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***Abstract*— Battery energy storage systems (BESS) are being deployed to provide a range of power system services. In this paper, the voltage support capabilities of a 10 MVA, 5 MWh BESS installed at a thermal power plant are explored. The study specifically relates to the voltage dips caused by starting of large boiler feed pump motors on the 11 kV supply of the power plant. The benefits of reactive power injection from BESS are explored via simulation and validation is provided from tests on the actual plant. The likely reduction in voltage dip if the BESS can contribute its rated reactive current is quantified. As a result, the motors experience higher starting torque and peak current, however as they start more quickly, the contribution to heating is expected to reduce. The effect on provision of other services demanded from the BESS and wider opportunities to provide voltage support are discussed.**

***Index Terms*— Batteries, energy storage, induction motors, reactive power, voltage control.**

I. Introduction

BESS are currently being deployed in power systems to provide a range of services, usually relating to peak lopping or frequency response applications. This paper focuses on the voltage support capabilities of a BESS, connected to the in-station 11 kV busbars of a conventional power plant, to improve regulation for the site load. The BESS is a 10 MW, 5 MWh facility and was commissioned with the purpose of participating in frequency response system services in Ireland's electricity market. The system services provided are Primary, Secondary and Tertiary Operating Reserve (POR, SOR, TOR1). The ability of the BESS to engage in these and other frequency services such as Fast Frequency Response has been discussed in [1] and the economic and carbon implications have been presented in [2].

The system service market is growing in scale in power systems such as the island of Ireland, due the need to accommodate high system non-synchronous penetration (SNSP) from sources such as wind, photovoltaics and HVDC import [3]. These sources tend to displace synchronous generation plant, which to date have been providing most of the system services required. This necessitates finding alternative solutions to provide the system services necessary to maintain power system stability in networks that operate with low-inertia and fewer conventional generation units. These system services include reactive power support in addition to frequency and reserve services [4].

There are a range of devices specifically designed for, and thus more targeted towards, reactive power provision and voltage support than BESS [5], [6]. It is acknowledged that a BESS would not normally compete with these devices. However, when the BESS is already in place for other applications, as in this study, then there is merit is exploring the additional value that can be obtained from the existing resource.

Although in-station voltage support is a niche application, the work also extends to the use of BESS for reactive power support in distribution networks [7], [8]. Additionally, opportunities exist in power systems that have a high penetration of rurally located renewable energy, such as wind in Ireland. This results in a switch to more distantly located generation at times of high wind infeed, perhaps leaving large load centers without alternative voltage support facilities. This has restricted economic dispatch where conventional synchronous generation near large load centers is constrained-on for the purpose of voltage support [9]. The BESS analyzed in this paper is located at a power plant that may be constrained-on for this purpose.

This paper presents observations captured by Phasor Measurement Units (PMU) installed at the plant. A simulation in DigSILENT PowerFactory is used to determine the likely benefit of reactive power injection from the BESS. These results are compared with analysis of initial tests of the application on the actual BESS, followed by a discussion of the implication and benefits of providing this service.

II. Observations of Boiler Feed Pump Starting

The turbo-generator has several boiler feed pumps employing induction motors rated at 4.6 MW. Additional boiler feed pumps are started when the power plant output is to be

This work was supported by Innovate UK and EPSRC under Grant EP/N508408/1.

increased, thus these operations frequently occur while the plant is operational. The induction motors employ direct online starting, in star, and are fed through the same 11 kV supply as the BESS. Starting of the boiler feed pump motors causes a sizable voltage dip on the site. As this power plant is ageing there is concern over the effect of these regular perturbations to the site voltage on the various systems and protection equipment within the plant.

PMUs have been installed on the site to monitor the BESS and site load, both at 11 kV and also the terminals of the 17 kV synchronous generator. The locations of the PMU within the power station are shown as red squares in Fig. 1.

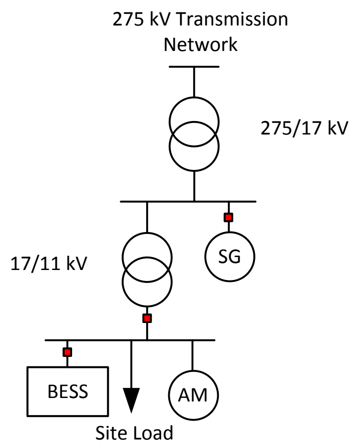


Figure 1. Connection of BESS, boiler feed pump and synchronous generator, with PMU monitoring locations in red.

The voltage on starting can be seen in Fig. 2. The voltage is observed to dip by 0.1 p.u. inside the power station, for approximately 4 seconds. The voltage on the transmission network and the turbo-generator 17 kV output only see minor fluctuations. Clearly such voltage variations inside a power station, particularly one that is aging, are not ideal.

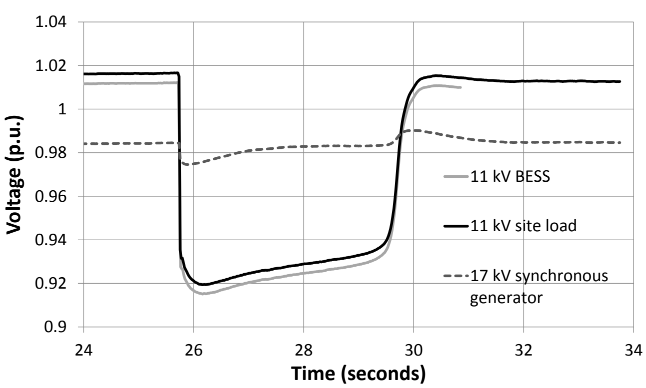


Figure 2. Voltage dip observed at the 11 kV site infeed, BESS and synchronous generator during motor starting.

Fig. 3 shows the reactive power drawn by the 11 kV network to support its voltage and the corresponding reactive power response from the synchronous generator. The contribution from the grid is estimated from these. Note that the PMU data is normalized to zero for ease of comparison. Prior to starting the motor, the synchronous generator was exporting approximately 25 Mvar and the site consuming approximately 12 Mvar. It is observed that the grid initially supplies a portion of the reactive power until the synchronous generator's excitation system reacts.

It should be noted that point on wave data from the PMU's fault recorder function indicates that saturation of the current transformers used by the PMU monitoring the 11 kV network occurs during this transient. The effect is most pronounced during the first second, meaning that caution should be exercised when interpreting the data from the start of the transient, for example, the active and reactive power calculated by the PMU.

Fig. 4 shows the active power drawn by the 11 kV network. The change can be assumed to be largely due to the starting of the boiler feed pump motor, with a small effect caused by the site load response to the voltage dip, such as from the power plant's other motors.

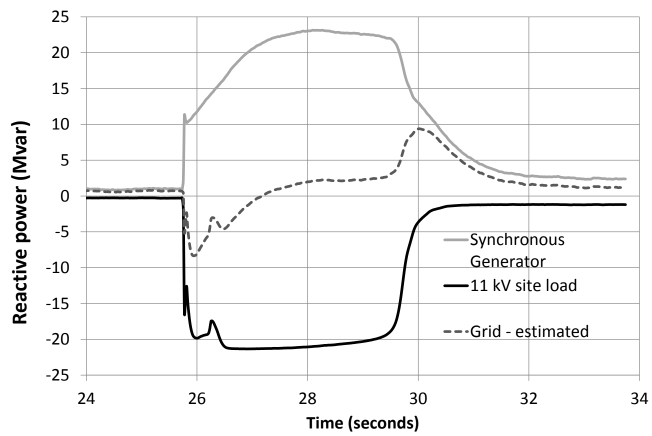


Figure 3. Reactive power drawn by the 11 kV site load, with synchronous generator response and estimated grid contribution.

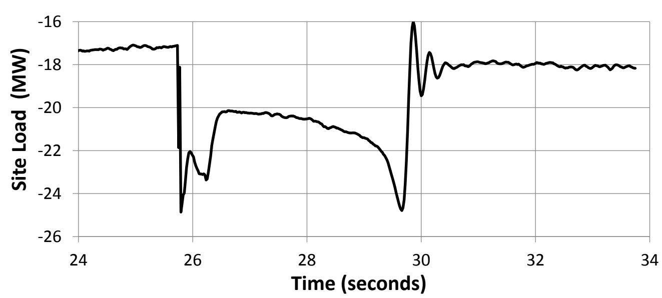


Figure 4. Active power of 11 kV site load during motor starting.

Given the location of the BESS, there is an opportunity to explore any support that can be provided. The BESS, while capable of reactive power support, is currently being used for active power export/import to support system frequency. Thus, any use of the converter for providing reactive current would have an effect on its ability to provide active power at the same time.

III. Simulation and Comparison with the Actual Plant

A. Simulation Set-up and Parameters

A simulation of the BESS and local network has been constructed in DigSILENT PowerFactory, and is representative of the schematic in Fig. 1. The key components are the BESS, motor, turbo-generator and 11 kV transformer. Standard models for these components are used [10].

In the model, the 4.6 MW motor's torque-speed characteristic and load are modified to be representative of both the actual motor data sheet and observed response. The 11 kV transformer is assumed to have a rating of 50 MVA, with a 16.6% reactance and X/R ratio of 70.

The tuned parameters used for the 'reactive path' of the PV controller in the DigSILENT BESS model are as follows; a reference voltage of 1.0 p.u., a measurement filter time constant of 0.02 seconds, which is intended include the response time of the BESS converter, and a maximum allowable reactive current of 1.0 p.u. rated converter current. The reactive current - voltage (Q-V) characteristic used is given in Fig. 5, which indicates example parameters. Results from two different sets of parameters for the Q-V characteristic will be presented; low gain / wide dead-band (Case-1) and high gain / narrow dead-band (Case-2). Case-1 represents an easily realizable implementation, while Case-2 will give an indication of the best response that can be achieved, although it might prove difficult to deploy on actual plant. The voltage dead-band and the gain used to translate voltage error to reactive current (both in per unit) are given in Table I for the two cases.

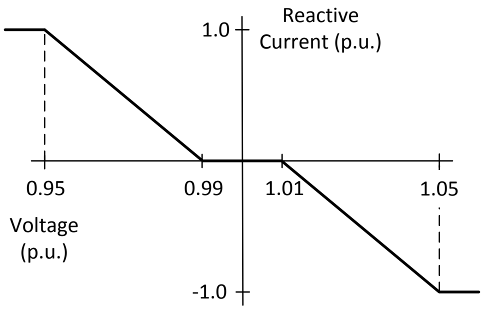


Figure 5. Q-V characteristic, shown for a deadband of ±0.01 p.u. and a gain of 25.

B. Simulation Results With and Without Reactive Power Injection from BESS

The boiler feed pump is started with the BESS initially switched off. The fluctuations of 11 kV site load, and synchronous generator terminal voltage are shown in Fig. 6. The reactive power draw from the 11 kV network is shown in Fig. 7, with the grid and synchronous generator response given in Fig. 8. It can be observed that the simulation provides similar response to that of the PMU measurements in Fig. 2 and Fig. 3. There are minor differences in the boiler feed pump motor starting time and the excitation response from the synchronous generator.

The simulation is then repeated with a reactive power response from the BESS. Fig. 6 presents the simulation results for both cases, indicating the improvement in 11 kV network voltage. The key results are also summarized in Table I. Case-2 provides an improvement in 11 kV network voltage of 0.035 p.u., meaning a reduction in voltage dip severity of one third. It can also be observed from Fig. 6 that it takes 24% less time for the pump to start when aided by reactive power injection from the BESS. Case-1 provides a more modest improvement in voltage of 0.008 p.u.

In Fig. 7, which compares the base case with Case-2, the contribution of reactive power from the BESS is shown to peak at 9.5 Mvar as the current is limited to 1.0 p.u. In addition the BESS reactive power injection is observed to cause the reactive power drawn by the motor to increase slightly during starting. As a result, the peak current drawn by the motor increases by 3.6%. The faster start-up time also implies that the motor will experience higher torque. These both suggest more stress on the motor itself, even if other components within the plant experience a reduced voltage fluctuation.

However, the 'I^2t' for Case-2 is actually only 80% of that without the BESS providing any reactive power, even if peak current is higher. Thus, heating and associated insulation degradation should be less, while conversely mechanical damage to winding insulation from greater forces on the windings may increase.

Fig. 8, also comparing Case-2 with the base case, indicates that the reactive power contribution from the synchronous machine and grid reduce, as would be expected.

TABLE I. Q-V Characteristic Settings and Simulation Results Summary

	Case-1	**Case-2**
Settings		
Dead-band	±0.06 p.u.	±0.01 p.u.
Gain	6	60
Results (all relative to no BESS base case)		
Voltage improvement	0.008 p.u.	0.035 p.u.
Reduction in starting time	6.7%	24.4%
Reduction in I^2t	6.3%	20.2%

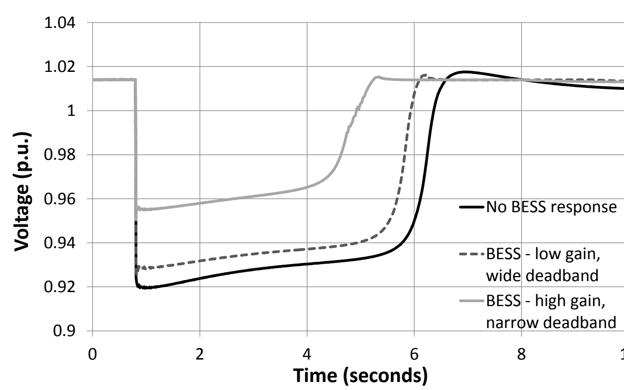


Figure 6. Simulated voltage dip during motor starting with different levels of BESS reactive power response.

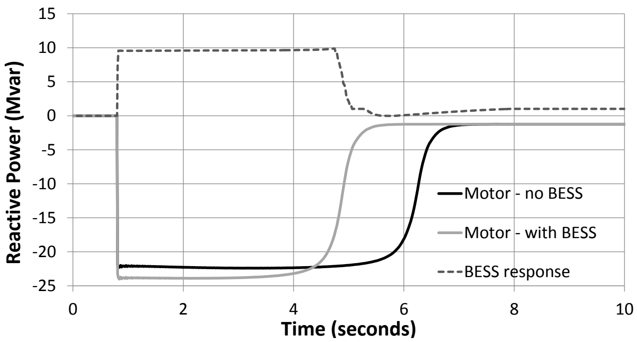


Figure 7. Simulated reactive power drawn by the motor and provided by the BESS (base case and Case-2).

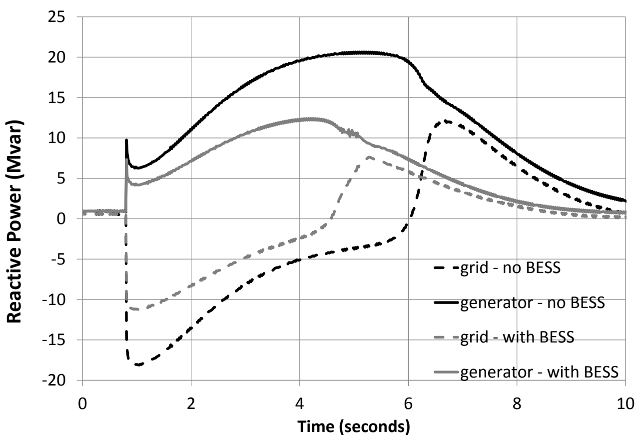


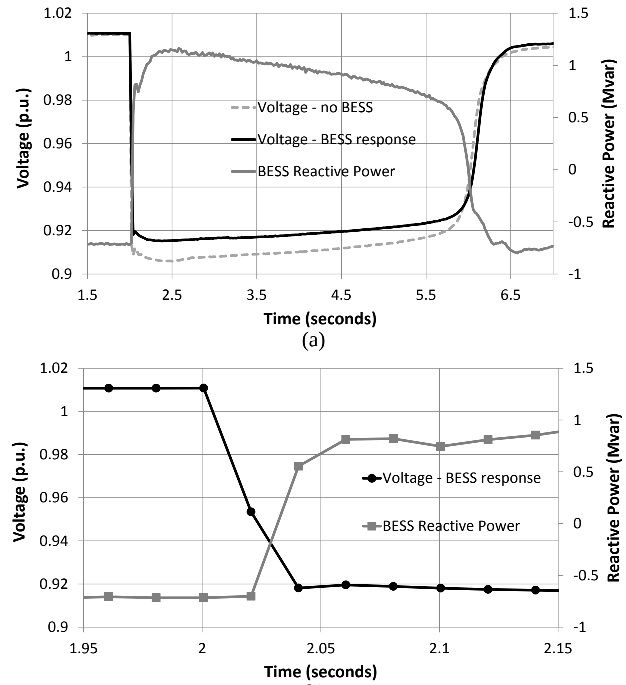
Figure 8. Simulated reactive power response from the synchronous generator and grid for the base case and Case-2.

C. Measurements from Tests on the BESS

Subsequent to the simulation study, initial testing of the scheme has been performed on the actual plant. The settings applied are similar to those of simulation Case-1. Traces showing 11 kV voltage and BESS reactive power response are presented in Fig. 9. It is worth noting that this test has been performed when the synchronous generator is offline. The initial steady-state voltage tends to be higher when the synchronous generator is operating, and the synchronous generator's excitation system, Fig. 3, improves voltage in the latter stages of the dip.

In Fig. 9 (a) it can be observed that the BESS supplied a peak of 1.85 Mvar to support voltage during motor starting. This is only part of the BESS's full capability. Nevertheless, it can be observed that the voltage rises compared to the base case with no BESS response, which is also shown in Fig. 9(a). Comparison of several transients has indicated voltage rises of between 0.007 p.u. and 0.009 p.u., which is approximately 75 to 100 V. The results, however, have been inconclusive on starting time. The start-up time can be affected by other variables, such as the network voltage prior to the start of the transient and perhaps also differences in pump loading conditions.

Fig. 9 (b) is an expanded view of the voltage dip and reactive power ramp in Fig. 9 (a). The PMU data points, reported at a rate of 50 Hz, are also plotted. Fig. 9 (b) indicates that the BESS converter speed of response is fast; with reactive power response occurring 20 ms after a voltage dip is recorded.



(b)

Figure 9. (a) Comparision of voltage dip observed with and without BESS response. BESS reactive power also shown. (b) Voltage and reactive power response at the start of the transient, indicating PMU data points.

IV. Discussion

The simulation and initial testing have indicated the benefit of using the BESS to provide voltage support. However, there are a number of other factors that should be considered.

The practical implementation of the high gain and narrow dead-band parameters for the Q-V characteristic in simulation Case-2 may prove problematic. The dead-band will be impacted by variation in steady-state voltage on the 11 kV network and measurement noise. The controller gain required to improve the voltage will be affected by network impedance and thus the location of the BESS. In any case, significant improvement over Case-1 should be possible on the plant.

Given that the BESS is providing a range of services to the power system, any use of capacity for supplying reactive power would impact the primary function of supplying active power for frequency containment. While the in-station voltage dip does not cause frequency deviation, an external voltage dip can quite often be accompanied by a frequency fluctuation, for example a loss of load following a fault. Thus, for the current operating arrangements, an override for provision of operating reserve and other frequency services might be required. In addition, as active power and reactive power are orthogonal a reasonable reactive power contribution could still be achieved without major impact on frequency services if the reactive current in the Q-V characteristic is restricted. This should not impact on the boiler feed pump support arrangement that has been presented, as given the short duration it is unlikely that a frequency event would occur at the same time.

The ability of the 10 MVA BESS to provide in-station voltage support is clear. But from the perspective of augmenting the synchronous generator's reactive power output to the grid, the benefits are much reduced. As an example, the synchronous generator has been observed to respond with in excess of 100 Mvar to a voltage dip of 0.1 p.u. on its terminals during a transmission fault. Thus, a 10 MVA BESS can only increase the overall plant capability by a small amount. The authors intend to assess the impact of different sized BESS in future work, for example the ability of much higher BESS capacity to provide system-wide reactive power services.

BESS are well suited for providing fast active power contributions and can displace the primary frequency response, and potentially emulate the inertia, from a much larger conventional plant [1]. However, due to the steady-state and overload ratings of power electronics often being equivalent, BESS will have more difficulty competing with synchronous generation to provide fault current to transmission faults.

There are, however, opportunities for a BESS to provide steady-state reactive power to the grid. Voltage support is becoming increasingly important as a constraint in economic dispatch. A minimum capacity of generation is required to be online near large load centers to support the voltage, particularly at times of high load [9]. However, the increasing energy contribution from wind tends to supply power from less populated parts of the network away from the load centers. Thus, it can be the case that at times of high wind in-feed, a synchronous unit is constrained-on for reactive power support, perhaps at the expense of curtailing wind.

The continuous nature of steady-state reactive power provision means that the commitment of a BESS to this service would restrict its ability to provide other system services. In [11] the value of frequency response is shown to vary with time and it is suggested that the minimum value is at high demand. Conversely, reactive power services tend to have most value when demand is high as this is when voltage support related constraints are active. If a variable pricing structure were introduced for system services it would enable service scheduling from BESS.

Due to reactive power provision often requiring a local solution, the inclusion of voltage support in the range of services provided by BESS may ultimately influence the choice of location for future BESS installations on the grid.

V. CONCLUSION

This work has presented PMU data from the internal 11 kV busbars of a conventional power plant that illustrates the type of voltage dip observed when the plant's 4.6 MW boiler feed pumps are started. A voltage dip of 0.1 p.u. and a reactive power draw of 20 Mvar occur. The site has a BESS, recently installed for the provision of frequency system services, however, such a resource spends much of its time on standby and so an opportunity to support the site voltage has been explored.

A simulation in DigSILENT PowerFactory has been used to demonstrate the potential benefit of reactive power provision from this 10 MVA BESS during motor starting. The results indicate that the voltage profile inside the power station can be improved. This also suggests faster start-up of the motor, and a slightly higher starting current drawn by the motor, leading to higher mechanical stress. However, the overall thermal effect during starting is expected to reduce.

PMU data showing the implementation of the control scheme on the actual BESS have been presented in this paper. While the response has not yet been maximized, this initial application does demonstrate that voltage dips can be reduced. If the full capability of the BESS were to be employed further improvements in voltage can be expected, as indicated by the simulation results.

The results highlight the benefits to systems within the power plant and usage of a similar scheme could be applied to BESS located in the distribution network. The ability to provide grid reactive support is discussed, along with both limitations and potential applications to accommodate higher wind penetrations. Providing multiple system services from a flexible resource, such as BESS, means services need to be scheduled or stacked, but the choice of which services are targeted will inevitably depend on the revenue that they can attract.

ACKNOWLEDGMENT

The authors would like to thank AES UK & Ireland, Fluence Energy, Eirgrid/SONI, The Utility Regulator, and Northern Ireland Electricity Networks for their valuable support.

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