Battery Energy Storage System Performance during Black-Start and Voltage and Frequency Disturbances

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Battery Energy Storage System Performance during Black-Start and Voltage and Frequency Disturbances

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***Abstract*—With the increasing penetration of Renewable Energy Resources (RESs) into power systems, concerns over grid blackout and stabilization solutions are being raised. Capability of Battery Energy Storage System (BESS) on balancing the variable generation profiles of Photovoltaic (PV) systems makes the BESS a modern grid solution. Furthermore, the BESS can help restore power in the event of blackout. In this paper, the contribution of BESS to facilitate their black-start capability is investigated. In addition, the role of the BESS in smoothing out fluctuations and disturbances associated with voltage and frequency changes, is assessed following an unexpected disturbance. To evaluate the dynamic performance and response of the BESS in recovering power during black-start and reducing disturbances, simulation studies were carried out considering IEEE 33 node test network, PV systems, and a BESS. Two critical case studies were considered to determine the level of BESS contribution in reducing disturbances' impacts and speeding network recovery. Results showed that, with the BESS, 100% of the total load of the network is supplied while it is not the case without the use of BESS. The BESS responds to sudden voltage and frequency changes. During voltage variation, the BESS injects reactive power to the network which could increase the network voltage at some nodes. Finally, the power drawn from MV grid is reduced due to BESS frequency response for applied reduction in the system frequency.**

Keywords—Battery energy storage system, Black-Start, Voltage and frequency disturbances

I. Introduction

Unprecedented awareness towards global warming creates a momentum for penetration of Renewable Energy Sources (RESs) into power systems. Uncertainty of large-scale renewable supply leads to increasing risks of blackouts as well as voltage and frequency disturbances in power grid. This will bring detrimental impacts on the economic development and people's daily life. Thus, electricity system operators have raised concerns to find solutions for the challenges of the RESs integration. For instance, National Grid Electricity System Operator (ESO) awards £85 million for black-start services in the south and midlands of the United Kingdom. These services reduce the dependence on the traditional providers of black start. The services are aimed broadening the number of solutions considering changes in nature of electricity generation [1, 2]. In 2018, Britain's transmission system operator "National Grid" has announced that the Battery Energy Storage System (BESS) is capable of proving the black start service and reducing the disturbances in the power grid. [3].

In the literature, numerous studies have focused on the role of RESs with the BESS in power systems. Those studies investigated recovering the power systems during the black start as well as BESS's contribution in maintaining frequency and voltage of the power systems stable during critical conditions . In [4], an optimization strategy was proposed for black-start of photovoltaic-battery energy storage systems. This strategy has improved the black-start ability of the power grid. It considered the limitations in overcharging and undercharging of the battery system. In [5], a black-start strategy was investigated for the microgrid with Photovoltaic (PV) and hybrid energy storage systems. The black-start strategy was presented based on the serial restoration strategy. The results showed that this framework helped decreasing the complexity of the hardware design and control algorithm. In [6], a large offshore wind farm equipped with a STATCOM and a BESS were considered to provide black-start capability for the grid. The simulation results showed that the STATCOM and BESS responded to the voltage changes fast. Furthermore, the STATCOM and BESS helped to cover the increased demand. Operation control strategy of a microgrid system with the BESS was studied in [7] for the grid connected and islanded mode. In the islanded model, the V/f control strategy was considered to have stable voltage and frequency for the PV system equipped with the BESS. The simulation studies demonstrated that the proposed control strategy could reduce the voltage fluctuation at the point of common coupling, which in turn lead to improving the stability of the system. In [8], a control methodology for the PV system equipped with the BESS was proposed. The methodology provided simultaneous voltage and frequency control. The methodology included two phases as day-ahead and real-time. A robust optimization problem was developed in day-ahead phase to maximize profits from frequency control, minimize the cost of reactive power compensation and batteries degradation. The optimization problem considered the uncertainty in electrical load, PV generation, and grid frequency. In real-time phase, the voltage profile was regulated and the state of battery charge was kept within permissible range. In [9], a strategy was proposed to enhance the resilience of a power system equipped with a BESS during black start. A robust optimization problem was developed to minimize the operational cost by load shedding. A careful review of the literature shows that the presence of the BESS helps the power system performing under extreme condition.

In this paper, the impacts of integration of the BESS on facilitating the black-start are investigated. In addition, an analysis to determine whether the addition of the BESS helps in the reduction of the effect of disturbances in voltage and frequency, is carried out. Consequently, it was examined whether the network is recovered faster during black start than the case without the BESS.

The rest of the paper is organized as follows: Section II presents the system definition for investigation of the BESS impacts. In Section III, improvements in power system performance during the black start and short circuit fault are analysed. In addition, the role of the BESS under voltage and frequency changes is evaluated. The paper finally concludes in Section IV.

II. System Description

The IEEE 33-node test network incorporating PV systems and two Diesel Generators (DGs) of 1250 kVA connected to nodes 3 and 13, is considered as the test network in this study as a microgrid [10]. The installation location of the PV systems and the DGs are shown in Fig. 1. The equivalent grid infeed at the 66-kV point of coupling has been modelled as a voltage source behind reactance. The reactance values in Positive-Phase Sequence (PPS) and Zero-Phase Sequence (ZPS) are derived based on a typical fault level, as listed in Table I. Furthermore, the electrical parameters for the feeder transformer are summarized in Table II. The transformer taps are automatically adjusted by an on-load tap changer (OLTC). The 33-node network lines and loads data are provided in [11]. The active and reactive power of the loads are changed during the day, as shown in Fig. 2 [11]. The active and reactive power of the PV systems are shown in Fig. 3 and Fig. 4, respectively.

To investigate the capability of the BESS, its dynamic model is integrated into the test network developed in DIgSILENT Power Factory 2022 environment. The BESS performance is evaluated through time-domain simulations by applying various disturbances. The control block diagram of the BESS model is shown in Fig. 5. It consists of a PQ control, a frequency control, and a charge control. The charge control is considered to maintain the State of Charge (SoC) of the BESS in a permissible range. The best installation location of the BESS, is chosen among the candidate nodes 18, 25 and 33 based on the study results. To understand where to facilitate the BESS installation considering costing, the equipment loading is firstly used as a measure to highlight required network reinforcements. In this regard, the line/transformer loading is analyzed, and it is concluded that node 18 is the most cost-effective location for the BESS installation.

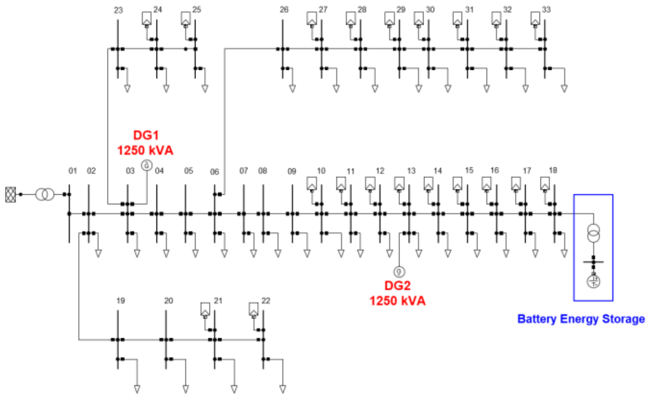

Fig. 1. The single-line diagram of the studied IEEE 33 Node test network

TABLE I. The Typical Fault Level Data at 66kV Terminal

Parameter	Minimum Short Circuit	Maximum Short Circuit
Initial Symmetrical Short-circuit Current, I_k'' (kA)	8.75	14.87
PPS resistance to reactance ratio	0.1	0.1
ZPS reactance to PPS reactance ratio	1	1
ZPS resistance to reactance ratio	0.1	0.1

TABLE II. The Typical Fault Level Data at 66kV Terminal

Parameter	Value
Rated Voltage	66kV/12.66kV
PPS Impedance	3%
PPS Resistance (p.u.)	0.5
Tap Changer Location and Type	HV side, On Load
Tap range & Increment	From -5% to +15% in 1.25% steps

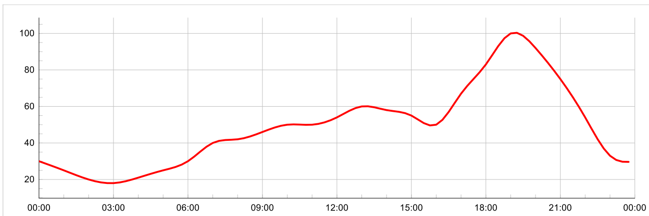

Fig. 2. The hourly profile for active and reactive power of the network loads (in percentage of the loads nominal power)

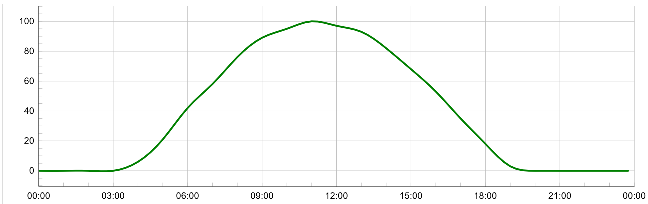

Fig. 3. The hourly active power of the PV systems (in percentage of the PVs nominal power)

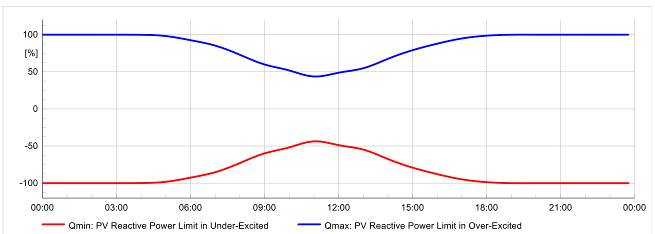

Fig. 4. The hourly profile for reactive power reserves of the PV units in over-exited and under-exited operations (in % of the PVs nominal power)

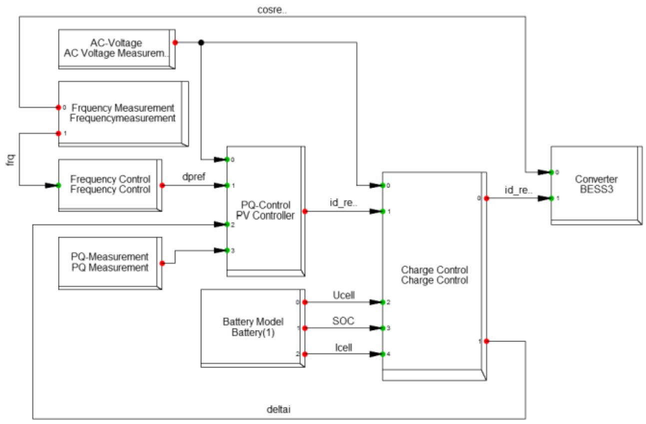

Fig. 5. The BESS control block diagram in PowerFactory

Considering the PV systems power generation profile, the power charging/discharging profile of the BESS could be as shown in Fig. 6. The nominal apparent power and active power of the BESS are 3 MVA and 2 MW, respectively. In addition, it is assumed that its capacity can be 10 MWh for both charging and discharging modes. The BESS is getting to be charged during the day when the PV systems generate active power. The charged BESS injects its power to the network in morning and evening periods.

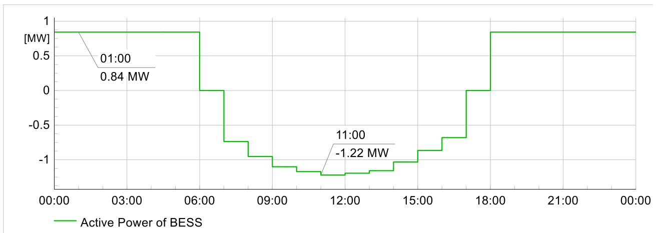

Fig. 6. The hourly active power profile of the BESS

III. SIMULATION RESULTS

A. Black-start study

In the black start-study, it is assumed that the 33-node test system is disconnected from the MV grid and all loads and generations are tripped off. Also, the two DGs are used to black-start of the test system in island mode operation. Two cases are considered to investigate the impacts of the BESS on recovering the distribution network as follows:

- Case 1: Two DGs are used to recover the network in island operation
- Case 2: A DG and the BESS recover the network in island operation

In Case 1, the restoration process of the test network is carried out without using the capability of the BESS. The applied events during the black-start under this case are illustrated in Table III. The simulation results are shown in Fig. 7 and Fig. 8 in terms of the network frequency and voltage magnitude along with the DGs power generation. Initially, DG1 is connected to the network while all other generations and loads are disconnected. Next, nine loads which consume about 23% of the network demand, are switched on in 6 stages, maintaining the frequency above 47Hz. Subsequently, DG2 is synchronized and connected to the network at t = 130 sec. Finally, 4 new loads are energized. In Case 1, the whole period of the black start takes 180 seconds and just 33% of total loads can be restored by the two DGs.

In Case 2, the DG1 and the BESS are initially in service.

TABLE III. THE APPLIED EVENTS DURING THE BLACK START IN CASE 1

Element	Time (sec)	Condition
Load 08	0	In service
Load 07	20	In service
Load 09	20	In service
Load 02	40	In service
Load 10	40	In service
Load 03	60	In service
Load 05	60	In service
Load 04	80	In service
Load 06	100	In service
DG2	130	In service
Load 26	150	In service
Load 27	150	In service
Load 28	150	In service
Load 29	150	In service

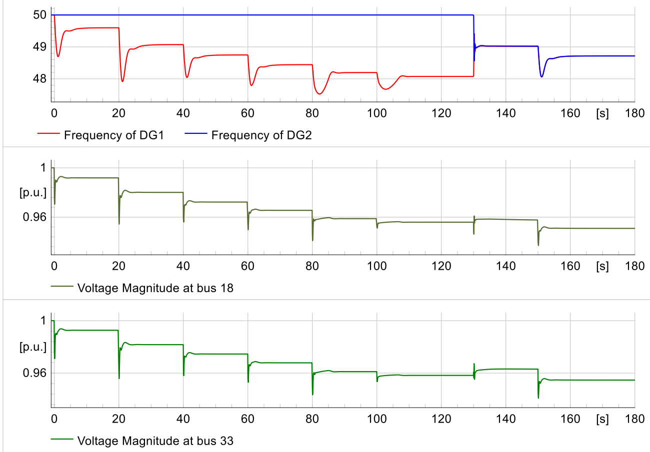

Fig. 7. Frequency at DG1 and DG2 terminals (top) and voltage magnitude at bus 18 (middle) and bus 33 (bottom) – Case 1

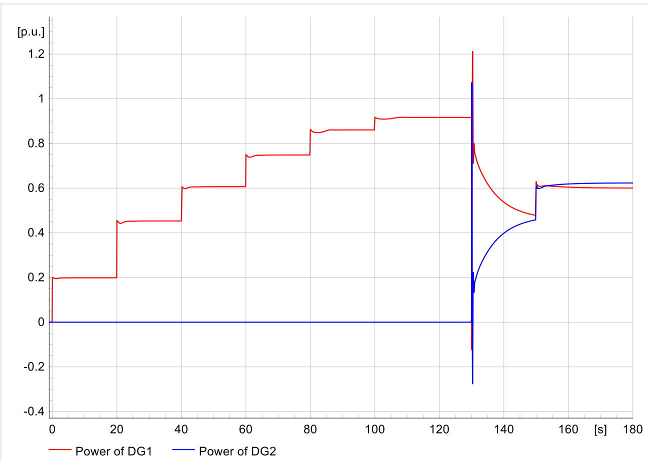

Fig. 8. The active power of the DGs (in per unit of 1.0 MW) – Case 1

TABLE IV. THE APPLIED EVENTS DURING THE BLACK START IN CASE 2

Element	Time (sec)	Condition
Load 02	1	In service
Load 03	1	In service
Load 05	1	In service
Load 07	1	In service
Load 08	1	In service
Load 09	1	In service
Load 10	1	In service
Load 04	20	In service
Load 06	20	In service

Load 11	20	In service
Load 12	20	In service
Load 13	20	In service
Load 14	20	In service
Load 15	40	In service
Load 16	40	In service
Load 17	40	In service
Load 18	40	In service
Load 26	60	In service
Load 27	60	In service
Load 28	60	In service
Load 29	60	In service
Load 19	80	In service
Load 20	80	In service
Load 21	80	In service
Load 22	80	In service
Load 22	100	In service

the restoration process of the islanded 33 node network is carried out according to the events listed in Table IV. In Case 2, 53% of the total loads can be supplied in 120 seconds using the BESS capabilities in the voltage and frequency controls. The simulation results are shown in Fig. 9 and Fig. 10 in terms of the network frequency and voltage magnitude along with the DGs power generation.

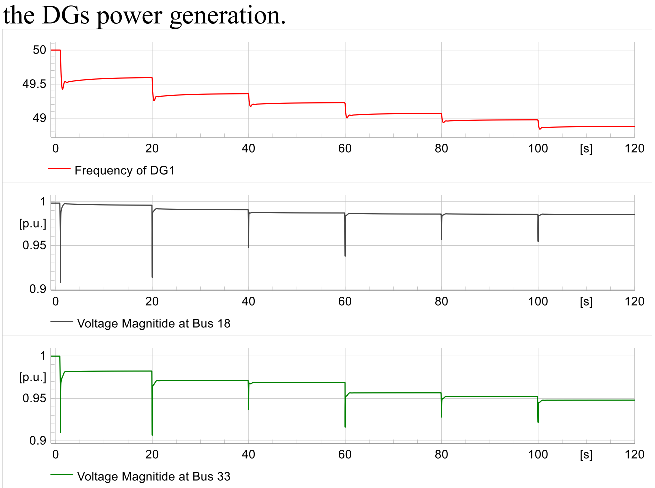

Fig. 9. Frequency at terminals of DG1 and DG2 (top), and voltage magnitude at bus 18 (middle) and bus 33 (bottom) – Case 2.

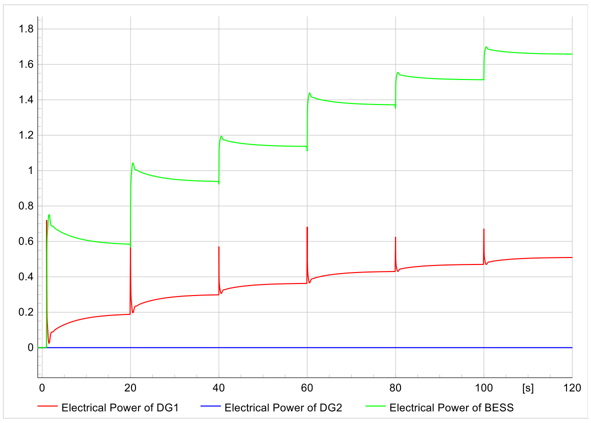

Fig. 10. The electrical power of DG1 and the BESS – Case 2

The simulation results show that the presence of the BESS helps recover the network faster than the case without the BESS. Additionally, with the BESS, 100% of the total load of the network can be supplied while it might not be the case without using the BESS.

B. *Frequency control study*

To investigate the capability of the BESS to modulate active power in frequency sensitive mode during the frequency steps, the two cases are defined as follows:

- Without BESS: A 1250kVA DG is connected to node 03 and the BESS is out of service.
- With BESS: A 1250kVA DG is connected to node 03 and the BESS is connected to bus 18.

In this study, the applied frequency control parameters used for DG1 and the BESS are listed in **Error! Reference source not found.**~~Table~~ V. The droop coefficient of the DGs and the BESS are set to 5% and 4%, respectively. Initially, the PV systems and DG2 are disconnected, and the network loads are consuming their maximum power. The applied frequency step-down change is depicted in Fig. 11 where the system frequency is instantly changed from 50Hz to 49.5Hz. The active power changes of DG1 and the BESS in response to the frequency change are shown in Fig. 12. The corresponding change in the generated active power by the MV grid are compared for the two cases with and without the BESS in Fig. 13. By incorporating the BESS to the network, the power drawn from the MV grid is reduced by 0.75MW, which comes from the BESS frequency response that is 25% for the applied 1% reduction in the system frequency.

C. *Voltage control study*

To investigate the capability of the BESS to support the network voltage during voltage changes, the two cases are defined similarly to the cases in the frequency control study. It is assumed that the BESS regulates its reactive power with a voltage droop of 12% to achieve 33% change in the BESS reactive power for 4% change in voltage.

Initially, the PV systems and DG2 are disconnected, and the network loads are consuming their maximum power. The voltage step-down change at the LV-side of the feeder transformer is shown in Fig. 14, where a 4% drop is applied. In addition, the corresponding changes in the reactive power of the BESS, DG1, and the MV grid in response to the applied voltage step-down are illustrated in Fig. 15. The BESS reactive power is increased 33% (0.45MVAr with base power of 3MVA), which is adjusted by 4% voltage drop at its terminal (see Fig. 16). The impact of the reactive power support by the BESS on the voltage magnitude at node 18 is highlighted in Fig. 17, where it limits the voltage drop to about 2% against 3% when the BESS is not in service.

TABLE V. THE FREQUENCY CONTROL PARAMETERS OF DG1 AND THE BESS

Equipment Name	Frequency dead-band (Hz)	Droop Coefficient (%)	Nominal Active Power (MW)
DG1	0	5	1
BESS	0.015	4	2

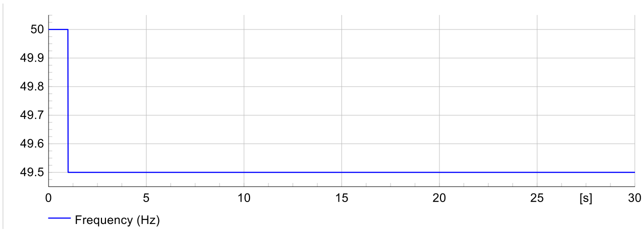

Fig. 11. The applied frequency step-down change

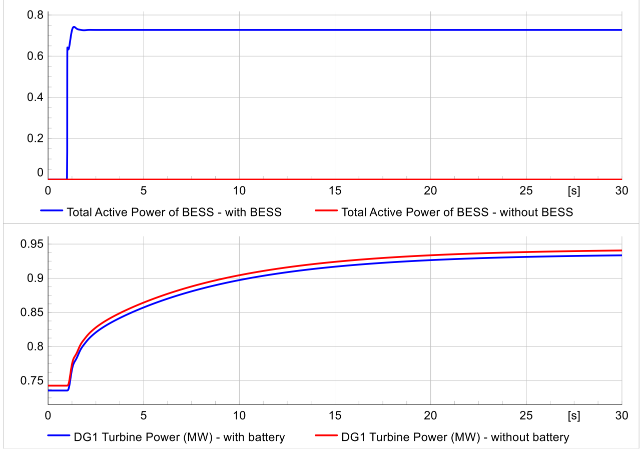

Fig. 12. DG1 and the BESS responses to a frequency step-down change.

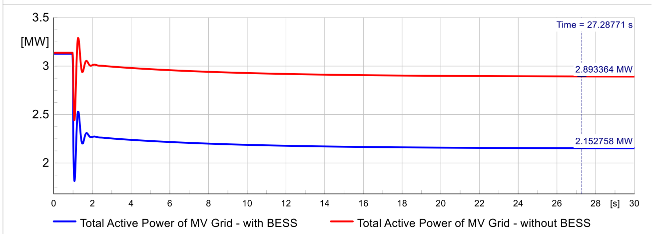

Fig. 13. The change in the generated active power by the MV grid in response to a frequency step-down change.

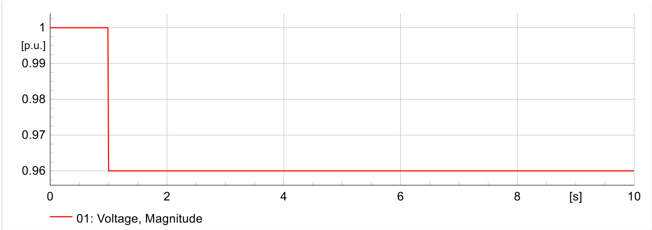

Fig. 14. The voltage step-down applied at the LV side of feeder transformer

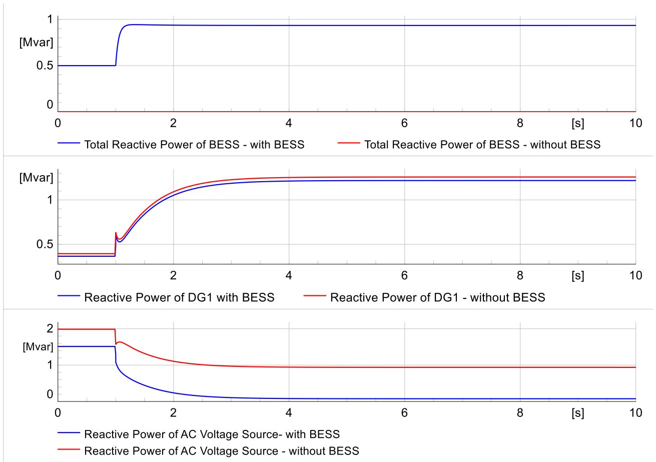

Fig. 15. Reasctive power of the BESS (top), the DG1 (middle), and the MV grid (bottom) in response to the applied voltage step-down.

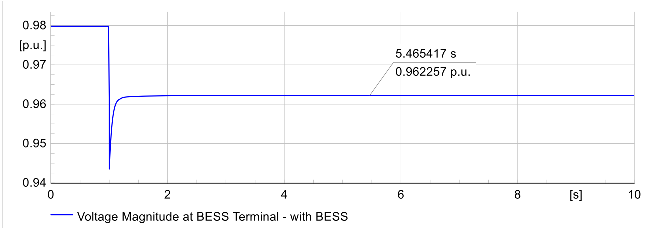

Fig. 16. The voltage magnitude at the LV-side of the BESS transformer in response to the applied voltage step-down

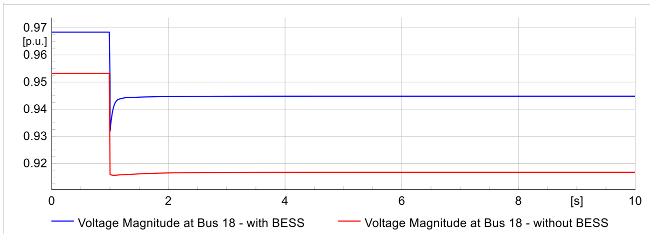

Fig. 17. The voltage magnitude at node 18 in response to the applied voltage step-down

D. Fault Ride Through (FRT) study

In this section, the impact of the BESS on facilitation to act in the case of short circuit faults is investigated by carrying out Fault Ride Through (FRT) studies. Towards having worst-case condition, the PV systems and therefore their participation in supporting the network voltage during the fault, are switched of the network. A three-phase short circuit fault is applied at the 66-kV terminal (at the HV-side of the feeder transformer) in duration of 0.82 seconds. The achieved simulation results are presented in Fig. 18 and Fig. 19. The reactive power of the BESS is shown in Fig. 18 where it is zero when the BESS is disconnected from the network (the red trace). When the BESS is connected to the network, it is initially operating at under-excited operation and consumes reactive power. While the BESS responds to the sudden voltage change and injects reactive power to the network by going to the over-excite operation. On the other hand, the voltage magnitude of the three critical nodes are compared for the cases with and without the BESS in Fig. 19. In addition, Table VI summarizes the key points of this figure in terms of the steady-state voltage magnitudes during and after the fault. The reactive power injection to the network by the BESS could increase the network voltage from 2% at bus 25 (far away from the BESS) to 13% at bus 18 (where the BESS is connected).

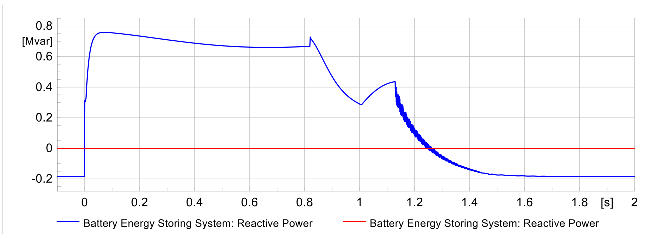

Fig. 18. The reactive power of the BESS

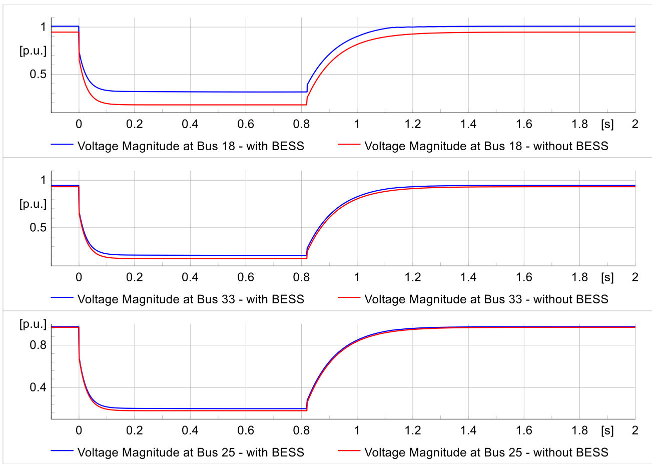

Fig. 19. Voltage magnitude at bus 18 (top), bus 25 (middle), and bus 33 (bottom) with and without the BESS

TABLE VI. THE BUSES VOLTAGE DURING AND AFTER THE FAULT WITH BESS AND WITHOUT THE BESS

Node	Voltage during fault (p.u.)		Voltage after fault (p.u.)	
	With BESS	**Without BESS**	**With BESS**	**Without BESS**
25	0.20	0.18	0.974	0.969
18	0.31	0.18	1.01	0.95
33	0.21	0.17	0.95	0.93

IV. CONCLUSION

In this study, effectiveness of a BESS in black-start, as well as its performance in voltage and frequency disturbances are assessed. In these regards, two study cases are investigated to determine whether the addition of the BESS helps black-start process and system stability against the disturbances. Simulation results show that in black-start process the network is recovered faster by using a BESS than without. In addition, the total system demand could be supplied in a black-start process with BESS, while it is not the case without using the BESS. On the other hand, the BESS quickly injects reactive current to the network in the case of sudden voltage drops, which in turn supports the network voltage. Furthermore, by incorporating the BESS to the network, the power drawn from the upstream MV grid is reduced due to the BESS frequency response for the applied reduction in the system frequency. For the future work, it is recommended that other generation types such as wind turbines will be added to the network.

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REFERENCES

[1] Black start from the bottom up: rethinking our most important back-up plan, National Grid ESO, Available at: https://www.nationalgrideso.com/news/black-start-bottom-rethinking-our-most-important-back-plan

[2] First of its kind tender sees Black Start contracts awarded in South West & Midlands, National Grid ESO, Available at: https://www.nationalgrideso.com/news/first-its-kind-tender-sees-black-start-contracts-awarded-south-west-midlands

[3] National Grid wants UK storage to provide black start next year, Available at: https://www.energy-storage.news/national-grid-wants-uk-storage-to-provide-black-start-next-year/

[4] J. Li, B. Noble, H. You, J. Qi, M. Kong, Sh. Zhang, and H. Zhang, "Stratified Optimization Strategy Used for Restoration With Photovoltaic-Battery Energy Storage Systems as Black-Start Resources," IEEE Access, vol. 7, pp. 127339 - 127352, 2019.

[5] Zh. Xu, P. Yang, Q. Zheng, and Zh. Zeng, "Study on Black Start Strategy of Microgrid with PV and Multiple Energy Storage Systems,"18th International Conference on Electrical Machines and Systems (ICEMS), 2015.

[6] S. K. Chaudhary, R. Teodorescu, J. R. Svensson, L. H. Kocewiak, Ph. Johnson, and B. Berggren, "Black Start Service from Offshore Wind Power Plant using IBESS", IEEE Madrid PowerTech Conference, 2021.

[7] K. Wang, Y. Ma, P. Ding, R. Mu, and R. Sun, "Operation Control Strategy for Photovoltaic/Battery Micro-grid", China International Conference on Electricity Distribution, 2018.

[8] H. Almasalma, and G. Deconinck, "Simultaneous Provision of Voltage and Frequency Control by PV-Battery Systems", IEEE Access, vol. 8, pp. 152820 – 152836, 2020.

[9] F. Yao, T. K. Chau, X. Zhang, H. Ho-Ching Iu, and T. Fernando, "An Integrated Transmission Expansion and Sectionalizing-Based Black Start Allocation of BESS Planning Strategy for Enhanced Power Grid Resilience", IEEE Access, vol. 8, pp. 148968 – 148979, 2020.

[10] M.E. Baran, F.F. Wu, "Network reconfiguration in distribution systems forloss reduction and load balancin," IEEE Transactions on Power Delivery, vol. 4, p. 1401–1407, 1989.

[11] M. Selcen Ayaz, M. Malekpour, R. Azizipanah-Abarghooee, and V. Terzija, "Local photovoltaic reactive power controller for increasing active distribution networks hosting capacity," IET Generation Transmission Distrib., vol. 14, pp. 5152-5162, 2020.