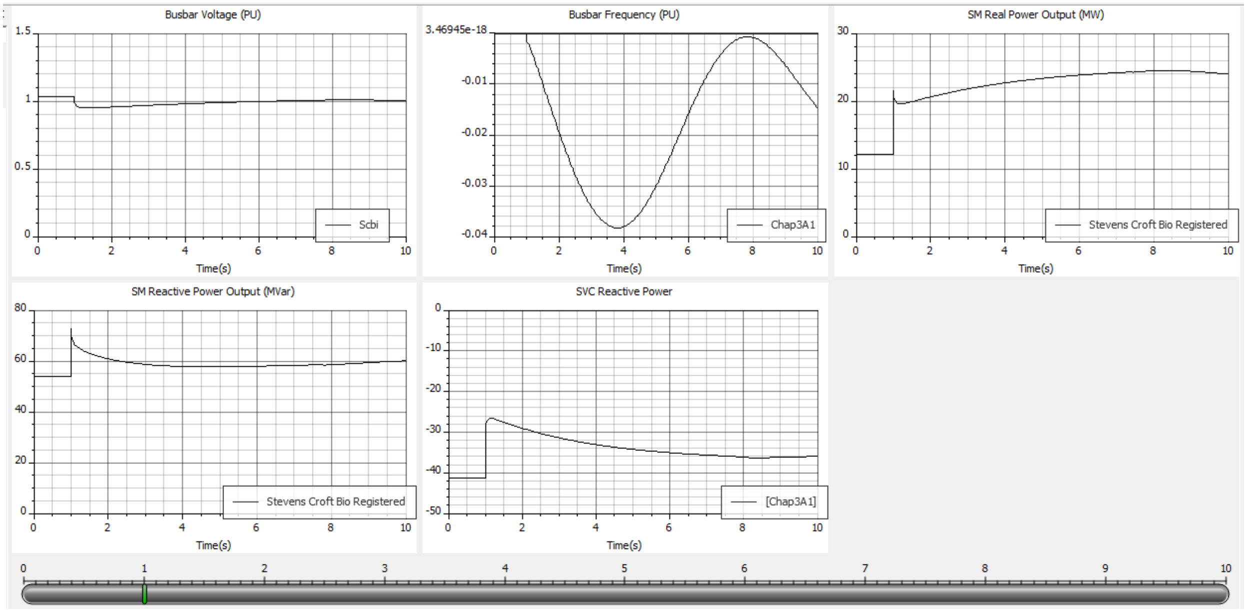
Results: 2.0% frequency dip, 4% voltage dip. Without SVC/Statcom the base case result was 4% and 6% respectively.



Test Condition: 20MVA Transformer Energisation with 20MW, 7.5MVAr LV Load:

Results: 4.0% frequency dip, 5% voltage dip. This represents the maximum block load capability due to the frequency limits.

Without SVC/Statcom the base case result was 4% and 6% respectively for a 10MVA demand.



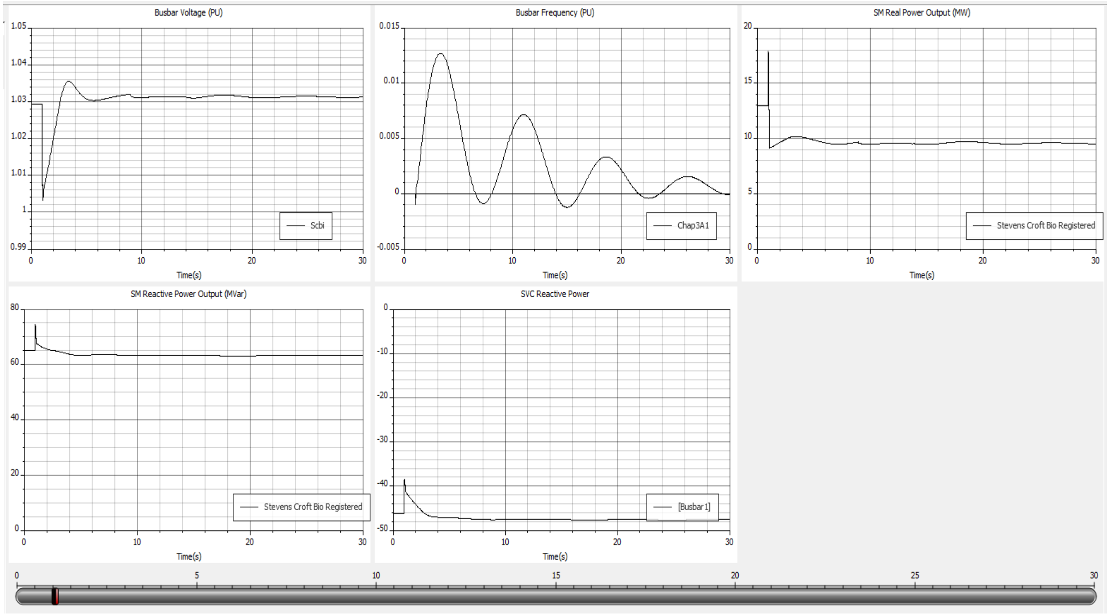
Evaluation 6 – Block Loading with Battery Support

There will be scenarios on a Microgrid where the Anchor Generator is supported by other DERs of varying technologies that can provide support to the Anchor in the form of active AND reactive power, such as a Battery.

Battery operation has been simulated by using 10 switched loads of 1MW. There is a 10ms delay between each load being switched in so that a total of 10MW is switched in within 100ms following the transformer energisation. SVC is still switched in.

Test Conditions: 10MVA Transformer Energisation with 10MW, 5MVAr LV Load,
Battery Operation:

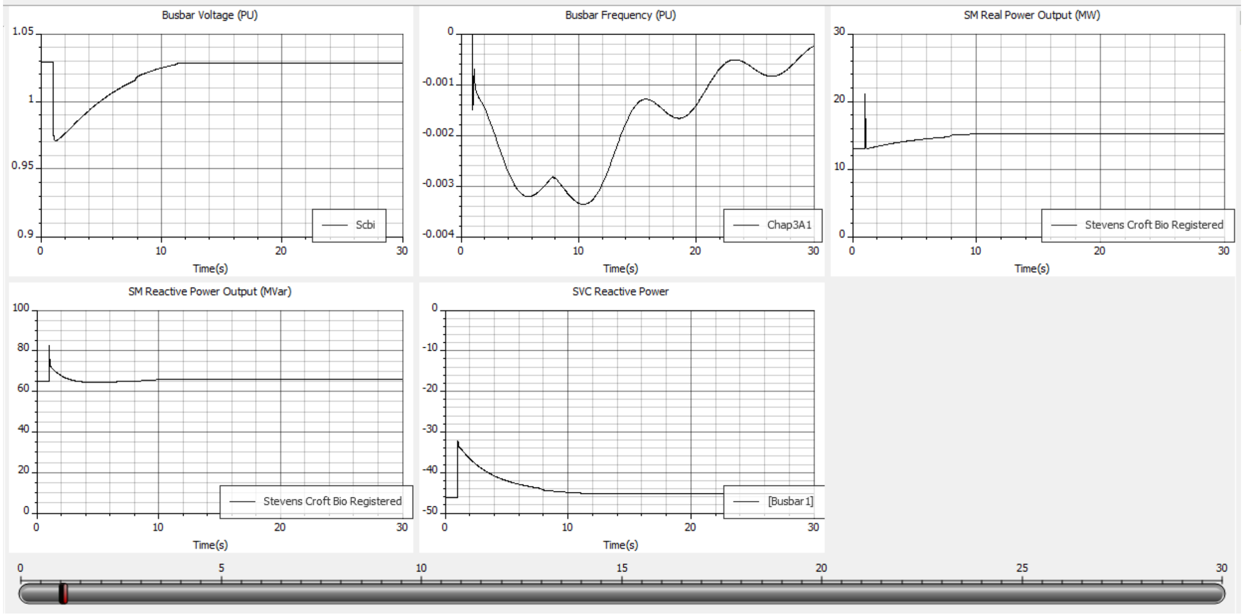
Results: 1.2% frequency rise, 2.5% voltage dip. Base case result without battery was 4% and 6% respectively.



Test Conditions: 19MVA Transformer Energisation with 19MW, 9.5MVAr LV Load, Battery Operation:

Results: 0.4% frequency rise, 6.0% voltage dip. This represents the maximum block load capability due to the voltage limits.

Base case result without battery was 4% and 6% respectively for a 10MVA demand.



ZIV Automation UK Ltd
5 Bamburgh Court
Team Valley Trading Estate
Gateshead
Tyne & Wear
NE11 0TX

ZIV Automation Ireland Ltd
The Burton Chambers
19—22 Dame Street
Dublin
Ireland

ZIV Automation Ltd
Parque Tecnológico
210 Zamudio
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