Grid impact analysis of hybrid energy storage systems

Kaiser Josef SEDILLO[1] (1), Dr. Wilhelm SÜßENBACHER[2] (2)

(1) University of Applied Sciences Upper Austria (FH Oberösterreich) / EFACEC
kaiser.sedillo@efacec.com, at.linkedin.com/in/kaisersedillo

(2) University of Applied Sciences Upper Austria (FH Oberösterreich)
wilhelm.suessenbacher@fh-wels.at

Abstract:

The increase penetration of intermittent energy sources creates a unique challenge on the European grid. The greatest concern is the reduction of rotational inertial. For this reason, a hybrid energy storage system (HESS) is proposed consisting of ultracapacitors and lithium-ion batteries. The goal is to compensate the traditional synchronous inertia with a synthetic/virtual inertia through a droop and swing equation method. This is then simulated within a grid benchmark to investigate the impact of such system using DigSilent Power Factory's RMS module. The criteria for such tests are set under the framework “requirements for grid connection of generators” according to “Commission Regulations (EU) 2016/631”.

The data from these simulations are consolidated into frequency and voltage graphs for evaluation. Based on the simulations and data of the grid impact study, the proposed HESS is able to meet the present regulations. It is capable of injecting sufficient synthetic inertia to mitigate high RoCoF and frequency fluctuations, whether it’s an under or over frequency. The system also illustrates that it can operate during islanding even at high %REP. It is also capable of fault-ride through Moreover, further evaluation show that is compact, practical and feasible enough to be integrated in the existing grid infrastructure. Therefore, the solution proposed in this research could be a vital component for future networks to integrate more intermittent renewable sources.

Keywords: Hybrid energy storage systems, Ultracapacitors, Supercapacitors, Lithium-ion batteries, Frequency regulation, Synthetic inertia, Virtual inertia, Rotational inertia, RoCoF

1 Introduction

With the increase in renewable energy penetration (%REP) on the European Grid, a problem arises in relation to the available rotational inertia. Traditional powerplants are displace with sources predominantly utilizing power electronic interfaces (PEI) which have limited inertial capacity. Additional capabilities must be connected to the network to maintain its stability during contingencies. The research main motivation is to provide a solution that could compensate such challenges.

---

[1] main author and researcher

[2] thesis supervisor

1.1 Background

Present solution on inertial injection consists of large-scale lithium-ion battery packs which also provide energy arbitrage during peak demand. However, these homogenous storage solutions often are too expensive to scale-up. On top of that, their chemistries limit their capability to deliver immediate power pulses which is essential in frequency regulation. Operating at higher discharge rates causes mechanical damage and hastens the deterioration of the cells. This limits the overall life cycle and operability of the system.

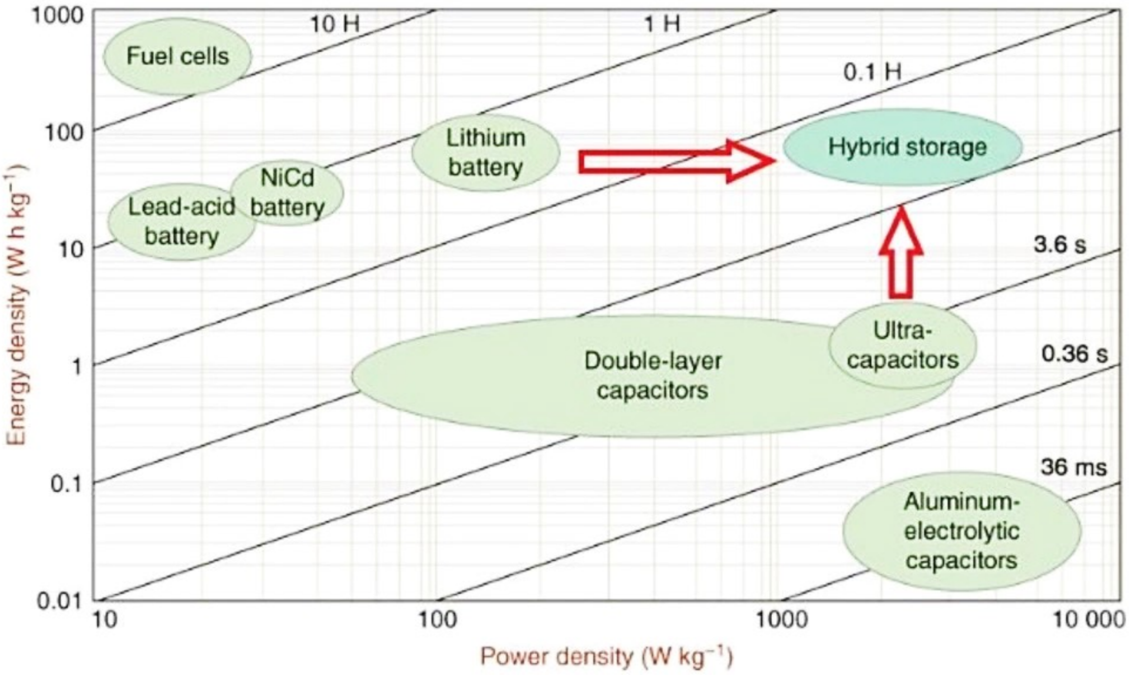


Figure 1 Ragone plot of different storage technologies. [1]

A hybrid energy storage system (HESS) resolves this limitation by combining electrochemical batteries with a fast-reacting ultracapacitor/supercapactiors. As seen in the Ragone plot in Figure 1, most storage technologies have decent energy densities. But they lack enough power density to operate (without electrode degredation) under 3 seconds during substantial losses of capacity due to intermittency at high %REP (renewable energy penetration). Hence, using a double-layer capacitor and a lithium-ion cell – a new robust, flexible and more capable system is conceived.

1.2 Goals and objectives

The study aims to develop a HESS model which can be used to simulate a wide range of grid criteria to determine its impact on the frequency and voltage characteristics of the network. Using DigSILENT PoweFactory™, the simulation fulfills the following:

- grid compliance of the system at 80%REP level
- system inertia requirements, capacity and size.
- estimated investment cost and comparison to legacy systems.

Satisfying these items will provide future framework and guidelines for grid simulations, economic assessments, and eventual integration. Thus, a better understanding on the overall technical and financial impact of proposed facility.

1.3 Limitations

The main focus of the research is on grid inertia and its relation to frequency regulation. Further studies are required on an actual layout of an operating transmission network since the simulation only utilizes a pseudo grid (PST16) as a benchmark. These network databases could require regulatory approvals, additional facility compliance testing or confidential access. Moreover, active demand response, fault ride through capabilities, islanding, contingency measures and other grid applications have limited test cases in this research since it evaluates a sole contingency measure within a narrow period. The thesis does not serve as a deep dive into other revenue streams which might be of further interest to the reader. Therefore, the goal is only to demonstrate a simple grid-compliant system HESS that can provide synthetic inertia at higher %REP on a single grid event per simulation.

2 Methodology

Computer simulations forms the bulk of all data acquisition. This is done through a careful analysis on a high %REP operational scenario. Specifically, a contingency measure designed to operate under a massive loss of energy and inertia which causes subsequent rapid increase in rate-of-change-of-frequency (RoCoF).

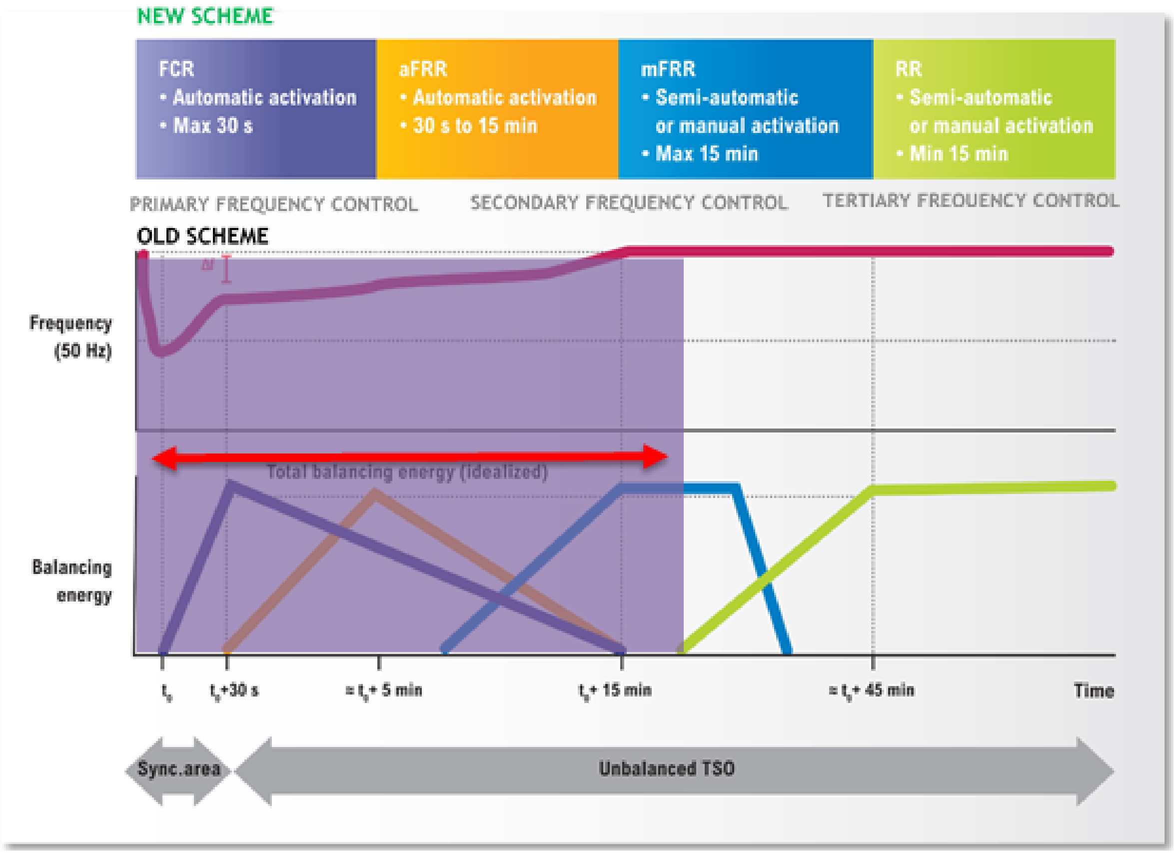


Figure 2 HESS operating/discharge range. [2]

To resolve such issue, a two-part method is proposed. A droop control provides the initial pulse or discharge to compensate the sub-three second fluctuation. The following fallout is then stabilized by a swing equation method to sustain the frequency up to its nominal value. The resulting system will integrate balancing mechanisms that provide both dynamic response and extended primary control which traditionally were the responsibility of synchronous generation. Thus, combining two regulating services – frequency containment reserve and frequency restoration reserve.

2.1 PST16 benchmark

The simulations utilize a test grid called PST16 benchmark system. It is a 400/220 kV 16-machine dynamic test system (synchronous generators) model made for DIgSILENT PowerFactory, consisting of 3 meshed areas interconnected by long-distance transmission lines. This was developed by academic researchers from the Institute of Electrical Power Systems at the Universität Duisburg-Essen to mimic the European grid. [3] The original model was shared through the Intelligent Electrical Power Grids (IEPG) Group of TU Delft under the ERASMUS partnership program. The intention is to assess the stability problems at higher %REP and evaluate inertial response of energy storage systems.

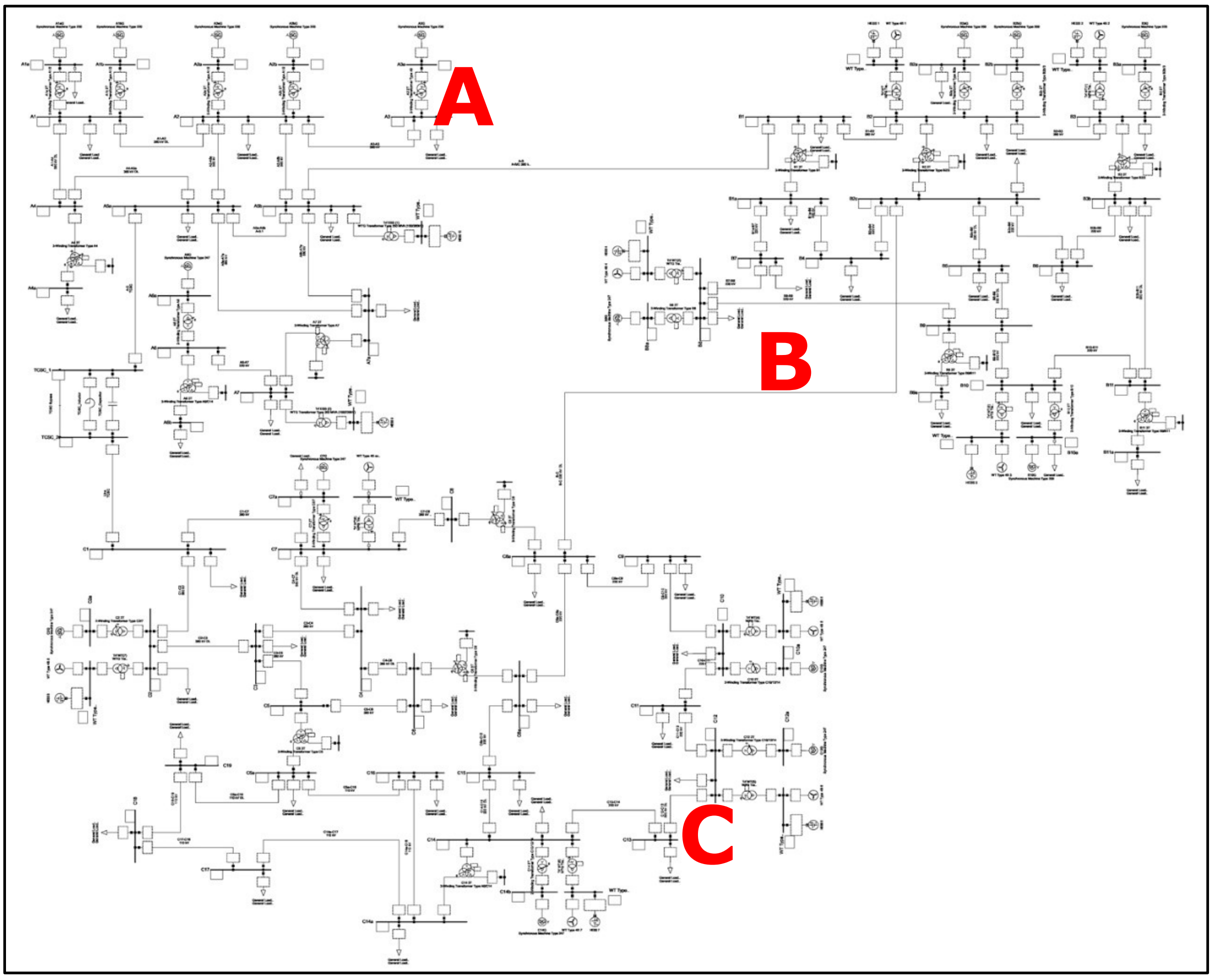


Figure 3 PST 16 Benchmark System from IEPG TU Delft.

The whole grid has three interconnected networks as seen in Figure 3. This version is modified to accommodate network topologies with various power flows and unequal inertial reserves. Network A do not have wind powerplants and most of its power generation rely on conventional energy sources. Grids B and C have different wind farm capacities but have similar energy storage capabilities which incorporate power electronic interfaces.

2.2 HESS model

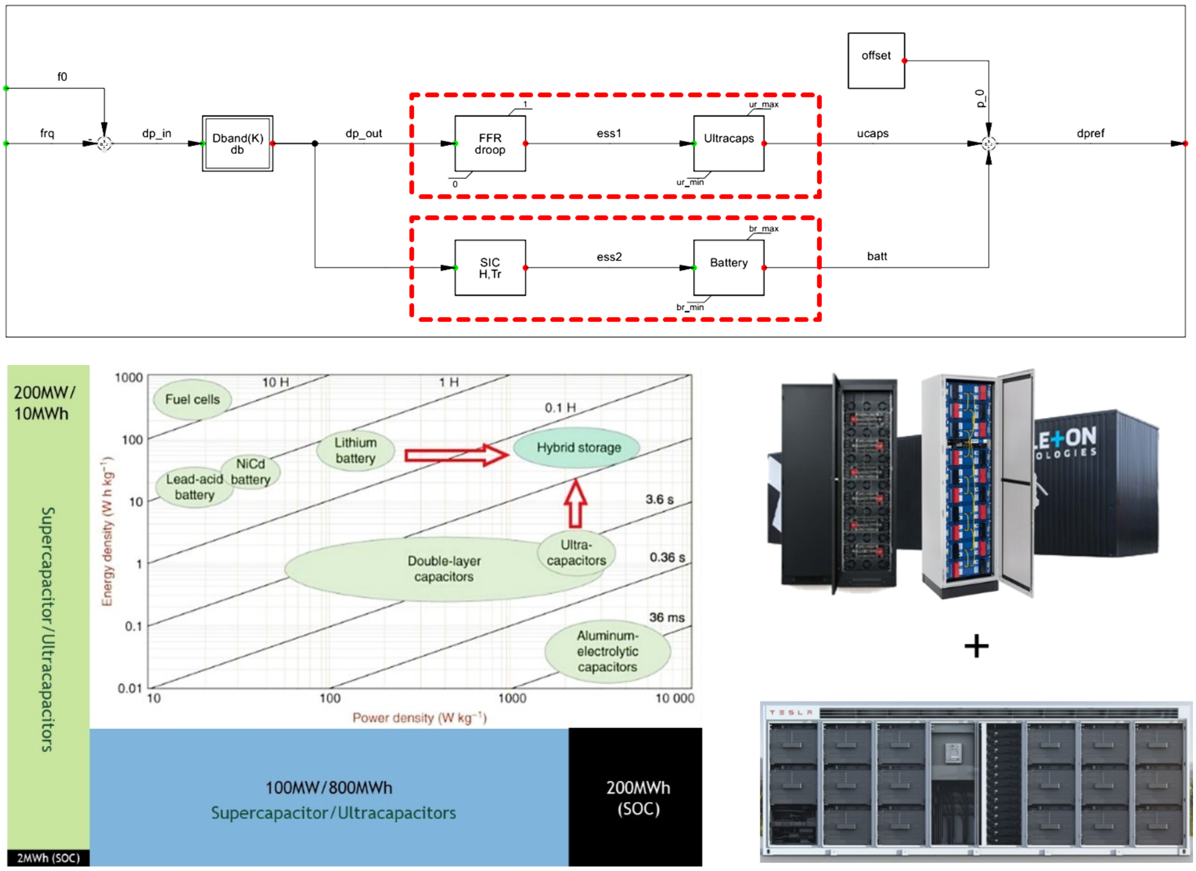


Figure 4 Proposed ultracapacitors + Li-Ion battery hybrid system and frequency control model.

The HESS configuration provides more flexibility in addressing grid instabilities compared with a homogenous storage solution. Adopting a multi-tier ESS enables two separate control topologies to operate at different balancing schemes which results to a much efficient inertial response resulting to a much robust network. Furthermore, this is more economical for large-scale frequency regulation. Electrochemical batteries have inherent limitations in terms of discharge and charge rates. Higher energy flow rate causes irreversible cell damage and reduces the overall service life. For this reason, traditional BESS are limited and are more expensive under similar applications with ultracapacitors to deliver burst power (less than 10 seconds). However, ultracapacitors alone have limited energy density and cannot feasibly sustain the nominal frequency requirements. Thus, by combining the two technologies, the batteries can shift most of its capacity on the recovery phase while the ultracapacitors focus on reducing the nadir.

As seen in Figure 4, the proposed frequency regulation is a combination of a droop and swing method (RoCoF) to form a virtual synchronous machine in a phased-locked loop configuration (PLL). The first method utilizes droop control through ultracapacitors which is responsible for fast frequency response. This injects the immediate synthetic inertial requirements after a grid event. The second method utilizes the swing equation with the RoCoF as the parameter for the active power contribution of the battery. A ramp (module) represents the various ESS technologies to mimic their response as per their allowable discharge/charge rates. These are distributed around the grid as a decentralized solution.

2.3 Grid compliance procedures

The simulation and results for this paper focuses more on the 80%REP case – assuming that future transmission networks will employ mostly RES and ESS to provide grid services. Presently, no existing large multi-area grids at the transmission or power wholesale market achieved this level of integration. In very rare cases, this kind of set-up are limited on small-area island systems or microgrid-tie networks due to the costs and ESS scaling limitations.

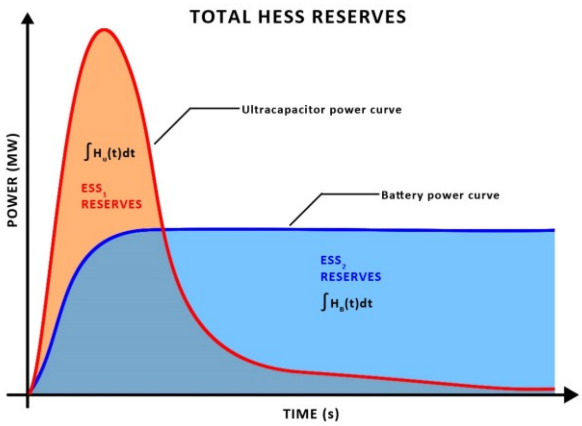
Regulations		Compliance measures
Requirements for grid connection of generators [COMMISSION REGULATION (EU) 2016/631]		
General requirements	Article 13	Simulating various load profiles and preset frequency conditions for over or underfrequency events. This is by establishing the prescribed dead bands, setting up the RoCoF and nadir limits for auto load shedding. This also include generation curtailment procedures to maintain frequency stability. A test scenario with different active power levels with respect to a given set of frequency deviations.
	Article 14(a)	Simulating a fault-ride through (FRT) scenario to assess the capability of the system to operate without disruption while clearing the fault
	Article 15 and Article 21	Testing synthetic inertia and fast active power response capability by simulating a major contingency under various Frequency Sensitive Modes. A preset topology of the grid benchmark will be established with all the appropriate ESS and RES settings at 80% integration. A test case wherein substantial amount of rotational inertia is lost and power park modules help facilitate energy frequency restoration.
	Article 16 and Article 22	Fulfilling the technical requirements on the specific installed capacity.
Simulation requirements	Article 54	Fulfilling the technical simulation requirements for type B power park modules.
	(2) With regard to the LFSM-O response simulation	Simulating an over-frequency scenario and creating a control methodology for active power modulation with high-frequency steps or ramps until reaching the minimum regulating level as stipulated from the code.
	Article 55	Fulfilling the technical simulation requirements for type C power park modules.
	(2) With regard to the LFSM-U response simulation	Simulating an under-frequency scenario and creating a control methodology for active power modulation with low-frequency steps or ramps until reaching the minimum regulating level as stipulated from the code.
	(4) With regard to the island operation simulation	Simulating an island operation of a control area wherein the active power output is regulated from an operating point without disconnection of the power park module from the island due to over- or underfrequency.
	(5) With regard to the simulation of the capability of providing synthetic inertia	Simulating a low frequency event and proposing a control methodology for a synthetic inertial response during very fast frequency deviations.
	(7) With regard to the power oscillations damping control simulation	Simulating active power oscillations and devising a control method to provide control.

Table 1 Software based compliance test as per ENTSO-E regulations. [4]

The grid compliance in Table 1 of the proposed system can be summarized into four requirements: LFSM-U/O, Voltage stability, Islanding and FRT. First, limited frequency sensitivity mode is a contingency measure provided by a power park module which activates during a sudden frequency rise or fall. The resulting network response is analyzed whether its values are within the boundaries of EU regulations. Second, this will also include an evaluation on the voltage levels within the simulation period. Third, islanding refers to the capability of a control area to remain engage regardless of disconnection from external networks. The HESS must provide the adequate synthetic or virtual inertial response to stabilize the frequency and voltage of the isolated grid. Lastly, the proposed system should demonstrate fault-ride through which is the ability to remain connected and operational regardless of low-voltage or near proximity faults.

2.4 Sizing reserves and economic evaluation

The resulting data from the simulations can be utilized to calculate a rough estimate on the asynchronous inertial reserves. The total energy needed to maintain normal levels also accounts the remaining synchronous sources. In this situation, conventional generation contributes to about 20% of the total inertia requirements. Hence, about 80% is contributed from HESS. The delivery, power and available energy reserve is vital in defining the total capacity of the network in curtailing sudden frequency and voltage fluctuations.



$$H_{SI} = \int_{t_n}^{t_{n+1}} H_u(t)dt + \int_{t_n}^{t_{n+1}} H_b(t)dt$$

where:

H_{SI} – total synthetic inertia requirement (MWs)

$H_u(t)$ – ultracapacitor active power curve (MW)

$H_b(t)$ – battery active power curve (MW)

dt – time interval of measurements (s)

t_{n+1} – required inertial response duration

t_n – frequency event

Figure 5 Expected synthetic inertia reserves per simulated ESS power curve.

A straight-forward estimate is proposed in this research by graphing the output data. The grid benchmark is tested under a specific scenario and event (80%REP and generation or load loss). The energy reserve required can then be estimated by integrating the resulting power curve, as seen in Figure 5 which is represented by the above equation.

3 Results and discussion

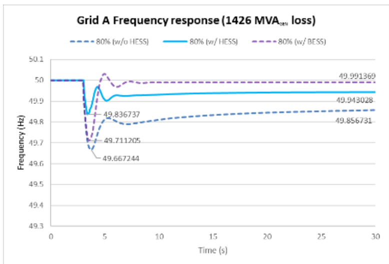
3.1 Grid response

There are three configurations simulated under 80%REP, various operational scenarios and events. These forms the specific contingency measures on which the size of the reserves is based. First, a simulation without any injection of synthetic inertial response. Second, with a homogenous Li-ion battery system and third – with the proposed HESS.

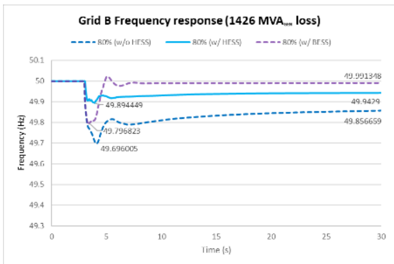
3.1.1 LFSM-U (underfrequency)

As seen in the frequency curves (Figure 6), the proposed HESS significantly contains the falling nadir during an event. It can also provide a better synthetic inertial response in comparison with a homogenous battery system. The reason for such deviation is because of the difference on the ultracapacitor and battery ramp rates. The former has an extremely high discharge rate and power density than the latter due to its means of storing energy [5] [6] (Figure 1). Nevertheless, the BESS has a slightly better recovery phase than the HESS. This is justifiable since the HESS control method is optimized to bring back the frequency to its minimum dead band level.

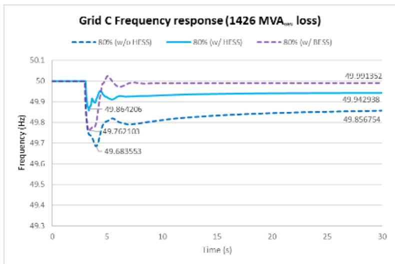
Subsequently, higher generation losses show the stark difference between all the operational scenarios. During an event at 80%REP, the proposed system reduced the nadir substantially to a much safer frequency value. It can be surmised from these results that a hybrid system is better able to curtail the nadir within regulatory boundaries beyond a 20% generation loss than a comparable homogenous system.



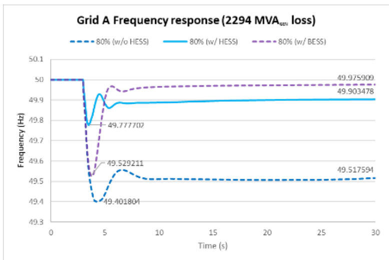
(a)



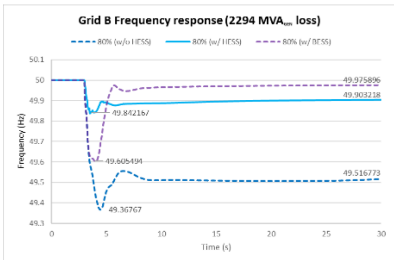
(b)



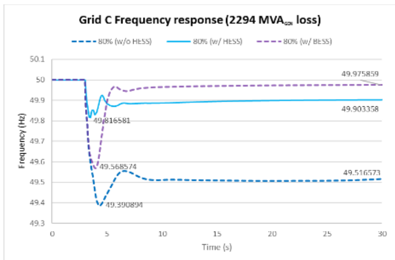
(c)



(d)



(e)

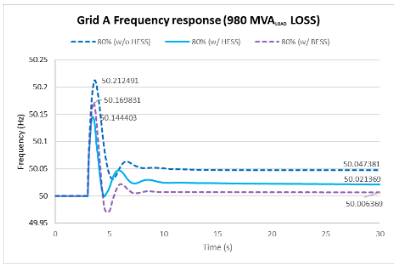


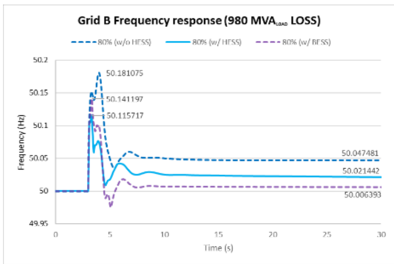
(f)

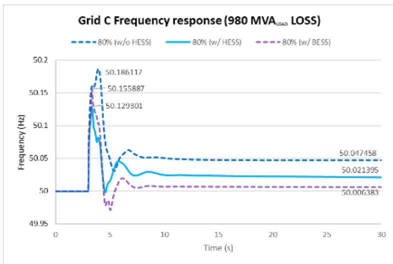
Figure 6 Grid frequencies at a generation loss. (a)(b)(c)1426MVA loss, (d)(e)(f)2294MVA loss.

3.1.2 LFSM-O (overfrequency)

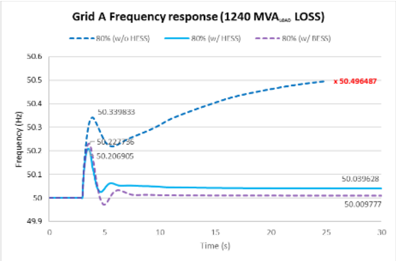
Similarly, HESS provides an overfrequency contingency which reduces the frequency zenith during a significant load loss in the network. It is capable to stabilize the system after a grid event. As seen in Figure 7, both hybrid and homogenous systems are able to contain the initial RoCoF and provide the necessary synthetic inertial response for the recovery phase. Without either system, the grid frequency rises and eventually trips the overfrequency relays (81O) of the TSOs control and protection systems.

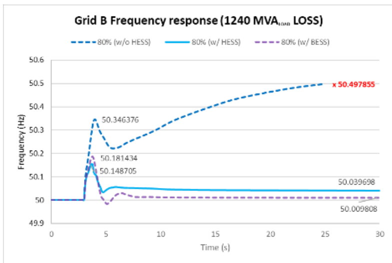


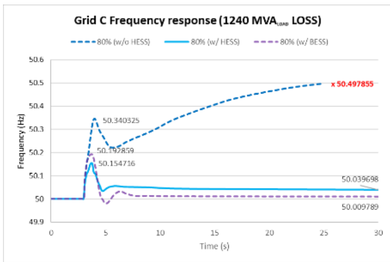




(a) (b) (c)



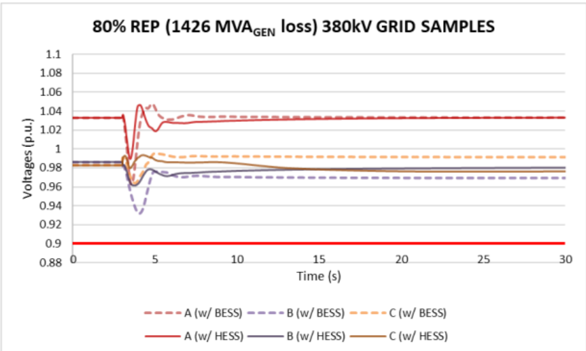


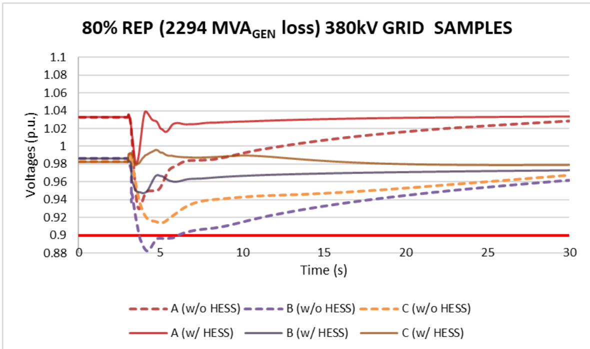


(d) (e) (f)

Figure 7 Grid frequencies at load losses. (a)(b)(c)980MVA loss, (d)(e)(f)1240MVA loss.

3.1.3 Undervoltage response





(a) (b)

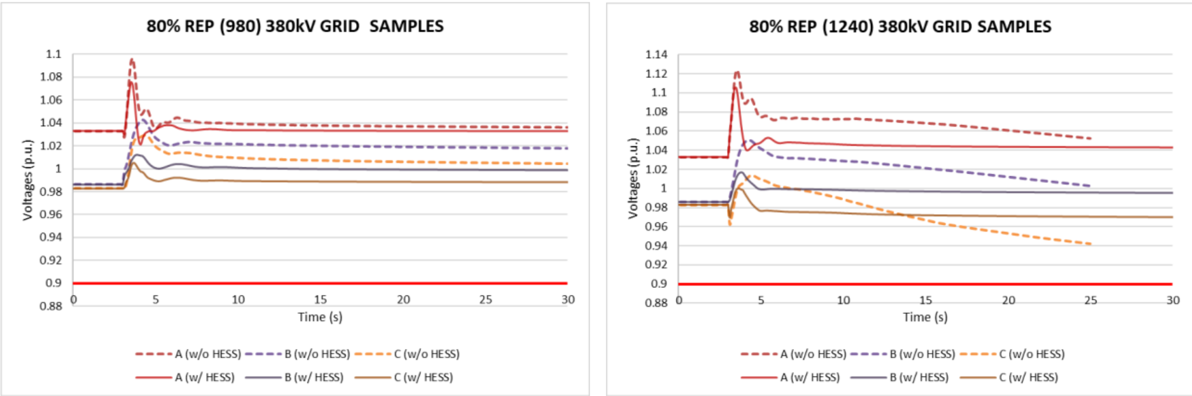
Figure 8 Bus voltage curves under a LFSM-U generation loss event. (a) 1426MVA (b)2294MVA.

(p.u.)	80% REP (1426)			80% REP (2294)	
Highest	Prefault	w/o HESS	w/ HESS	w/o HESS	w/ HESS
1	1.03903	1.030962	1.037816	1.02883	1.033535
2	1.0366	1.02912	1.03439	1.020142	1.029359
3	1.03296	1.028026	1.033026	1.017174	1.026502
4	1.02817	1.02209	1.024724	1.00986	1.02484
5	1.02419	1.013875	1.024279	1.008626	1.014479
Lowest	…	…	…	…	…
5	0.94208	**0.89975**	0.925289	**0.898924**	0.928762
4	0.9415	**0.89624**	0.922447	**0.898924**	0.92853
3	0.94065	**0.887215**	0.920062	**0.896237**	0.925925
2	0.92523	**0.884003**	0.919708	**0.89317**	0.924809
1	0.92452	**0.884003**	0.919485	**0.89317**	0.924281

Table 2 Resulting bus voltages under LFSM-U conditions. Acceptable range, 0.9-1.1 p.u.

Table 2 shows that, if unmitigated, some areas in the grid experiences voltage dips which are below the allowable 0.9-1.1 p.u. range [4] [7]. In comparison, the system can provide the optimal synthetic or virtual inertial response to maintain operational levels without the grid suffering from low voltage events.

3.1.4 Overvoltage response



(a) (b)

Figure 9 Bus voltage curves under a LFSM-O load loss event. (a) 980MVA (b)1240MVA.

(p.u.)	80% REP (980)		80% REP (1240)	
Highest	w/o HESS	w/ HESS	w/o HESS	w/ HESS
1	1.059869	1.041741	1.090857	1.084707
2	1.05827	1.041447	1.057217	1.04396
3	1.054797	1.035467	1.055654	1.042842
4	1.042764	1.032787	1.053787	1.040627
5	1.042171	1.024003	1.052542	1.039546
Lowest	…	…	…	…
5	0.959903	0.945627	**0.884207**	0.921597
4	0.953908	0.941923	**0.881667**	0.918789
3	0.949232	0.941352	**0.877884**	0.918046
2	0.945138	0.925171	**0.870231**	0.916716
1	0.932827	0.924887	**0.848006**	0.915973

Table 3 Resulting bus voltages under LFSM-O conditions. Acceptable range, 0.9-1.1 p.u.

Similarly, Table 3 shows the highest and lowest bus voltage levels within the simulation period. In this case, overvoltage events cause cascading relay trips (59) and isolate some areas of the network around the 25s mark. This resulted to generation shedding which in turn cause the undervoltage events around the grid.

3.2 Islanding

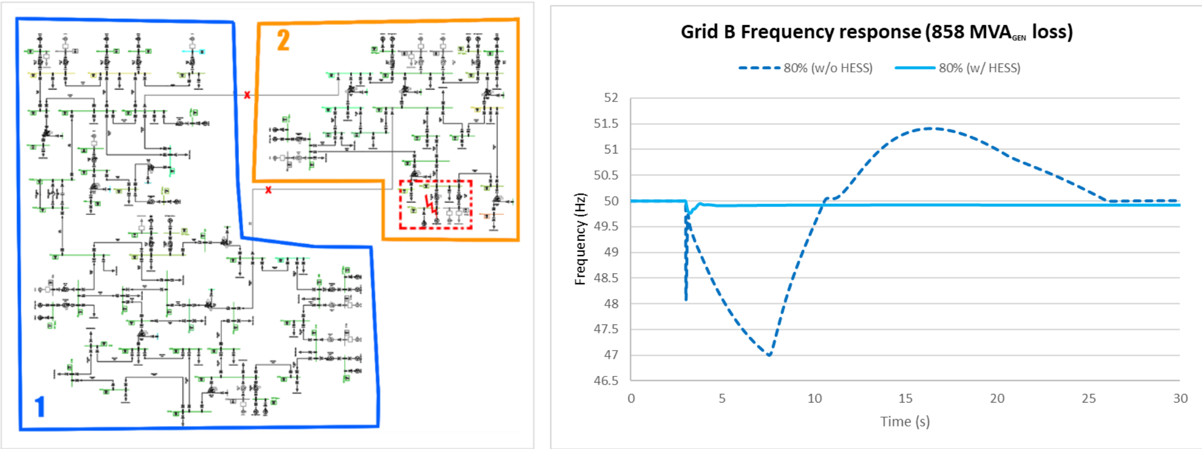
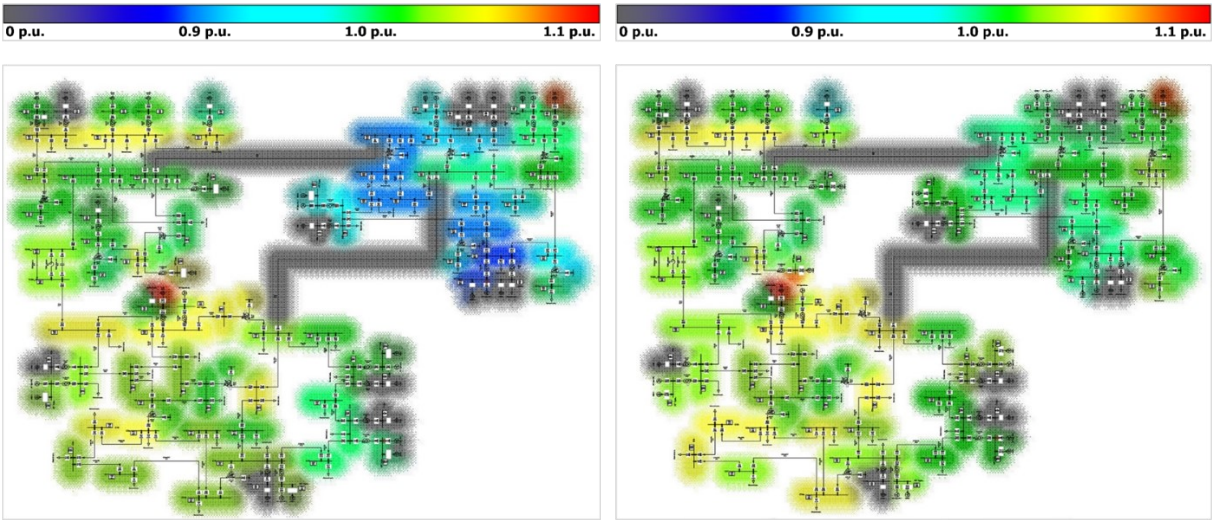


Figure 10 Islanding scenario and its corresponding frequency response under a generation loss event.

The system can provide sufficient synthetic inertial response to sustain an islanding contingency. As shown in Figure 10, Grid B will experience multi-tier trip events that leads to a massive blackout of the network without an energy storage system. Moreover, the proposed solution maintains the voltage levels within the parameters of steady-state operation as seen in the heatmaps below (Figure 11).



(a) (b)

Figure 11 Voltage heatmaps comparing (a)without and (b)with HESS respectively.

3.3 Fault-ride through

Under ENTSO-E guidelines, the proposed HESS must also demonstrate fault-ride through. The system should remain operational even during low voltage conditions caused by bus faults. Figure 12 demonstrates the FRT profile in red lines. This is the allowable limit according to grid regulations under Article 14(a) NC RfG [7] . The system can withstand the undervoltage incident on BUS C12 (380kV) as per the operational scenario describe. It has only a retained voltage, Uret = 0.35 p.u. which is above than the required limit. Furthermore, the system voltage instantaneously recovers Urec = 0.98 p.u. within 200ms upon fault clearing. Thus, the steady-state is achieved faster post-fault.

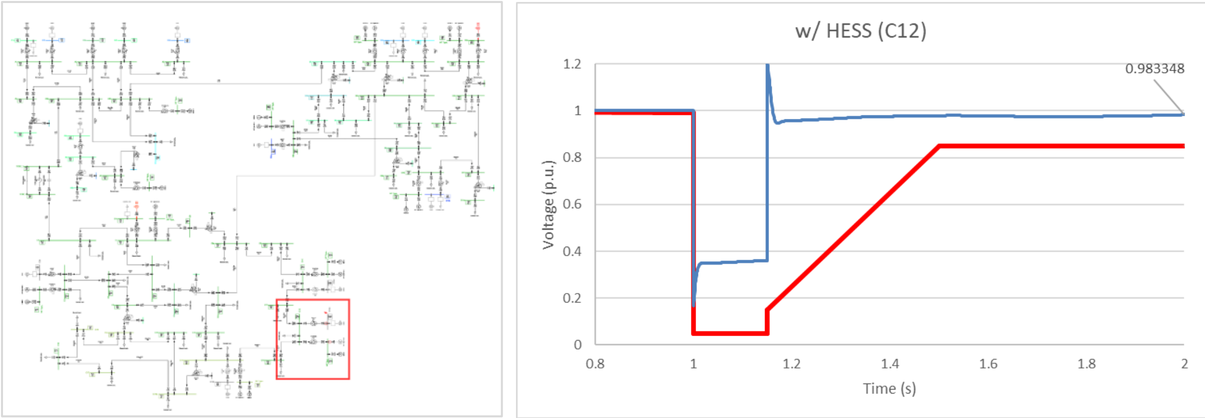
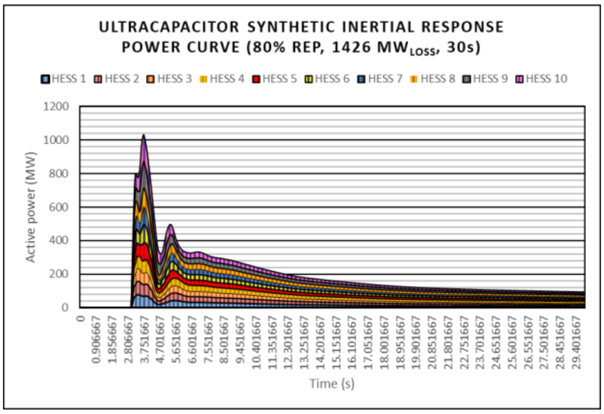
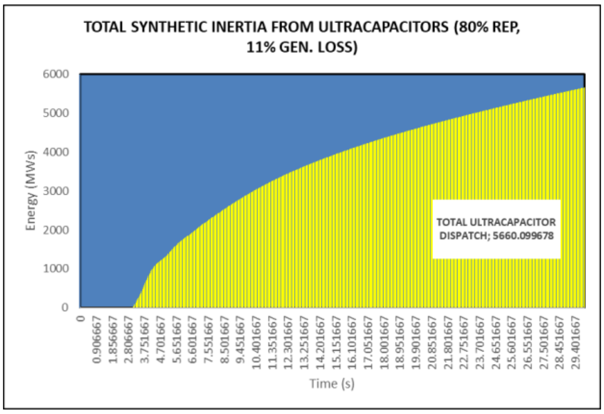


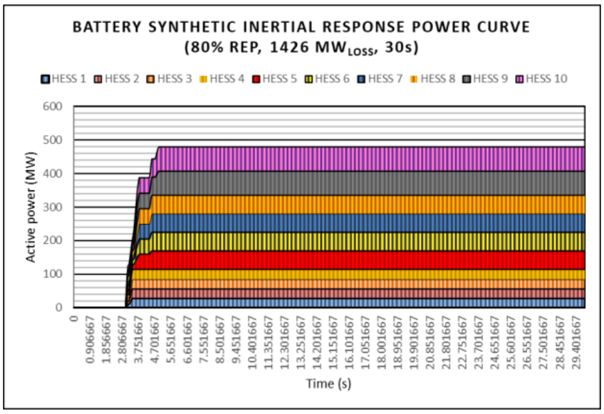
Figure 12 Operational scenario and FRT response of the proposed HESS.

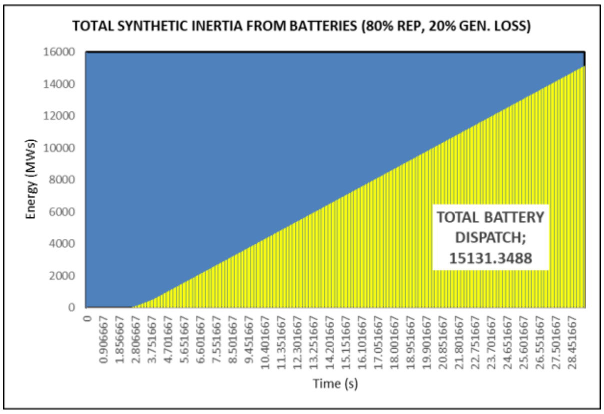
3.4 System size and capacity





(a) (b)





(c) (d)

Figure 13 Synthetic inertial response. (a)UC component (b)UC dispatch (c)Batt component (d)Batt dispatch

As discuss previously (Figure 5), the resulting graphical data of the simulation can be utilized to estimate the required reserves. The synthetic inertial response of a HESS can be divided into components (Figure 13). Using the equation on the first operational scenario (11% loss), the total ultracapacitor dispatch (primary component) needed is around ~6000MWs. This is equivalent to around 1.7MWh of energy reserve. Within this period, the battery dispatch only needed around ~15000MWs which is equivalent to 4.2MWh of energy reserves. However, sizing a battery is quite different. To maintain a 1E discharge rate, the capacity should match the peak response which is around 500MW. Therefore, the final specification of the secondary component is 500MW/500MWh.

3.5 Economic analysis

Assuming a price parity between the two technologies, the economic feasibility of a hybrid solution could be compared to a homogenous system at a constant cost per storage. In this way, the effect of the ramp and discharge rate on the total investment value can be clearly describe. For example, it is assumed that the cost per energy for both technologies is $600/kWh. Battery manufactures normally recommend a discharge/charge rate of 1E to maximize the lifecycle of Li-ion cells. Without considering other configurations for a homogenous system, the total investment cost would almost be twice that of a hybridized solution. It could be argued that an equivalent set-up with a discharge rate of 2E is more appropriate and more cost-effective than the latter. However, there are some factors (such as performance, cycles, replacement cost, etc.) that needs to be considered to substantiate the technicalities which is beyond the scope of this study. Hence, on basic terms, a HESS is more economical than a BESS for this specific purpose.

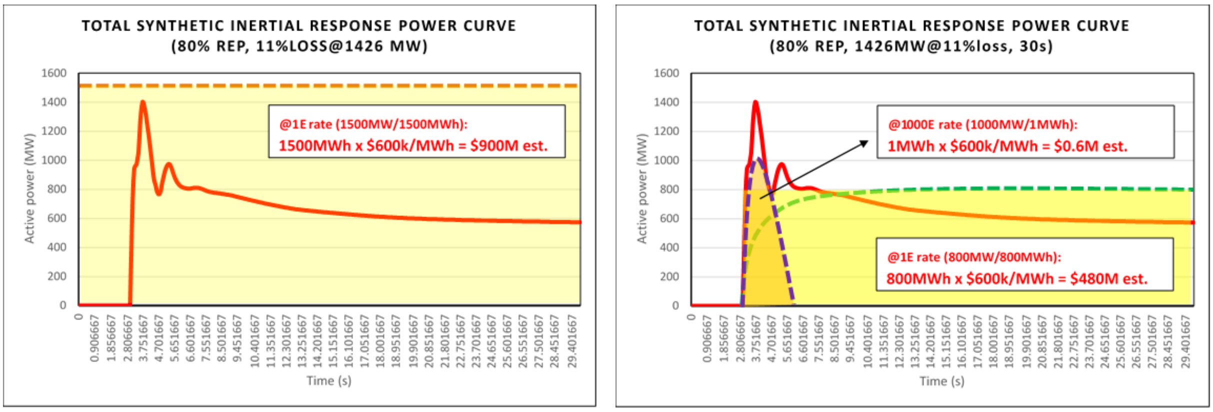


Figure 14 Estimated cost of (a) BESS (b) HESS under allowable discharge rates.

Demand fluctuations and inertial response are traditionally supplemented by peaking powerplants. However, at higher levels of %REP, these conventional gas turbines are not able to black start or dispatch quickly as RoCoF suddenly increases. A recent configuration addresses this issue by combining a peaker plant with a BESS called a load following power plant. [8] [9] The battery component provides the frequency regulation, inertial response and the initial restoration reserves. This enables the gas turbine to operate with more flexibility as a secondary component.

Using Figure 14, the HESS is compared to an equivalent LFPP solution. However, this time the information on battery costs and CCGT are from Tesla [10] and EIA's Annual Energy Outlook 2019. In addition, a Tesla Megapack set-up with a high discharge/charge rate component for frequency regulation is utilized in comparison. [11] As seen in Figure 15, the cost of the battery significantly affects the disparity or deviation in initial capital requirements of each solution. If batteries remain as expensive as it is, LFPPs are an attractive investment than homogenous or hybrid solution. However, with the decreasing trend in prices of Li-ion cells, this will soon change in the future.

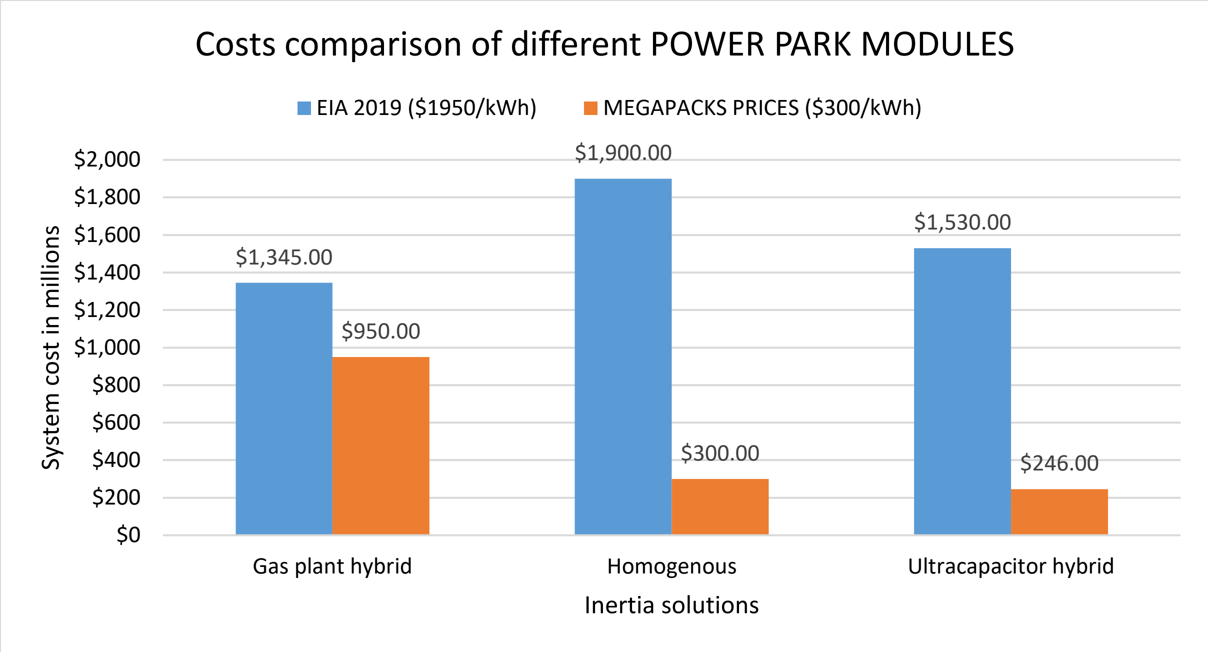


Figure 15 Cost comparison of different inertial response solutions.

4 Conclusion

The research shows that a hybrid energy storage system, which combines an ultracapacitor and Li-ion battery, enables the integration of more renewable energy sources to the network. With the appropriate size and capacity, it is able to comply with EU grid regulations and mandates. In addition, the synthetic inertia reserves needed to supplement the remaining synchronous generous generators at 80%REP are practical enough due to the reduction on the size of the battery component. The estimated cost of the proposed system is cheaper than conventional solutions. Nevertheless, this still depends on the cost per kWh of lithium-ion cells.

5 Recommendation

The research shows that it is possible to combine two different storage technologies with two distinct energy and power density characteristics. In lieu of this, future investigation could be carried out on other mediums such as hydrogen, flow batteries, pump-storage and other slow dispatching sources in combination with a battery or ultracapacitor. Hybridization is a key concept which could help solve the Gordian energy knot.

References

[1] R. K. Pandey, Fundamentals of electroceramics: materials, devices, and applications, Hoboken, New Jersey: Wiley, 2018.

[2] „Electricity balancing in Europe,“ ENTSO-E, Brussels, November, 2018.

[3] U. Bachmann, M. El-Sharkawi , I. Erlich und S. Teeuwsen, „Genetic Algorithm and Decision Tree based Oscillatory Stability Assessment,“ in *IEEE Transactions on Power Systems*, 2005.

[4] European Commission, „Establishing a network code on requirements for grid connection of generators,“ *COMMISSION REGULATION (EU) 2016/631,* 14 April 2016.

[5] H. Helmholtz, „Ueber einige Gesetze der Vertheilung elektrischer Ströme in körperlichen Leitern mit Anwendung auf die thierisch-elektrischen Versuche,“ *Annalen der Physik und Chemie,* Bd. 6, Nr. 165, pp. 211-233, 1853.

[6] F. Diaz-Gonzalez, O. Gomis-Bellmunt und A. Sumper, Energy storage in power systems, Wiley, 2016, p. 288.

[7] European Commission, „Establishing a Network Code on Demand Connection,“ *COMMISSION REGULATION (EU) 2016/1388,* 17 August 2016.

[8] G. Masters, Renewable and Efficient Electric Power Systems, 2nd Hrsg., New Jersey: Wiley, 2013.

[9] R. Rapier, „The Load Following Power Plant: The New Peaker,“ GE, Boston, 2017.

[10] Z. Shahan, „Tesla Megapack, Powerpack, & Powerwall Battery Storage Prices Per kWh,“ CleanTechnica, 2020.

[11] „Resolution E-4949. Pacific Gas and Electric request approval of four energy storage facilities with the following counterparties: mNOC, Dynegy, Hummingbird Energy Storage, LLC and Tesla,“ Public Utilities Commission of the State of California, San Francisco, 2018.

Acknowledgement

This research is in partnership with the Intelligent Electrical Power Grids (IEPG) Group - TU Delft under the ERASMUS exchange program. I would like to thank Dr. Jose Rueda Torres and Dr. Elyas Rakhshani for giving me a chance to pursue this topic as well as providing me with the grid benchmark and necessary data to carry out the simulations. I would also like to thank my supervisor Dr. Wilhelm Süßenbacher for sharing his insights on energy markets and grid regulations. Moreover, I would also like to express my sincerest gratitude to Dr. Robert Höller for assisting me along the way, the whole MSc SES team, all the professors for their continuous support of the program and making it one of the best in FH Oberösterreich.