Using Virtual Synchronous Generators to Resolve Microgrid Protection Challenges

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***Abstract*—Microgrids and related microgrid technologies enable networks to keep power on when the normal supply is unavailable as well as provide the ability to support high penetrations of renewable and distributed generation. Microgrids, particularly those that operate with significant penetrations of renewable generation, present unique protection challenges. One challenge is a shortage or absence of inertia that can leak to system stability issues and, from a protections standpoint, rapid protection operation. Another challenge is that the fault current characteristics of inverter-based generation in the microgrid are very different from synchronous generators and can vary by vendor, product, and settings.**

A Virtual Synchronous Generator (VSG) in a Battery Energy Storage System (BESS) can address these two challenges. A VSG consists of an inverter with intelligent controls and automation. As the name implies, a VSG has characteristics that are like a synchronous generator. The short circuit capabilities and ability to supply virtual inertia provide a solution to these two challenges. In addition, because it is based on inverter-based power electronics, the VSG provides fast responses that can be tuned to suit the needs of the application. The combination of a VSG in a BESS with smart automation also enables distributed black start support, including from 100% renewable generation.

A BESS with VSG was demonstrated in a large renewable microgrid in South Australia. The ESCRI-SA Dalrymple project went into operation in 2018, and supports a 91 MW wind farm, more than 3 MW of distributed rooftop solar interconnected with hundreds of kilometers of transmission and distribution lines. This project is characterized by high reliability and is a critical component of the protection schemes the transmission system operator (TSO) uses for customer reliability in a network with high renewable share, both outside and within the microgrid. providing support across the TSO's network and within the microgrid through seamless islanding capabilities. This work describes the protection used, characterizes it in the framework of common North American protection schemes, and provides insight on adapting the grid-forming technology and approaches from South Australia to North American utility networks.

Keywords—microgrid; protection; battery; virutal synchronous generator

I. INTRODUCTION

Electricity networks globally are deploying increasingly higher contributions and penetrations of renewable generation. At the same time, network stress from increasingly severe climate and weather events, are creating reliability challenges for electrical networks. Battery energy storage systems (BESS), particularly those leveraging microgrid technologies, can successfully meet these challenges at utility-scale.

A. Virtual Synchronous Generator (VSG)

VSG are an application of control and automation to power electronic inverters. They are part of the broader class of Virtual Synchronous Machines (VSM) that are designed to mimic the behavior of traditional synchronous generators, including reciprocating diesel generators and gas turbines, and synchronous condensers. VSM allow grid-forming inverters to provide network stabilization services that have been traditionally sourced from synchronous generators, as shown in Fig. 1.

In addition to providing ancillary services that traditional synchronous generators provide, VSGs offer high-speed, low-latency response enabling operation with high renewable penetration and seamless islanding to improve reliability. More information about the practical applications and algorithms for VSG may be found in [1].

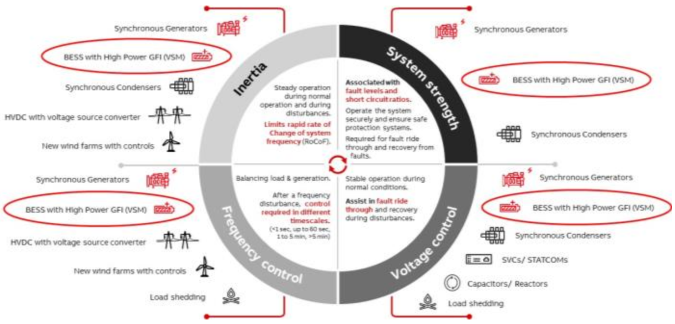

Fig. 1. Technology map of four ancillary services that stabilize grids [2]

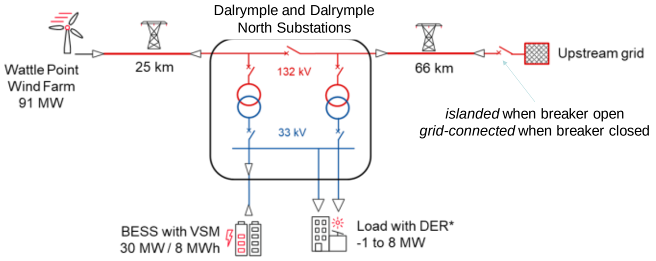

Fig. 2. High-level single line diagram of major microgrid network assests

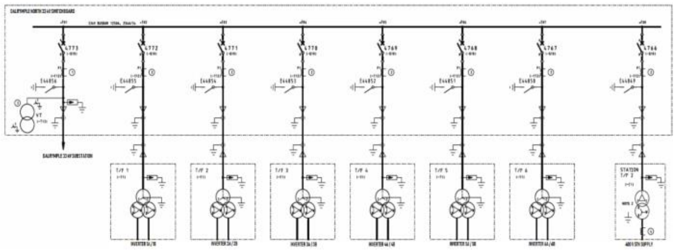

Fig. 3. Dalrymple North 33 kV switchboard

B. ESCRI-SA Dalrymple BESS

The ESCRI-SA Darlymple BESS is in a 33 kV medium voltage network at the end of a long 132 kV radial feeder on the Lower Yorke Peninsula. The 132 kV feeder interconnects the 91 MW Wattle Point Wind Farm with the rest of the South Australia state network, as well as several local towns on the peninsula. Combined, the local towns have a native peak load of about 8 MW and host more than 3 MW of solar photovoltaic generation embedded in the network, primarily on rooftops or otherwise in the distribution system. Prior to the commissioning of the BESS, the peninsula would have 4 to 5 unplanned outages per year due to frequent lighting strikes interrupting the service from the single radial supply line. When islanded from the rest of the upstream state network, all generation in the microgrid comes from solar and wind. The network can operate continuously on [100%] renewable generation when there is adequate wind and solar resource. The BESS was established in a new terminal substation, the Dalrymple North substation. See Fig. 2.

The network serving the rest of the state of South Australia also features significant renewable generation. In 2019, the combined installed capacity of wind and solar generation was about 2400 MW, representing about 170% of the average system demand of 1400 MW, and more than five time the minimum demand [3]. The South Australia state network connects with the rest of the east Australian National Electricity Market (NEM) network via two connections: the 150 kV, 220 MW Murraylink bipolar HVDC connection and the 650 MW Heywood Interconnector 275 kV double-circuit AC connection. The South Australia electric network is operated by the transmission system operator (TSO), ElectraNet.

II. Transmission, Distribution, and Battery Protection

Satisfactory performance of the existing transmission and distribution protection systems under both grid-connected and islanded conditions is a fundamental requirement. The microgrid includes the protection systems at Wattle Point Windfarm, Dalrymple 132 / 33 kV substation, the ESCRI-SA Dalrymple BESS facility and the Dalrymple distribution network. These protection systems include 132 kV feeder current differential and distance protection, 132 / 33 kV transformer biased differential protection, 33 kV high impedance bus zone protection, 33 kV feeder distance protection, and 33 kV and 11 kV overcurrent protection.

The connection and protection arrangements between Dalrymple North and the existing Dalrymple substation are relatively straight-forward and conventional. Dalrymple North substation comprises of an 8 panel 33 kV switchboard, which is connected to the Dalrymple substation's 33 kV bus via an incoming 33 kV circuit breaker and a 33 kV buried cross-linked polyethylene (XLPE) cable of around 1 km in length. In addition to the incomer from Dalrymple substation, the Dalrymple North 33 kV switchboard houses 33 / 0.375 kV generator transformer circuit breakers and a 33 / 0.4 kV station supply transformer circuit breaker. Fig. 3 illustrates the 33 kV arrangement at Dalrymple North substation.

At Dalrymple substation, the existing 33 kV bus zone high impedance protection was extended to include the Dalrymple North connection. The 33 kV cable between Dalrymple and Dalrymple North substations is protected by duplicated current differential protection using an optical fiber communications media that was installed with the power cable. The current differential protection relays at Dalrymple substation also include the connection point frequency and voltage protection mandated by Australian National Electricity Rules. The Dalrymple North 33 kV switchboard is equipped with current checked arc flash detection arranged to protect the 33 kV bus and configured to trip all circuit breakers. Each transformer feeder circuit breaker is equipped with overcurrent and earth fault protection incorporating an instantaneous high set stage and a time delayed low set stage.

Integrating the ESCRI-SA Dalrymple BESS into the edge of the South Australian network presented a series of challenges to ElectraNet's existing protection and control systems. To prevent potential out-of-phase reclose, the existing transmission system auto-reclose systems needed to be modified. Existing transformer automatic voltage regulation schemes at Dalrymple substation's 33 kV connection bus were required to be modified to allow the BESS to perform the voltage regulation function. Existing protection systems required assessing to determine satisfactory performance under both grid-connected and islanded conditions.

The BESS was specified with a minimum 800 A @ 3 sec fault contribution at the Dalrymple 33 kV bus and it was initially envisaged during conceptual design phase that satisfactory settings could be applied to all protection systems within alternate setting groups invoked during islanded conditions, automatically, via a signal from the Islanding Detection Scheme (IDS). In addition to integration with the IDS, the BESS participates as an asset in the System Integrity Protection Scheme (SIPS), supporting stable operation of the broader South Australian electricity transmission network during contingency events.

A. System Integrity Protection Scheme (SIPS)

On September 28th, 2016 in the mid-north region of South Australia, during what has been described as a one in fifty-year storm, two tornados severely damaged three 275 kV transmission lines causing them to trip. Nine windfarms connected to these lines significantly reduced their output in response to the faults which developed as a result of the damage to the transmission lines. As the output from the connected synchronous generation sources within the Australian NEM network automatically increased in an attempt to rebalance generation and load, the angular separation between the South Australian electricity transmission network and the remainder of the Australian NEM network increased to the point where system stability could no longer be maintained. At this time an automatic remedial action scheme detected the loss of synchronism and islanded the South Australian electricity transmission network to stabilize the remainder of the Australian NEM network. Following islanding the frequency collapsed at a rate of 6 Hertz per second resulting in a system blackout event that caused over 850,000 customers to lose power. The resulting analysis of the event published by the Australian Energy Market Operator (AEMO) recognized that with the increase of renewable generation, it was necessary to consider alternatives to traditional synchronous generators for the provision essential non-energy system services (such as voltage control, frequency control, inertia, and system strength). AEMO concluded that, following multiple losses of generation and subsequent disconnection from the Australian NEM network, the South Australian network is unlikely to be stabilized through traditional under frequency and under voltage load shedding systems and the consequent blackout system is inevitable. AEMO offered 19 key recommendations, including the development of special protection schemes and modified operational procedures to improve network stability [4].

The System Integrity Protection Scheme (SIPS) is a remedial action scheme that was developed to prevent similar events and "is designed to detect multiple generation loss in South Australia and respond appropriately to prevent separation of the South Australian power system from the NEM. The SIPS was commissioned in December 2017 (with the ESCRI SA Dalrymple BESS component of the scheme commissioned in December 2018)." [ibid]

The SIPS incorporates the following three discrete stages:

Stage 1) A directional, active power measurement element arranged to measure the import power across the Heywood Interconnector and in the event of the active power import breaching an 800 MW threshold, or a rising above 700 MW at a rate of increase in excess of 1.67 MW/s, trigger fast MW injection response from BESS;

Stage 2) A predictive Out-of-Step Trip Scheme arranged to detect impending loss of synchronism between the South Australian network and the remainder of the NEM network and provide response by tripping 200 MW of load from various distribution substations within South Australia; and

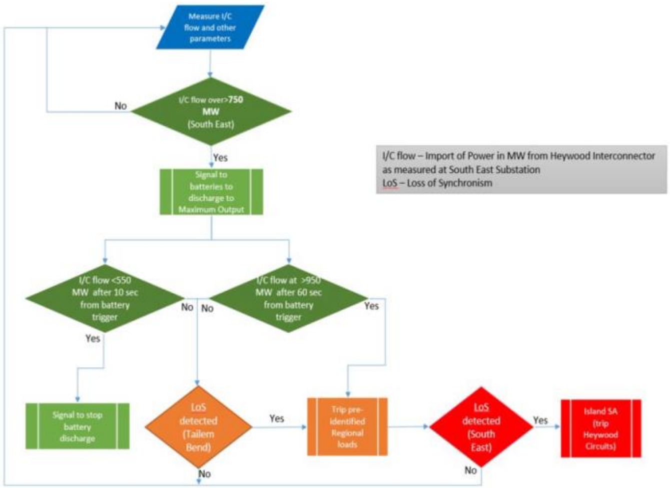

Fig. 4. Schematic of the design of the SIPS [5]

Stage 3) The existing Out-of-Step Trip Scheme which is arranged to detect the loss of synchronism between the south Australian network and the remainder of the NEM network and sever the interconnection to prevent disturbances emanating in South Australia spreading into the remainder of the NEM network.

Stages 1 and 2 are implemented to stabilize power swings that would otherwise lead to Stage 3. Power system studies undertaken by both ElectraNet and AEMO demonstrated that for the majority of contingencies, including simulations of the 2016 System Black[out] event, operation of the SIPS would successfully check unstable power swings and restore system stability. An overview of the SIPS operation is shown in Fig. 4.

During integration tests between the SIPS and the ESCRI-SA Dalrymple BESS, the BESS output ramped from 0 MW to 30 MW in under 250 msec after receipt of the SIPS signal, during which time it was able to hold the 33 kV bus voltage within satisfactory limits. Fig. 5 shows the BESS response to the SIPS trigger.

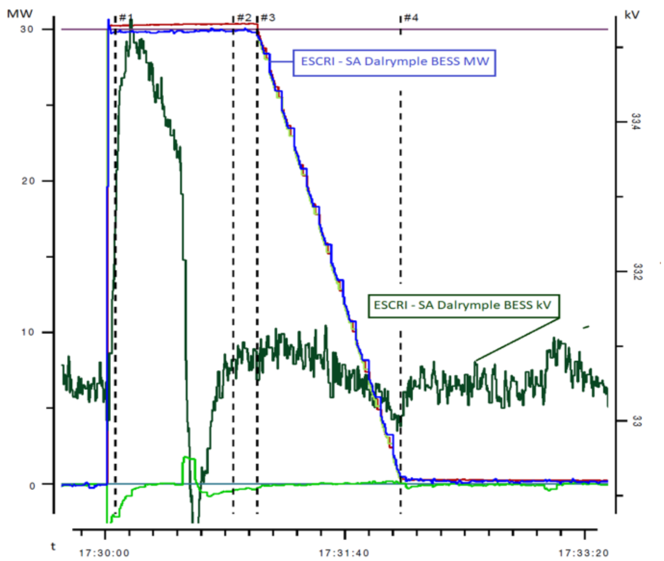

Fig. 5. ESCRI-SA Dalrymple BESS response to SIPS Stage 1 trigger

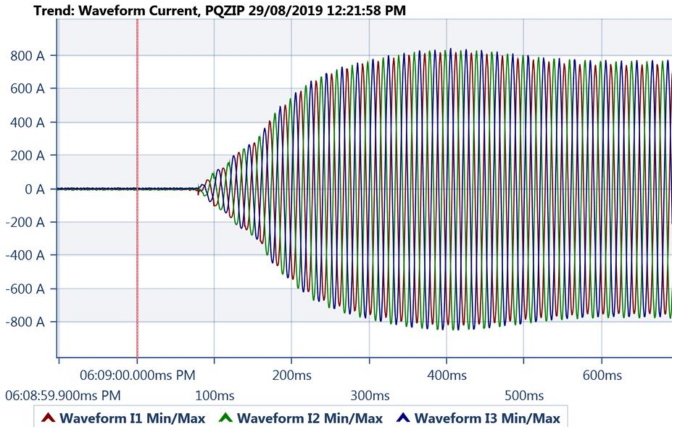

Fig. 6. Onset of fast power injection shown as three-phase currents from the ESCRI-SA Dalrymple BESS upon receipt of the Stage 1 SIPS trigger

The blue, red, and green lines in Fig. 5 shows the active power response from the BESS on each phase. The active power ramps sharply up to 30 MW at time #1, 17:30:00, and is held steady until time #3 (just after 17:31:00), and slowly ramps down until time #4 (just after 17:32:00). During this time, the BESS supports the system voltage (shown in black), which stabilizes after the initial ramp by time #2 (just after 17:30:50).

Fig. 6 shows the recorded output of three-phase currents from the BESS when commanded by SIPS to ramp the output up to the 30 MW nameplate capacity of the BESS. The instant of receiving the command is marked by the red vertical line in the plot – this is triggered by Stage 1 of the SIPS scheme, discussed previously. The BESS responds within 100 msec.

B. Islanding Detection Scheme (IDS)

A series of conceptual power system studies during the ESCRI-SA project conception identified that to guarantee stability within the microgrid in the event of a separation from the transmission network, Wattle Point Wind Farm's active power output must be curtailed to less than 30 MW within 150 msec of islanding. Although the dynamic response of the wind farm's Type 1 wind turbine generators to an islanding event results in an inherent active power output adjustment, a trip of a large portion of the wind far was deemed necessary to guarantee stability. The wind farm's 55 wind turbine generators are arranged into five collector circuit breakers designated by consecutive letters A-E. By tripping collector circuit breakers B-E in the event of an islanding occurrence, the wind farm's active power output is reduced to a maximum of 21.5 MW, which is within the continuous absorption capacity of the battery system. From there, the BESS's control system issues a MW limit to the wind farm to regulate its state of charge in islanded operation.

A range of local islanding detection methods were considered, including methods based on detecting vector shift and rate of change of frequency (RoCoF). However, they were subsequently discounted due to the large non-detection zone associated with the settings required to discriminate between non-islanding disturbances and potential nuisance tripping associated with the settings required to reliably detect all

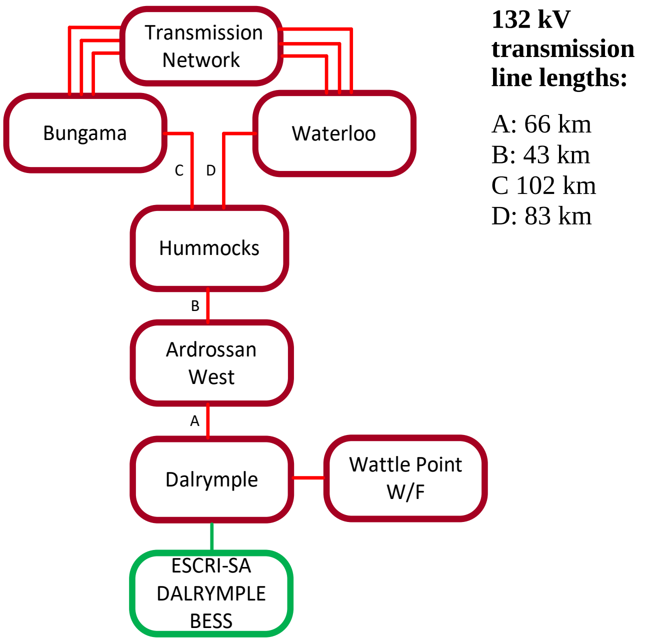

Fig. 7. Islanding Detection Scheme (IDS) Topology

islanding occurrences. Consequently, a remote IDS was implemented to monitor the connection of the radial network, primarily, at the Bungama and Waterloo substations, where stronger interconnection is achieved north of Dalrymple. The IDS comprises a Central Unit deployed at Dalrymple Substation and four Peripheral Units deployed at Ardrossan West, Hummocks, Waterloo and Bungama substations. Refer to Fig. 7 for a topology schematic.

The Peripheral and Central Units communicate over a redundant communications ring over a synchronous digital hierarchy (SDH) communications network. Protection signaling equipment is installed at Dalrymple substation and Wattle Point Wind Farm to facilitate a Direct Transfer Trip. The IDS detects islanding of the ESCRI-SA Dalrymple BESS by monitoring the status of the switchgear at Dalrymple, Ardrossan West, Hummocks, Bungama and Waterloo substations and the operation of protection systems associated with the (A) Dalrymple – Ardrossan West, (B) Ardrossan West – Hummocks, (C) Hummocks – Bungama or (D) Hummocks – Waterloo transmission lines. Each Peripheral Unit monitors the switchgear and protection systems within the substation where it is located. The Central Unit monitors the switchgear and protection systems at Dalrymple substation and initiates the necessary trip and control functions. In total, 15 circuit breakers, 32 disconnectors and 16 protection relays are monitored by the IDS. Islanding of the ESCRI-SA Dalrymple BESS is declared by the disconnection of line A or line B or the disconnection of lines C and D (A+B+[C.D]).

In the event of the IDS detecting disconnection from the network, the Central Unit initiates the tripping of circuit breakers at Dalrymple substation to localize the microgrid, initiates the tripping of the collector circuit breakers at Wattle Point Wind Farm and provides an indication to the VSG controller that islanding has occurred. On restoration of the upstream network, either by auto-reclose systems or manually, the IDS provides an indication to the Network Control Operator that the automatic sequence which re-synchronizes the microgrid to the network may be initiated.

The IDS was utilized to address some of the challenges presented by the integration of the BESS into the transmission network. The IDS receives a state of health signal from the BESS controllers which is combined with its own internal monitoring logic. If the BESS controllers and the IDS are healthy, outputs from the IDS are used to block the existing Dalrymple auto-reclose and voltage regulation systems. In the event of the IDS or BESS developing a fault the blocking signals are removed and the existing auto-reclose and voltage regulation systems are restored.

C. *Local BESS protection*

The grid forming inverters are at the core of the ESCRI-SA Dalrymple BESS. In addition to all other protection devices discussed previously, the inverters employ inbuilt passive protective elements alongside external protection devices. Those are kept to a required minimum set of functions and include:

- Under- and overvoltage;
- Under- and overfrequency;
- Overcurrent protection on the inverters and AC circuit breakers;
- DC cable overload protection;
- Fuses on AC and DC sides of the inverters and within the battery racks;
- Temperature, over- and undervoltage, overcurrent protection within the Battery Management System;
- Insulation monitoring.

When islanded, the BESS operates as the voltage/frequency reference in the microgrid and is the largest generating asset remaining online. It therefore requires the capability not only to withstand the faults on the network but also to provide an adequate amount of fault current for clearing faults on the 33 kV distribution feeders, the 132 kV line to the Wattle Point Wind farm, as well as within the Wattle Point Wind Farm itself. To boost reliability of supply, the protection settings on these elements were set quite wide such that the selectivity is warranted. This provides the protection devices within the network and the wind farm a chance to clear the fault, and the BESS is the last asset to trip. The BESS inverters have a capability to supply up to 2 per unit (pu) of rated current up to 2 seconds, and for longer duration if the overload is smaller magnitude. This is achieved primarily through appropriate heat management within the inverter modules.

The same protection settings are kept in grid connected and islanded operation to enable a proper response from the BESS to the bulk electric system operation within wide voltage and frequency ranges. Overfrequency protection settings facilitate a transition to islanded operation, which is commonly accompanied by a large frequency transient. This supports unplanned islanding events when the wind farm is generating up to its nameplate capacity of 91 MW, which is about three times the continuous rating of the 30 MW BESS.

One of the challenges encountered in the project execution was related to the requirement to guarantee continuous uninterrupted operation of the BESS when exposed to frequency disturbances, particularly steep Rate of Change of Frequency (RoCoF) events in the NEM. South Australia imposes a mandatory requirement for connecting generators to withstand 3 Hz/sec for 1 sec and 4 Hz/sec for 250 msec. The former is more challenging to achieve due to its longer duration and invokes a longer inertial response from the BESS. Identical to a traditional synchronous generator, the virtual inertia of the BESS reacts to RoCoF events and injects/absorbs power for negative/positive RoCoF events, respectively. The inertia time constant of the BESS was configured to provide +/-30 MW for a -/+3 Hz/sec RoCoF event. Thus, if a negative 3 Hz/sec grid RoCoF event coincides with a continuous discharge at 30 MW, the resulting total output from the plant could reach almost double of its nameplate capacity, albeit for only a few hundred milliseconds. While the BESS inverters are capable of such overload for a short duration, this was more challenging to achieve for the BESS batteries due to the relatively tight overcurrent protection in the Battery Management System, particularly when power absorption at nameplate capacity coincides with a positive RoCoF event. Although this is an extremely unlikely scenario, the issue was successfully solved through inclusion of additional functional logic on the BESS controller and a change to the Battery Management System settings in collaboration with the battery supplier.

III. Distributed Black Start Support

The ESCRI-SA Dalrymple BESS is capable of black starting the lower Yorke Peninsula’s 33 kV distribution network. This is achieved through a soft energization of the BESS coupling transformers (6 x 6 MVA) and one of the substation transformers (25 MVA) with the subsequent pick up of the two 33 kV distribution feeder at nominal voltage. The transformer energization instant is illustrated in Fig. 8 as voltage waveforms and Fig. 9 as current waveforms. While the voltage is ramped up over one second, the currents are so insignificant that they remain below the pick-up threshold of the high-speed recorder. This method eliminates transformer and cable inrush completely.

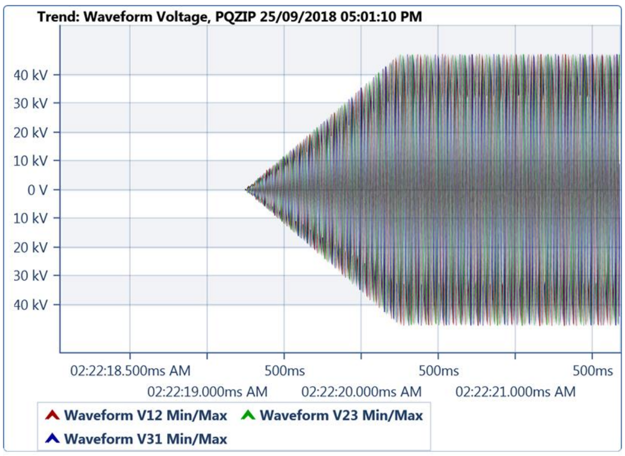

Fig. 8. Ramp-up of voltage by the BESS to soft energize transformers in the local network

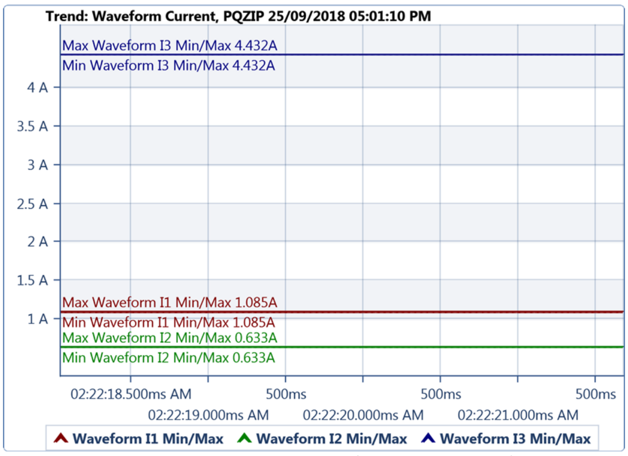

Fig. 9. Resulting currents when BESS soft energizes transformers were so small that they were not captured by the high-speed recorder

The active and reactive power profiles of the 33 kV feeders during this consecutive load feeder pick-up by the BESS are shown in Fig. 10. The typical inrush profile occurs as cold load is picked up and the downstream distribution transformers are energized at nominal voltage.

Traditionally, system restoration is carried out in a top-down direction, that is, initially black start units at the large power generation stations are restarted following a system blackout event. Subsequently, the transmission lines and transformers are re-energized, allowing the cranking power to flow to other plants and incrementally restoring supply to loads.

The ESCRI-SA Dalrymple BESS has demonstrated that the power supply can be quickly restored locally using an appropriate grid forming inverter with utility-scale energy storage. Fault current is available from the BESS once it is up and running in islanded operation. Eliminating the transformer inrush also reduces the potential of harmful overvoltage effects, such as switching and harmonic overvoltages and ferroresonance. In general, it is advisable to load the live system as soon as practical to introduce damping and prevent resonance effects.

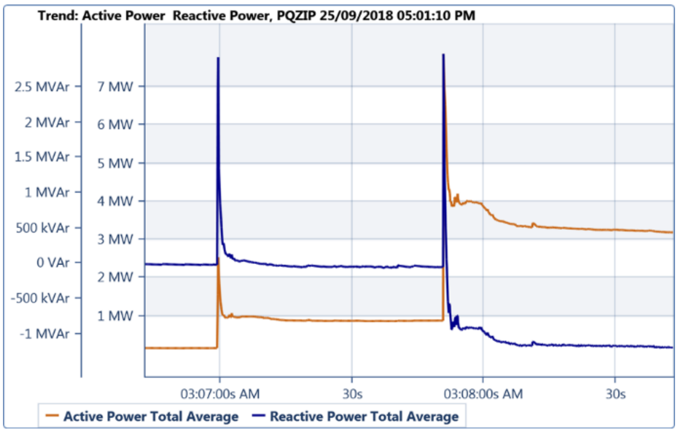

Fig. 10. BESS active and reactive power profiles for consecutive energization of two 33 kV distribution load feeders

During energization, the frequency and voltage need to be maintained within an acceptable range. Since the VSG in the grid forming inverter behaves similarly to a synchronous generator the dynamics of the system behavior will be dictated by the selected parameters of those control components. The parameters of the VSG's synthetic inertia, governor, Automatic Voltage Regulator (AVR), and rotor flux model can all be selected. Depending on the desired parameter values, the frequency and voltage variations during the restoration process may be temporarily allowed to go outside of the preferred bounds. The selection of these may also be constrained by other operational requirements, such as the inertial response in grid-connected operation.

Some advanced converters have the capability to switch parameters dynamically while operating, which allows adjustments for specific situations. This allows the VSG to be tuned for specific scenarios. For instance, the magnitude of the virtual inertia can be raised for the black start process making the frequency stiffer. Care needs to be taken when selecting parameter values since changing parameters of some, in particular faster inner control loops, may lead to undesired interaction between the BESS and power system devices and cause oscillations. System restoration may involve complex phenomena that are best studied using Electromagnetic Transients (EMT) simulation models.

The system restoration approach from the VSG BESS can not only reduce outage time from rapid pick-up of the distribution system but can also serve as a source for energization of upstream transmission lines. This bottom-up approach to system restoration provides additional flexibility in system operation. However, the flexibility from these capabilities can add complexity in managing system restoration out of multiple additional locations. With an appropriate level of network automation, operator intervention can be reduced to a reasonable minimum.

IV. Protection Schemes Context for North America

The ESCRI-SA Dalrymple BESS offers several features that are likely to be increasingly desirable in North American networks, particularly as the adoption of variable renewable generation continues to accelerate. The protection schemes presented here are based on the Australian market but are readily adapted to North American schemes.

From a North American terminology point of view, the System Protection Integrity Scheme (SIPS) that is used for the ElectraNet state grid is a term that is defined broadly. IEEE includes Special Protection Systems (SPS) and Remedial Action Schemes (RAS), among several other schemes within SIPS [6]. SIPS is an overly inclusive term for use in the NERC reliability standards [7].

Although SPS and RAS have been used interchangeably in the past, in NERC territory RAS replaced SPS. Refer to [ibid]. However, the SIPS in this project could not formally be classified as a Remedial Action Scheme (RAS) as defined by North American Electric Reliability Corporation (NERC), because it, for example, also includes Out-Of-Step (OOS) protection [8].

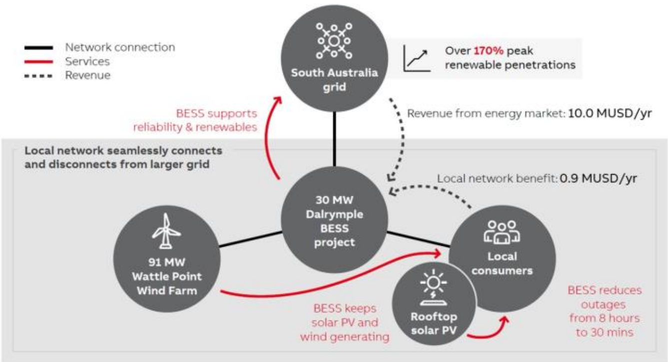

Fig. 11. Summary of the network and revenue benefits for the ESCRI-SA Dalrymple BESS [9]

V. Conclusion

The Dalrymple BESS provides regulated network benefits by increasing stability and reliability. The ability to integrate these services in with the protection and control schemes affords the project a variety of new values that stack to provide benefits for the network operator. In addition to supporting protection schemes across the state, within the microgrid, and within the BESS, the BESS also provides non-regulated benefits by participating in energy markets. Market participation results in new revenue opportunities to keep costs low for the benefiting network customers.

The regulated network benefits include providing back up to towns in the area, by seamlessly transitioning to an island with the wind farm when upstream outages occur and reducing unserved energy for ElectraNet's customers. When it is interconnected with the NEM in non-islanded operation, the system provides both virtual inertia and fast active power injection to enhance the reliability of South Australia's network and support power system operation with the high penetration of wind and solar in the state. It also assists the interstate interconnectors with stability and reliability of the state's power system. Along with these regulated benefits, the project increases its commercial value by participating in the national electricity market (NEM) providing frequency ancillary services and energy arbitrage. A summary of the economic and technical benefits of the project to the network is given in Fig. 11.

VSG can improve the stability and reliability of utility networks. By mimicking the technical operations of traditional synchronous machines, but with tunable and very fast performance, the protection and controls to integrate them into the network can be adapted to fit within traditional protection schemes. Beyond integration benefits, the ESCRI-SA Dalrymple BESS has also added a significant contribution to two of ElectraNet's protection schemes, the SIPS and IDS. For ElectraNet, the BESS with VSG have strengthened the performance of their protection and control systems. For example, since the BESS commissioning there have been several unplanned islanding events. With the support of the VSG, the local network has experience improved continuity of supply, reducing Dalrymple customer outages from 11 hours down to 30 minutes over the first 2 years of commercial operation.

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