TECHNO-ECONOMIC ANALYSIS OF BATTERY ENERGY STORAGE SYSTEMS TO IMPROVE FREQUENCY RESPONSE IN SMALL, RENEWABLE-DOMINANT POWER SYSTEMS: THE CASE OF SRI LANKA

Nilan Hemachandra
Ceylon Electricity Board
Sri Lanka
nilanmgnd@gmail.com

Asanka S. Rodrigo
Department of Electrical Engineering
University of Moratuwa
Sri Lanka
asankar@uom.lk

Tilak Siyambalapitiya
Resource Management Associates (Pvt) Ltd
Colombo, Sri Lanka
tilak@rmaenergy.lk

***Abstract*— Thermal power plants; coal-fired steam, combined cycle, gas turbines, and reciprocating engines serve a large portion of the electricity demand in Sri Lanka, while large and small hydropower plants, and converter-and-inverter-based generation such as wind and solar, serve the balance. The power system of Sri Lanka is islanded and smaller in size, with a lesser amount of connected synchronous machines, compared with larger power systems. Accordingly, the power system of Sri Lanka can be classified as a low-inertia power system.**

Even before Non-Conventional Renewable Energy (NCRE) additions, the power system was largely dependent on under-frequency load shedding (UFLS) to recover after a disconnection of a large generator. Introducing more NCRE to the power system has worsened the situation further.

On the path to achieving 70% of the renewable energy target by 2030, higher penetration of solar and wind generation can be expected soon. Apart from the advantages of renewable dominance, Sri Lanka would face additional challenges such as maintaining frequency stability due to reducing power system inertia.

This study is on possible methods to improve frequency stability. The possibility of using grid-scale BESS to improve frequency stability was studied through dynamic modelling. Costs were analyzed and comparative costs of different BESS utilization scenarios were evaluated using forecast BESS costs. Finally, the technical and economic viability of BESS for improving the frequency stability is presented and discussed.

Keywords: Battery Energy Storage Systems, Frequency Response, Non-conventional Renewable Energy, PSS/E

I. INTRODUCTION

The world is moving towards more non-conventional renewable energy (NCRE) sources for electricity generation. The main reason for this move is the environmental credentials of NCRE. Many countries have set their goals to achieve carbon-neutral electricity generation. Accordingly, Sri Lanka has a goal of achieving 70% of electricity generation from renewable energy by 2030. As the power system is small and islanded, Sri Lanka has additional challenges in achieving the aforementioned goal.

Studying the effects of increased penetration of NCRE in the growing power system, replacing the conventional energy sources such as coal-fired steam, combined cycle, gas turbines, and major hydropower plants, has increasing importance for an islanded power system.

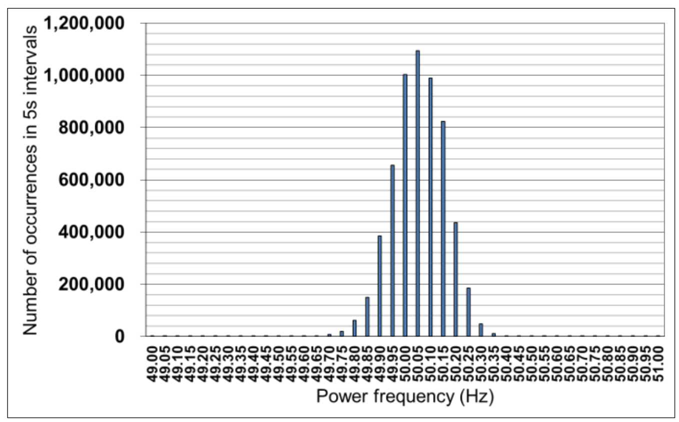

Figure 1: Frequency variations in the power system of Sri Lanka in 2021 (Source: Ceylon Electricity Board)

Fig. 1 shows details of frequency variations in the power system during the year 2021. It is clear to see that the number of frequency variations is higher in the power system. One of the main reasons for such variations is the lower power system inertia caused by the size of synchronous machines connected, the nature of loads connected, and the small, islanded nature of the power system.

This paper demonstrates the effects of battery energy storage systems (BESS) to improve frequency response of the power system. An economic assessment using BESS to improve frequency response is presented in the latter part of the paper.

II. The Effect of Battery Energy Storage Systems on Frequency Response

A. Introduction to Battery Energy Storage Systems (BESS)

Fig. 2 shows a basic block diagram of a BESS. The battery storage is used to store energy. The function of the power conversion system (PCS) is to convert dc to ac and ac to dc to transfer power to the grid, to supply loads or transfer power from the grid, to charge the batteries. The energy management system (EMS) controls the functions of the BESS and monitors its condition.[1]

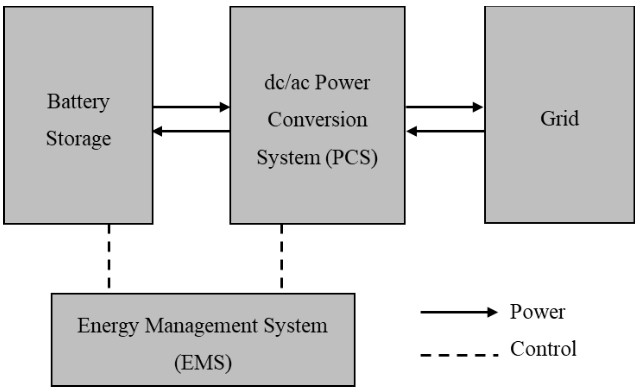

Figure 2: Block diagram of BESS

Table 1: Global BESS projects over 1 MW by the type of technology in 2018 [1]

Global battery energy storage projects over 1MW by technology type	
Technology type	**%**
Lithium-ion based	78.3
Sodium-Sulfur	8.9
Lead-Acid	8.3
Vanadium-Flow	3.2
Other	1.3

Lithium-ion-based battery storage technology is the most commonly-used technology (Table 1). It has more desirable properties compared with other technologies, which makes it more suitable for grid-scale battery storage projects. The advantages of this technology are higher efficiency and higher capacity, and it is a commercialized technology. Despite its comparatively higher cost, scarcity of material, and safety risks in high temperatures, it is widely used for grid-scale battery energy storage system projects. [1]

Sodium-Sulfur battery storage technology is emerging as it provides performance similar to lithium-ion batteries but at a lower cost. Sodium and Sulfur are abundant and cheap. The batteries have a higher energy density and higher efficiency. A disadvantage of this technology is that it requires 300-350 ºC operating temperature to keep the electrodes in the liquid form which is not the case with other battery technologies as they use solid electrodes. In turn, it has safety risks due to high operating temperatures. High operating temperatures also increase the corrosion of compound materials. [1]

Lead-acid batteries are the most mature technology. They are reliable and have a longer lifetime. The cost of batteries is lower but they have demerits such as lower efficiency, limited usable capacity, a limited number of charging cycles and the use of environmentally hazardous materials. [1]

B. Modelling and validating the power system model of Sri Lanka in PSS/E for BESS simulations

The power system of Sri Lanka as of September 2019 was modelled using parameters obtained from dispatch models of 2016 and 2025 (forecast), which were available at the National System Control Centre, Ceylon Electricity Board.

The developed PSS/E model was validated with two actual disturbances that occurred in the power system of Sri Lanka. They are as follows.

- The disturbance caused due to the disconnection of 130 MW of Yugadhanavi power station generation on 17 Jul 2019 at 9:19 hours.
- The disturbance caused due to the disconnection of 200 MW of Lakvijaya power station generation on 21 Dec 2019 at 21:10 hours.

Simulated and actual frequency variations are compared in Fig. 3 and 4.

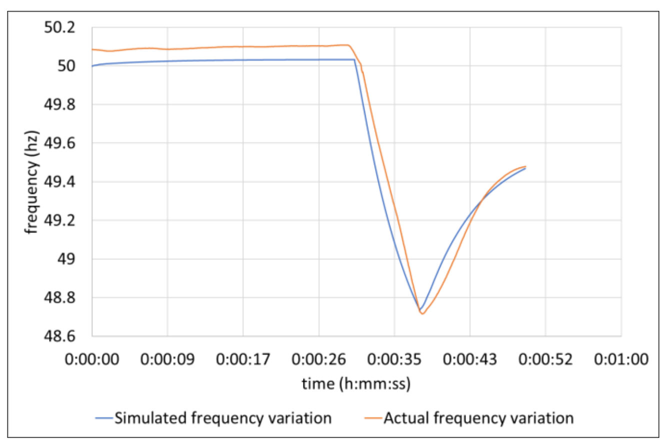

Figure 3: Comparison of actual and simulated frequency variations for thedisturbance on 17 Jul 2019 at 9:19 hours

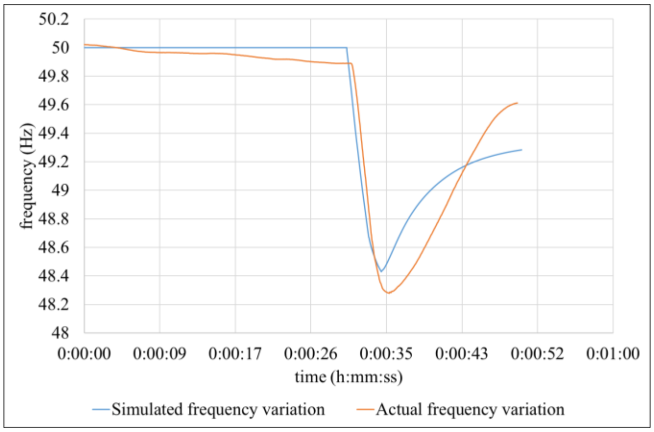

Figure 4: Comparison of actual and simulated frequency variations for the disturbance on 21 Dec 2019 at 21:10 hours

The deviation of frequency in simulations from the actual may be due to the following reasons

- The actual behaviour of loads might be different from the simulated load model
- The power flow in the simulation might be different from the actual power flow at the time
- Actual under-frequency load shedding (UFLS) might be different from simulated UFLS.
- NCRE connected to the grid might have responded differently to frequency variations

Although the simulated results did not have an exact match, they are reasonable enough to approve the developed model for the purpose of the study.

C. Modelling of a battery energy storage system in the validated power system model

1) Modelling of the battery energy storage system for the Steady-state simulation

A BESS of 100 MW was modelled in the validated power system model. A flexible alternating current transmission (FACTS) device was modelled to incorporate a frequency-dependent signal to the BESS since the BESS model in PSS/E does not include a direct method to obtain the system frequency. [2]

2) Modelling of the battery energy storage system for the dynamic simulation

The EPRI battery energy storage model (CBEST) was used for the dynamic modelling of the BESS. [6] The active power input to the CBEST model is PAUX and the active power output of the CBEST model is POUT. The Chateauguay auxiliary signal model (CHAAUT), a frequency-dependent auxiliary signal model was used to input frequency variations to the CBEST BESS model. The output of the CHAAUT model, which is a power auxiliary signal, was set as the input (PAUX) to the CBEST model. To map the auxiliary power output of the CHAAUT model to the PAUX input of the CBEST model, a code written in the FORTRAN programming language was incorporated. [2] [3]

The allowed power frequency operation range in the power system is 49.5-50.5 Hz (50±0.5 Hz). Considering regular frequency variations, the dead band to activate the BESS during frequency variations was set to ±0.4 Hz for the dynamic simulation. This is to avoid the frequent triggering of the BESS. Positive and negative slopes were selected as 25 MW/0.1Hz and -25 MW/0.1Hz, respectively, to keep the performance of the BESS in line with actual BESS ramp times. The transducer time constant was set to 1s.

D. Simulating dynamic frequency response of BESS for generation disconnections

The generation dispatch was set to a hydro-dominant case and the total generation was set to 2000 MW for all simulations to retain the consistency of the simulations.

The frequency responses in the PSS/E model of the power system were observed by disconnecting generation, with and without the BESS.

E. Results of dynamic simulations of the BESS

Fig. 5 shows frequency responses when 150MW of generation is disconnected, with and without the BESS. Fig. 6 shows the active power support from the BESS during the event. Fig. 7 shows the active power support from the frequency controlling generator.

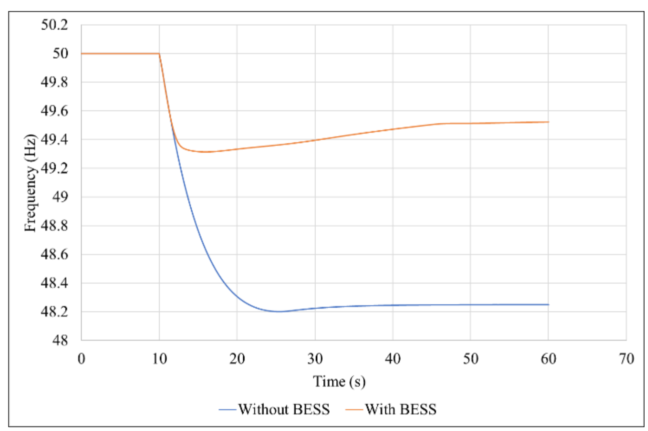

Figure 5: Frequency responses for 150 MW of generation disconnection

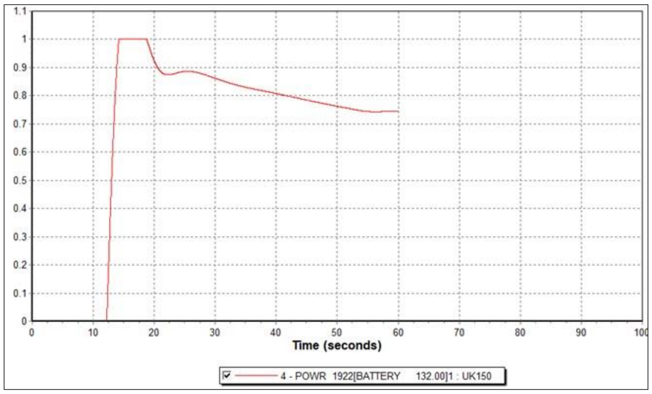

Figure 6: Active power support (per unit) from the BESS for 150 MW of generation disconnection (60 s simulation)

Figure 7: Active power support (per unit) from the frequency controlling hydro generator for 150 MW of generation disconnection (60 s simulation)

The minimum frequency reached improved to 49.32 Hz with the BESS compared with 48.2 Hz without the BESS (Fig. 5). The introduction of the BESS avoided the operation of under-frequency load shedding (UFLS) during the event. The BESS reached its maximum power delivery within 2s from the activation, according to the defined logic of operation for the simulation (Fig. 6). The response of the usual frequency control generator is slower compared with the response of the BESS (Fig. 7). The frequency response has improved significantly for the generation disconnection with the BESS.

F. Validation of results of dynamic simulations of the BESS

The BESS reached its full load within 2s after the disturbance in the simulation (Fig. 6). This BESS dynamic frequency response closely corresponds to the BESS dynamic frequency response in the simulations of the study [4]. Study [4] also provided an actual BESS response obtained from a PMU monitoring of the 10 MW BESS at Kilroot Power Station, Northern Ireland, which closely tally with the BESS dynamic frequency responses of simulations.

Further, the developed PSS/E model used for simulations was validated with the actual frequency responses.

Hence, it can be concluded that the simulation results of the study are valid.

III. Cost Analysis of Battery Energy Storage Systems for the Power System of Sri Lanka

A. The main initial capital cost components of BESS

A BESS comprises several main cost components. The total BESS cost can be estimated by adding the cost of each cost component together. The main cost components are costs of the battery pack, the power conversion system (PCS), the balance of plant (BOP), construction, and commissioning (C&C).[5]

The cost of the battery pack includes costs of electrodes, electrolytes, separators, packaging, and all the other parts that belong to the battery storage. Li-ion batteries were considered for the study because it is the most widely used and commercialized technology for large-scale BESS. Usually, the cost of the battery pack is stated in $/kWh or a similar unit. The cost of the power conversion system includes costs of inverters, inverter controls, packaging, and the other parts of the power conversion system. The cost of the power conversion system is represented in $/kW or a similar unit. The power conversion system considered in this study is for a stand-alone BESS. The cost of the balance of the plant includes costs of transformers, auxiliary systems, wiring, supervisory control, and data acquisition (SCADA) systems, controls, etc. This cost is usually stated in $/kW or a similar unit. The cost of construction and commissioning (C&C) includes costs of designing, procurement, transport, labour, grid integration, taxes, administrative expenses, etc. [5]

B. Levelized cost of storage for BESS (LCOS)

The levelized cost of storage (LCOS) represents the cost of an electrical energy unit delivered from the BESS to the grid. LCOS can be stated in $/kWh or a similar unit. It is calculated as the summation of discounted costs, divided by the discounted total energy delivered during the life of the BESS. [6], [7]

$$\text{LCOS}=\frac{\sum_{t=1}^{t=T}\text{Discounted Capital Costs}_t+\sum_{t=1}^{t=T}\text{Discounted O\&M Costs}_t+\sum_{t=1}^{t=T}\text{Discounted Charging Cost}_t}{\sum_{t=1}^{t=T}\text{Discounted energy supplied}_t}$$

t=year, T=Project life

C. Capital cost projections for standalone BESS

The National Renewable Energy Laboratory, Colorado, USA has been developing cost projections for BESS capital costs every year based on reputed, well-known publications on battery energy storage systems. [8]

Their projected costs are further classified as low, mid, and high for 4-hour BESS (Fig. 8). Fig. 9 shows cost projections for 2-, 4-, and 6-hour batteries using the mid-cost projection. [8]

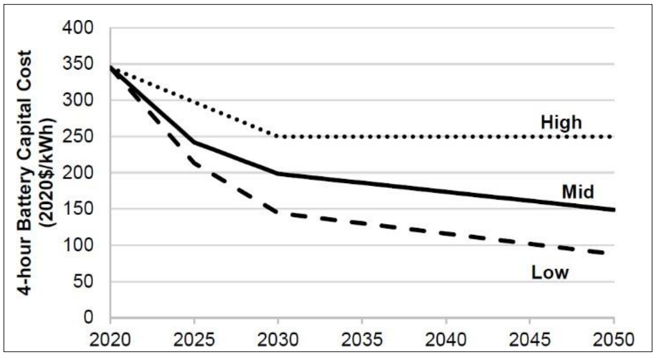

Figure 8: Battery capital cost projections for years 2020-2050 for a 4-hour BESS, 2021 update[8]

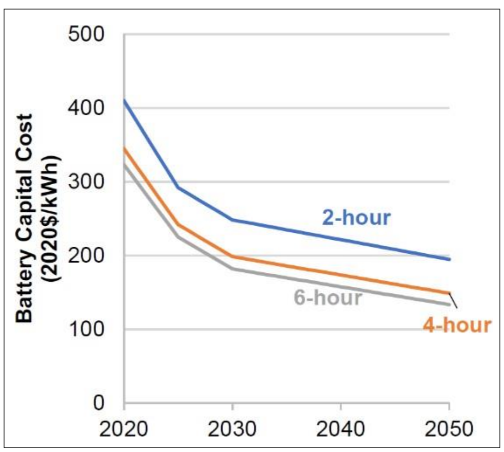

Figure 9: Cost projections for years 2020-2050 for 2-, 4-, and 6-hour BESS using the mid-cost projection [8]

The sample data assumed from Fig. 8 and 9 for the cost analysis are shown in Tables 3, 4, and 5.

Table 1: Cost projections for a 4-hour BESS [8]

BESS capital cost estimation ($/kWh)	Low	Mid	High
2025	212	242	295
2030	143	198	248
2050	87	149	248

Table 2: Cost projections for a 2-hour BESS [8]

BESS capital cost estimation ($/kWh)	Low	Mid	High
2025	263	300	366
2030	181	250	313
2050	114	195	325

Table 3: Cost projections for a 1-hour BESS [8]

BESS capital cost estimation ($/kWh)	Low	Mid	High
2025	333	380	463
2030	225	311	390
2050	137	234	390

D. Calculating levelized costs of storage for BESS for Sri Lanka

The specifications of the BESS and the parameters used for calculations are shown in Table 6.

Table 4: Battery energy storage system specifications, parameters for calculations

Parameters	
Power Rating (MW)	100
Depth of Discharge Cycles/Day	1
Operating days/year	350
Project life(years)	20
Unit cost of energy source used for charging(Rs/kWh)	21
Efficiency %	85%

Initial capital costs were calculated using the cost projections in Tables 3, 4, and 5. The annual augmentation cost represents the expenses to maintain full usable energy storage capacity over the life of the BESS. Annual augmentation costs were assumed to be 2.5% of the battery storage costs. Battery storage costs were assumed to be 55%, 45%, and 35% of the initial capital costs for 4-hour, 2-hour, and 1-hour BESS, respectively, for the calculations. [7]

Annual charging costs were calculated using

$$\text{Charging cost(\$)} = \frac{\text{unit cost of energy source of charging (\$/kWh)}}{\text{Efficiency}} \times \text{Total generation}_{\text{year t}}$$

The annual O&M costs were assumed to be 1% of initial capital costs [7]. An economic discount rate of 10% in real terms was assumed as it is the rate used in cost analyses for public projects in Sri Lanka.

E. Results of the levelized cost of storage calculations

Calculated Levelized costs of Storage (LCOS) using the data in Tables 3-6 are shown in Tables 7, 8, and 9.

Table 5: Calculated Levelized Cost of Storage (LCOS) for a 4-hour BESS

	Levelized cost of storage estimations for BESS ($/kWh)		
Year	**Low**	**Mid**	**High**
2025	0.22	0.23	0.25
2030	0.19	0.21	0.23
2050	0.17	0.19	0.23

Table 6: Calculated Levelized Cost of Storage (LCOS) for a 2-hour BESS

	Levelized cost of storage estimations for BESS ($/kWh)		
Year	**Low**	**Mid**	**High**
2025	0.23	0.25	0.27
2030	0.20	0.23	0.25
2050	0.18	0.21	0.26

Table 7: Calculated Levelized Cost of Storage (LCOS) for a 1-hour BESS

	Levelized cost of storage estimations for BESS ($/kWh)		
Year	**Low**	**Mid**	**High**
2025	0.26	0.27	0.30
2030	0.22	0.25	0.28
2050	0.19	0.22	0.28

F. Analyzing the use of a BESS only for the frequency corrective purpose

Table 8: UFLS events in 2020 in the power system of Sri Lanka [9]

UFLS stage	No of occurrences	Energy loss (MWh)
I	10	103.7
II	4	44.4
III	2	31.1
IV	0	0
V	1	30.6
df/dt	0	0
Total energy loss(MWh)		209.8

The total energy loss due to UFLS in 2020 was around 209.8 MWh (Table 10).

The cost of energy not served (ENS) was assumed to be 134 Rs/kWh, the same figure used in the long-term generation expansion plan of the Ceylon Electricity Board. The cost of unserved energy due to UFLS in 2020 was calculated by multiplying the cost of ENS (134 Rs/kWh) by the total energy loss (209.8 MWh), which results in $ 0.16 million (The USD conversion rate used is 180 Rs/USD (2020)). The present value of BESS capital costs for a 1-hour system in 2020 was calculated to be about $ 54 million. The annual cost for the 1-hour BESS was estimated by dividing the present value by the annuity factor at a discount rate of 10% for a project life of 20 years (8.51), which is $ 6.3 million. Accordingly, the annual cost for the BESS is significantly higher than the annual economic value of ENS in 2020.

In this comparison, it was assumed that the energy loss due to UFLS stage I can be avoided with the BESS, while the energy loss due to UFLS stages II, III, and IV may also be reduced significantly by the BESS.

Table 11 shows the frequency distribution below 49.6 Hz in 2021. Samples are taken in 5-second intervals. So, it can be assumed that the duration of each occurrence is 5 seconds.

Table 9: Frequency distribution below 49.6 Hz in 2021 [9]

Frequency (Hz)	Occurrence	Energy required for frequency correction (MWh)
49.6	863	47.9
49.55	458	28.6
49.5	262	18.2
49.45	176	13.4
49.4	137	11.4
49.35	97	8.8
49.3	83	8.1
49.25	44	4.6
49.2	41	4.6
49.15	33	3.9
49.1	20	2.5
49.05	17	2.2
49	56	7.8
Total energy required for the frequency correction (MWh)		162.0

The energy required for precise frequency control was around 162 MWh in 2021 (Table 11) which can be accomplished by using the 1-hour BESS (System frequency bias was assumed at 10MW/0.1Hz).

It can be understood from the data in Tables 10 and 11 that if the BESS was used for the frequency correction only, the annual energy requirement from the BESS for frequency support would be below 1 GWh.

IV. DISCUSSION

As shown in Section II, one method to improve the frequency response is to use battery energy storage systems (BESS). In the comparative simulations with and without the BESS, it was shown that the frequency nadir and the rate of change of frequency (ROCOF) can be improved significantly with the aid of the BESS. The BESS can reduce a large portion of annual UFLS events in Sri Lanka. The reason behind this improvement is the low ramp time that can be achieved by the BESS compared to traditional frequency control methods. By selecting an appropriate operation logic, the ramp times can be reduced to a range of one hundred milliseconds from no load to full load of the BESS.

As described in Section III, economic analyses were performed. The cost of a unit delivered from the 4-hour BESS was calculated to be 0.22-0.25 $/kWh in 2025, 0.19-0.23 $/kWh in 2030, and 0.17-0.23 $/kWh in 2050. Similarly, it was found that the cost of energy delivered from a 1- hour BESS was calculated to be 0.26-0.30 $/kWh in 2025, 0.22-0.28 $/kWh in 2030, and 0.19-0.28 $/kWh in 2050. (Charging cost was assumed to be 0.12 $/kWh [9]). The costs were still on the high side compared with the average annual cost of generation in Sri Lanka at the time of the study [9].

It was clear to see from Section III F that utilizing BESS only for the purpose of frequency correction is not economical since the annual cost for BESS is significantly higher than the annual economic value of ENS.

V. CONCLUSION

Due to the inherent characteristics of the power system of Sri Lanka, it has been difficult to avoid the impact of generation disconnections on the power supply to consumers. Connecting more inverter-and-converter-based generation will further reduce the system inertia in the future. Battery energy storage systems can be used to improve the frequency response significantly during generation disconnections. BESS can also reduce the amount of spinning reserve to be maintained which will be an additional advantage. With the growth of the power system, the dominance of hydro sources in electricity generation will be reduced in the future and the power system will consist of more thermal power plants, which has high startup times and low ramp rates, in addition to non-conventional renewable-based power plants. In such a power system, BESS will play a significant role.

Utilizing BESS only to avoid UFLS and to correct frequency may not be economical due to high upfront and augmentation costs. However, combining it with other purposes such as load shifting, intermittency control for the wind and solar power generation, peaking support, a fast frequency reserve, and load frequency control, can be a viable option in the future since the BESS can then be operated for a planned number of hours per day.

In a hydro-limited period, the opportunity costs of hydro can be very high. On the other hand, there will be practical issues due to low reservoir levels to operate them for spinning reserve. In such cases, BESS will be a useful option in the future power system.

VI. RECOMMENDATIONS FOR FUTURE WORK

The optimal size of BESS for the power system can bestudied after identifying the intended purpose of a BESS for the power system. The operational logic best suited for the power system can also be analyzed in detail.

Utilizing synthetic inertia from wind power plants to improve the power system inertia and frequency response canalso be studied for the power system.

REFERENCES

[1] L. Thomée, “Lithium-Ion Battery Storage for Frequency Control -Tentative Implementation in theNordic Power System,” CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, 2018.

[2] *PSS®E 33.5 MODEL LIBRARY*. Schenectady: Siemens Industry, Inc., 2013. [Online]. Available:www.siemens.com/power-technologies

[3] S. Han, “A study on alternative method of self– starting generator using ESS,” *Journal of International Council on Electrical Engineering*,vol. 9, no. 1, pp. 1–7, Jan. 2018, doi: 10.1080/22348972.2018.1558921.

[4] P. V. Brogan, R. J. Best, D. J. Morrow, K. McKinley, and M. L. Kubik, “Effect of BESS Response on Frequency and RoCoF During Underfrequency Transients,” *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 575–583, Jan. 2019, doi: 10.1109/TPWRS.2018.2862147.

[5] K. Mongird *et al.*, “Energy Storage Technology and Cost Characterization Report,” 2019. [Online]. Available: https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf

[6] “Lasard’s levelized cost of storage analysis-version5.0,” Nov. 2019.

[7] S. M. Deorah, N. Abhyankar, S. Arora, A. Gambhir,and A. Phadke, “Estimating the Cost of Grid-Scale Lithium-Ion Battery Storage in India Energy Technologies Area Lawrence Berkeley National Laboratory,” Apr. 2020. [Online]. Available: https://eta-publications.lbl.gov/sites/default/files/lbnl- 2001314.pdf

[8] W. Cole, A. W. Frazier, and C. Augustine, “Cost Projections for Utility-Scale Battery Storage: 2021 Update,” Jun. 2021. [Online]. Available: https://www.nrel.gov/docs/fy21osti/79236.pdf

[9] Ceylon Electricity Board, “Annual Report 2020.”