Extending the Energy Storage Lifetime: A Hybrid Power-Sharing Method

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Extending the Energy Storage Lifetime: A Hybrid Power-Sharing Method

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***Abstract*—The increased adoption of renewable energy sources is reducing the overall inertial response capability of the modern electric power grid, which translates into larger frequency variation in both transient and pseudo-steady-state operation. Energy storage system (ESS) has the potential to play a significant role in regulating the frequency of more renewable electric power grid. This service is commonly known as frequency response or enhanced frequency response (EFR). Lithium-ion (Li-ion) battery is a popular choice as an ESS to provide EFR. However, EFR is very dynamic and the battery may have to provide high and fast response. This may accelerate the aging process of the battery. To overcome this issue, hybrid ESS (HESS) comprised of Li-ion battery and supercapacitor (SC) have been proposed in the literature. HESS typically works through power-sharing method (PSM). This work deals with the design of power sharing controllers able to enable the provision of EFR services from HESS. Keeping the battery lifetime in mind, proposed controllers employ a hybrid PSM by combining both proportional integral (PI) control and Fuzzy logic to maintain the battery state of charge (SOC) as close to the reference as possible while providing EFR. Results show that the lifetime of the Li-ion battery can be significantly extended by using the proposed controllers. However, this depends on the capacity of the SC that is used to support the Li-ion battery. Numerous simulation results are provided to demonstrate the suitability of the proposed controllers.**

***Index Terms*—Battery Lifetime, Hybrid Energy Storage System, Li- ion Battery, Power Sharing Method, Supercapacitor.**

I. Introduction

Electric power grid decarbonization is going to play a significant role in combating the adverse effect of climate change. Renewable energy sources (RES) are a key player in this regard [1]–[5]. However, RES are variable and depends on weather conditions. Moreover, RES are typically connected to the grid through power electronic converters. As a result, the overall inertial response capability of the power grid is decreasing. This translates into larger frequency variation in both transient and pseudo-steady state operation of the grid. To overcome this issue and to maintain the smooth integration of RES into the grid, frequency response or enhanced frequency response (EFR) [6] concept was born. In EFR scheme, energy storage system (EES) can provide frequency support to the grid by injecting or absorbing the power. This scheme helps to stabilize the grid in the presence of intermittent power sources.

Out of various EES available in the market, batteries became very popular [7] to provide the EFR or other kind of ancillary services to the traditional grid or to smooth the power output in micro-grid. Battery EES (BESS) have matured considerably both in power and energy density in the last decade, specially various variants of lithium-ion (Li-ion) battery [8]–[10]. BESS are capable to respond very quickly to high frequency regulation signal to provide the EFR service [11]. However, this degrades the battery lifetime as very fast and regular charging and discharging are involved [12]. This has a considerable economic and environmental impact. To overcome this issue, researchers came up with the hybrid energy storage system (HESS) concept [13]. HESS is basically a combination of different ESS. In HESS, particular limitation of one ESS is compensated by another type of ESS that is less sensitive to the issue of the other ESS. Li-ion BESS lifetime degrades in high frequency operation. This issue can be mitigated by considering a HESS with supercapacitor (SC). SC has high power density and very fast response time, however low energy density as opposed Li-ion battery.

A SC is a double-layer electrochemical capacitor that can store thousand times more energy than a typical capacitor. It has an energy density about 20% of a battery which can process a larger number of charge and discharge cycles and have ability to supply much higher currents than batteries [14], [15]. This combination of Li-ion battery and SC can be very useful as this can protect the battery from fast charging and discharging by smoothing the power output with the aid of SC. The SC provides a protection by reducing the charge or discharge stress that may occur in the Li-ion battery. As a result, the lifetime of battery can be extended resulting in more economically viable and green operation of the HESS.

As mentioned previously, HESS comprised of Li-ion battery and SC is a very suitable choice for providing grid ancillary services e.g. EFR [16]–[18]. As such in this work, the focus is on this kind of HESS. The operation of HESS is typically controlled by power sharing between the ESSs i.e. Li-ion battery and SC. The objective of this work is to design efficient power sharing controllers for HESS. The focus is

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on maximizing the lifetime of Li-ion battery while providing satisfactory EFR service to the grid.

The rest of the paper is organized as follows: Sec. II discusses the mathematical modeling while control design study is performed in Sec. III, results and discussions are given in Sec. IV, and finally Sec. V concludes this paper.

II. MODEL DERIVATION

A. Li-ion Battery Model

A lithium-ion battery is a type of rechargeable battery where during discharging, the lithium ions are moving from negative to positive and vice versa for the charging state. According to [19], discharging (1) and charging (2) are expressed as follow:

$$\begin{aligned} V_{\text{bat}} &= R_b I + f_1(it, i^*, i), \\ f_1(it, i^*, i) &= E_0 - K\frac{Q_b}{Q_b - it} i^* - K\frac{Q_b}{Q_b - it} it + Ae^{-Bit} \end{aligned} \tag{1}$$

$$\begin{aligned} V_{\text{bat}} &= R_b I + f_2(it, i^*, i), \\ f_2(it, i^*, i) &= E_0 - K\frac{Q_b}{0.1Q_b - it} i^* - K\frac{Q_b}{Q_b - it} it + Ae^{-Bit} \end{aligned} \tag{2}$$

where E_0 is the open circuit voltage of the battery, K is defined as the polarization constant, α is the exponential zone amplitude of the battery, and β is the inverse of the exponential zone time constant. Formula for calculating the State of Charge is:

$$\text{SOC}_{BESS}(t) = \text{SOC}_0 - \frac{1}{Q_{BESS}} \int_{t_0}^{t} I_{BESS}(s) ds \tag{3}$$

where Q_{BESS} is the battery capacity. Battery degradation factors such as thermal and ageing effect are not taken into account in eq. (3) to simplify the analysis. Moreover, it is assumed that BESS are connected in series.

B. Supercapacitor Model

Usually SC is used for renewable energy applications where high power density and fast response are needed to maintain the performance of the battery to be at good condition. Other than that, SCs are mainly used to deal with high and fast transient charging such as hybrid cards, buses, trains, elevator, etc. those examples are using a high instant braking and short – term energy storage [20]. The model of SC is expressed as:

$$\begin{aligned} V_{SC} &= \frac{N_S Q_T d}{N_p N_e e e_0 A_i} - R_{SC} i_{SC} + \\ &\quad + \frac{2 N_e N_s R T}{F} \sinh^{-1}\left(\frac{Q_T}{N_P N_e^2 A_i \sqrt{8RTee_0c}}\right), \\ Q_T &= N_P Q_C \int i_{sc} dt. \end{aligned} \tag{4}$$

Where N_S and N_P are number of connections in series and parallel respectively. A_i and c are respectively the interfacial area between electrode and electrolyte, and the molar concentration. F and R are Faraday constant and ideal gas constant respectively. N_e is the number of layers of electrodes with d and T as molecular radius and operating temperature. e and e_0 are the permittivity of material and free space respectively. The following equation [20] is showing how to obtain the SOC_{SCSS}.

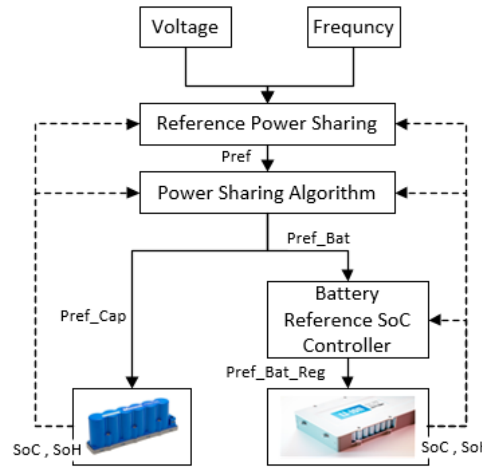


Figure 1. Overview of PSM method [21].

$$\text{SOC}_{SCSS}(t) = \text{SOC}_0 - \frac{1}{Q_{SCSS}} \int_{t_0}^{t} I_{SCSS}(s) ds \tag{5}$$

where Q_{SCSS} is the electric charge in Coulomb.

C. Power Sharing Method

Power Sharing Method (PSM) main purpose is to maximize the performance of SC so that it can reduce the battery stress. The algorithm works in three steps to generate the power references for HESS. In the first-stage, reference power is computed using the energy systems operator signal and the actual frequency. It is normalized using droop method. In the second-stage, reference power of battery and supercapacitors are computed. Finally, a controller is added to for battery SOC regulation. An overview of PSM is given in Fig. 1. Some popular PSMs are summarized below:

1) Low Pass Filter (LPF) Approach: LPF is a filter that passes signals with a frequency lower than the cut off frequency. This approach use the low frequency signal for the battery and high frequency for the SC. It is easy to implement. However, choosing the cut-off frequency is very crucial. The cut-off frequency choice can significantly effect the sizing of HESS.

2) First Rule Based (FRB) Approach: FRB method aims to maximize the SC's performance in a certain voltage range i.e. choosing the voltage range of SC so that it can maintain high performance in those maximum and minimum working voltages. However, the limit needed to be considered carefully because it may damage the SC badly.

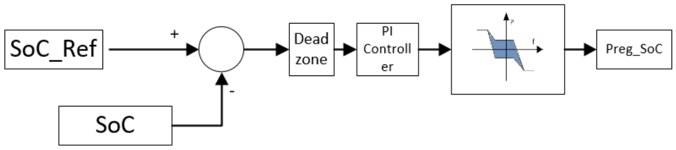


Figure 2. Battery SoC Controller [21].

3) Hybrid Approach: Hybrid technique is a combination of LPF and FRB to obtain the power reference for HESS. In this method, the power reference of battery and SC will be generated through combination of both methods (LPF and FRB). Here, LPF and FRB compliments each other.

III. CONTROLLER DESIGN

A. EFR Controller

EFR usage is to enhance frequency [22] stability while considering the rate of change of frequency (ROCOF). The ESSs asset provide a proportional power response when it is higher than frequency insensitive band which is $\Delta f = \pm 0.05$Hz for wide band and $\Delta f = \pm 0.015$Hz for narrow band frequency response. Frequency response is a necessary part of any AC power system and usually procured via ancillary service market. Frequency response is used for the energy storage system to determine the performance of it. To alleviate this problem, National Grid (NG) has provided a control scheme called Enhanced Frequency Response (EFR) which aimed fully at Energy Storage System (EESs). National Grid (NG) is the transmission system operator of Great Britain (GB), and it is responsible for delivering any transmission system of the National Electricity Transmission System (NETS). NG do provide conventional frequency control actions such as primary, secondary and high â frequency response which does not support for frequency regulation and frequency containment. Because those cause, NG invent new frequency response called Enhanced Frequency Response (EFR).

B. PI Controller

A PI controller is a feedback mechanism widely used in industrial control system and a variety of other applications requiring continuously modulated control. A PI-based battery SOC controller considered in this work is given in Fig. 2, where dead-zone and a dynamic saturation block is implemented in order to respond to system operator requirement.

C. Fuzzy Logic Controller (FLC)

FLC is developed to manage the SOC of each ESS assets when the frequency deviation is within ± 0.25Hz from the nominal frequency as stipulated in the EFR guidelines. If the SOC of the asset is either lower or higher than the envelope, FLC will instruct it to charge or discharge to be within the desired envelop.

Table I
BATTERY'S PERFORMANCE WITHOUT SOC CONTROLLER.

Battery Performance			
Method	SOC(%)	Voltage (V)	Power (w)
LPF	67.93	1.1×10^7	4.8×10^{10}
FRB	69.78	1.1×10^4	4×10^7
Hybrid	77.73	2.6×10^9	9.7×10^{12}

Table II
BATTERY WITH PI CONTROLLER PERFORMANCE.

Battery with PI Controller Performance			
Method	SOC(%)	Voltage (V)	Power (MW)
LPF	67.92	263.6	0.96
FRB	69.77	263.6	0.96
Hybrid	77.7	263.6	0.96

IV. RESULTS AND DISCUSSIONS

A. PSM Approach

1) SoC Without Controller: Purpose of this project is to share the required power between BESS and SC while considering the lifetime of both sources specially to extend the battery lifetime. Results are given in Table I. Table I shows how the battery performs without using a controller. It shows that the performances are burst out drastically due to unstable performance and only first rule method has been applied to it. It is not enough to handle such swift shifting performance on the battery each second. Therefore, unstable result may be occurred as it run through time.

2) SoC With Controller: Controller is added to ensure regulation of the battery SOC. A PI controller method is considered in the simulation. The basic structures include dead zone block, PI controller, and opeartor requirement which is EFR. Dead zone block gives a minimization to the battery use if the SoC value is within a certain range (in range ± 0.5). the parameters of the PI controller are chosen to optimize the regulation capacity of the battery. Output of PI will be processed in term of TSO requirement. Results are summarized in Table II. EFR introduces the ability to response at very fast within a short duration [20]. Through a lot of experiment, researcher of NG found out that EFR cannot be compatible with the existing services because there was not a facility to manage the transition between one service and another. This problem on design was one of the considerations that led to a conclusion to extend response from 10 second to 15 minutes.

B. EFR with Battery Model

Managing a frequency in 50 Hz requires many distribute generation sources against a varying load. National Grid, which is the main distribution network operator in UK have introduce a new method called Enhanced Frequency Response (EFR). EFR is invented to support the energy storage system-based frequency regulation. All the simulation results in this section are performed using Matlab/Simulink. Results will be divided into three sections:

- EFR with BESS and Ramp Rate.

- EFR + FLC with BESS and Ramp Rate.
- EFR + FLC + PID with BESS and Ramp Rate.

1) EFR with BESS and Ramp Rate: Frequency data which has been provided by National grid will be used to determine the frequency deviation as an input to EFR. Frequency reference is the nominal system frequency which is 50 Hz. Rate of Change of Frequency (ROCOF) is used for fast load shedding, to speed up operation time in over and under frequency situations and to detect loss of grid [23].

$$\left(-\frac{1}{0.45}\frac{df}{dt}-0.01\right) \leq \frac{d\mathrm{P}_{EESS}}{dt} \leq \left(-\frac{1}{0.45}\frac{df}{dt}+0.01\right) \qquad (6)$$

Inside the envelopes, the maximum and minimum of ramp rates $\left(\frac{d\mathrm{P}_{EESS}}{dt}\right)$ depends on the value of ROCOF $\left(\frac{df}{dt}\right)$.

2) EFR + FLC with BESS and Ramp Rate.: A controller is added to see the difference between using a controller and without using it. A FLC controller is taken into consideration for the simulation. A membership function is a working area of certain input from FLC to work in a size of a shape. A triangle shape MF is chosen because it can give more accurate and straighter forward implementation. In fuzzification stage, frequency deviation and SOC regulation error will be transformed into linguistic value. After deciding the membership functions, a rule base should be defined as well because theoretically, FLC is used the If-then method to specify the output.

3) EFR + FLC + PI with BESS and Ramp Rate: After doing a simulation with using FLC alone, it does not give any satisfactory result. Another method to improve the performance is by adding another controller so it could enhance the power output. PID controller consist of Proportional-Integral-Derivative controller. Proportional control provides an immediate action to the controller error, integral control will use the constant error by driving it to zero or near zero which will help to keep the system uniformed used to control the system alone and therefore can affect the entire loop. Derivative control acts upon the change of the error that is controller the specific function but will not be used in this simulation.

The figure 3 shows that the SOC is decreasing but still maintain the SOC near to the reference. EFR without a controller is showing a large deviation compare with the controller. The faster the SOC decreasing, the earlier the battery will degrade. Using a controller can slow down the SOC decrease because it's job is to maintain and optimize the output of the system to be better. The voltage that is produced using 3 different model shows that FLC + PID controller able to smooth the voltage rather than just a normal FLC. The performance of EFR with BESS to produces power output shows a different based on EFR with and without using FLC. It shows a slightly difference between both. However, adding a PI gives a significant improvement. Results are summarized in Table III.

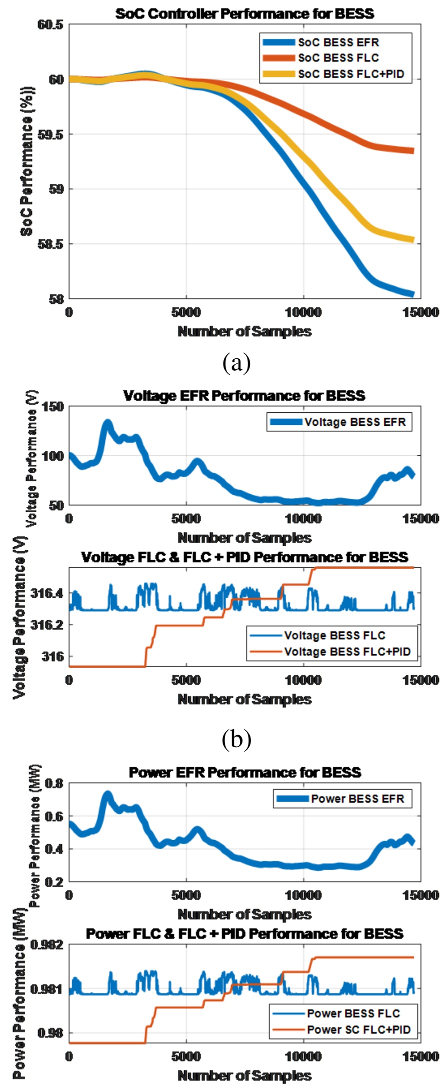


Figure 3. Simulation results with BESS, (a). SOC Controller Performance, (b). Voltage Controller Performance, (c). Power Controller Performance.

Table III
SC PERFORMANCE.

EFR with BESS Response.			
Method	SOC(%)	Voltage (V)	Power (MW)
EFR	58.04	78.75	4.3
FLC	59.35	316.3	9.8
FLC+PID	59.53	316.6	9.8

Table IV
EFR WITH SCSS RESPONSE.

EFR with SCSS Response			
Method	SOC(%)	Voltage (V)	Power (MW)
EFR	57.98	55.99	5.3
FLC	59.7	51.05	4.4
FLC+PID	59.33	53.13	4.8

C. Enhanced Frequency Response with Supercapacitor Model

1) EFR with SCSS & Ramp Rate: The same simulation scenario is considered as the BESS. However, instead of using BESS, the SC model will be considered to investigate the performance of EFR.

2) EFR + FLC with SCSS & Ramp Rate: Here, a fuzzy logic control is used to manage the SOC of ESS asset. If the frequency deviation result is within ± 0.25 Hz, then it will be assigned in EFR characteristic. If the SOC of the model is lower or higher than the reference, FLC will instruct to either charge or discharge following the lower or higher envelope.

3) EFR + FLC + PI with SCSS & Ramp Rate: PI is a controller which is used to reduce error of a system by proportional and integral operation. Proportional gives an effect as the errors are multiplied with certain gain value. Integral can increase the static accuracy and eliminates error which by control output proportionally to the sum of the error. Combining both FLC and PI may give a better result. The model is like the BESS. The result of three methods are given in Fig. 4.

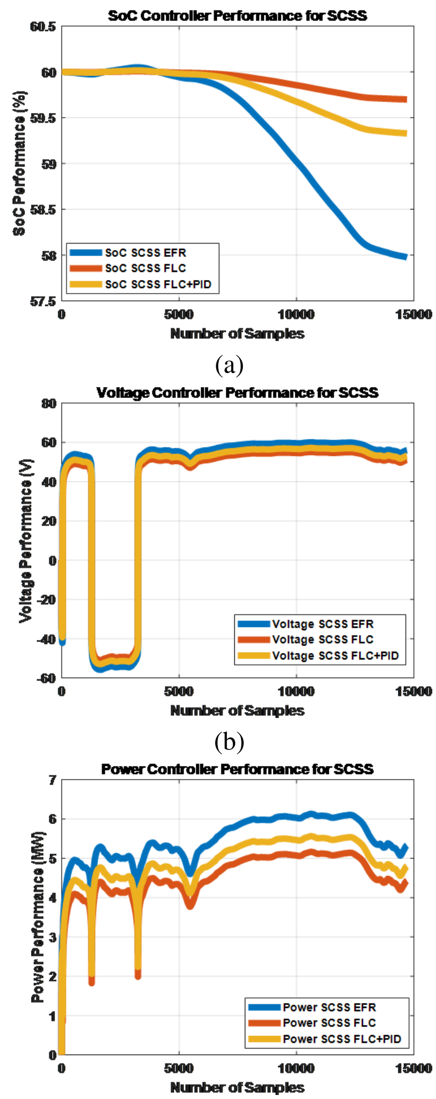
As shown in Fig. 4, SC provides a better performance compare when it does not connect with EFR controller. As a result, using FLC and PID can improve the SC's SOC. The same happen for the voltage (Figure 4 (b)) and power (Figure 4 (c)) after being simulated. Turns out, the result show that all 3 methods give a stable and better result compared to when it does not have the EFR controller and other controllers. Table 6 indicates the result of SC connected with EFR controller to enhance the output performance.

D. Battery Lifespan.

Any type of battery storage application needs to consider about End of Life (EoL) parameter. Number of throughput cycles (N_eff) for battery aging is built based on [24] as shown below:

$$N_{eff} = \int \frac{|I(t)|}{2Q} dt \tag{7}$$

Q is the capacity of battery and $I(t)$ is the instantaneous battery current value. The lower the value of N_{eff} means increasing the battery lifetime. A simulation to determine the battery lifetime have been simulated through Simulink with using different kinds of the method (PSM, EFR, FLC, and PID). Results are shown in Fig. 5. For three kinds of method of controller that are applied showing that EFR controller with and without PID showing a similar graph. Turns out that adding a controller can restraint the battery lifetime. With this controller, it manages to control the SOC to be as close as possible to the reference value.



(a) (b) (c)

Figure 4. Simulation results with BESS, (a). SoC Controller Performance, (b). Voltage Controller Performance, (c). Power Controller Performance

V. Conclusion and Future Works

This paper shows the impact of enhanced frequency response to energy storage system. Battery and SC are chosen as HESS because of the advantages that can be produced by combining both sources. Battery provides high power with fast response time but it is costly and not capable to be used for high frequency. A SC is chosen to support the battery to deal more with fast frequency variations. EFR is developed to integrate the ESS properly so that it allows to manage the SOC in certain service windows. However, EFR does produces a result which can be improved by adding another controller to support it. A FLC and PID are simulated to see if both controller either gives an improvement or becomes a distraction for the model. Through extensive simulation, the results are obtained. Evidently, EFR controller does gives a good result using either BESS or SCSS. EFR successes to maintain the SOC as close as possible to the reference value but, a reduction to the power outputs happen for both sources. To overcome this problem, a controller is added to support the performance. In fact, to achieve the best result, both controllers needed to collaborate instead of using either one of them. Future works would be use a different types of controller such

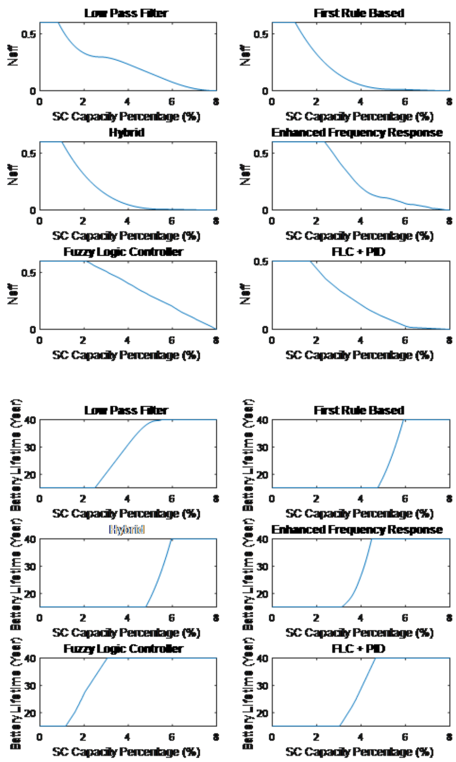


Figure 5. Battery Lifespan.

as Model Predictive Control (MPC) or Generalized Predictive Control (GPC) to achieve a better performance for EFR and the ESS. A different choice of membership function for FLC can be used to enhance the performance of FLC. Potential membership functions could be narrow-topped or trapezoidal. Additionally, another PSM approach can be tested instead of combining both LPF with FRB. A second rule based can be taken as consideration. Lastly, optimization can be taken into account. As we know that optimization does improve the performance for a high and fast charging system which will be useful to minimize the error and enhance the output performance maximally.

References

[1] H. Ahmed, S. Biricik, and M. Benbouzid, "Enhanced frequency adaptive demodulation technique for grid-connected converters," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 11, pp. 11 053–11 062, 2021.

[2] ——, "Low-pass filtering or gain tuning free simple dc offset rejection technique for single and three-phase systems," *Electric Power Systems Research*, vol. 186, p. 106422, 2020.

[3] H. Ahmed, R. Ushirobira, and D. Efimov, "On robust synchronization of nonlinear systems with application to grid integration of renewable energy sources," *Annual Reviews in Control*, vol. 52, pp. 213–221, 2021.

[4] H. Ahmed, M. L. Pay, M. Benbouzid, Y. Amirat, and E. Elbouchikhi, "Gain normalized adaptive observer for three-phase system," *International Journal of Electrical Power & Energy Systems*, vol. 118, p. 105821, 2020.

[5] H. Ahmed and M. Benbouzid, "On the enhancement of generalized integrator-based adaptive filter dynamic tuning range," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 10, pp. 7449–7457, 2020.

[6] B. Gundogdu, D. Gladwin, and D. Stone, "Battery energy management strategies for uk firm frequency response services and energy arbitrage," *The Journal of Engineering*, 2019.

[7] S. B. Elghali, R. Outbib, and M. Benbouzid, "Selecting and optimal sizing of hybridized energy storage systems for tidal energy integration into power grid," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 1, pp. 113–122, 2019.

[8] F. Poloei, A. Akbari, and Y.-F. Liu, "A moving window least mean square approach to state of charge estimation for lithium ion batteries," in *2019 1st Global Power, Energy and Communication Conference (GPECOM)*. IEEE, 2019, pp. 398–402.

[9] E. Mouncef, B. Mostafa, and E. Naoufl, "Online parameter estimation of a lithium-ion battery based on sunflower optimization algorithm," in *2020 2nd Global Power, Energy and Communication Conference (GPECOM)*. IEEE, 2020, pp. 53–58.

[10] H. Ahmed and A. Ullah, "Exponential moving average extended kalman filter for robust battery state-of-charge estimation," in *2022 International Conference on Innovations in Science, Engineering and Technology (ICISET-2022)*. IEEE, 2022, pp. 1–6.

[11] D. Greenwood, K. Y. Lim, C. Patsios, P. Lyons, Y. S. Lim, and P. Taylor, "Frequency response services designed for energy storage," *Applied Energy*, vol. 203, pp. 115–127, 2017.

[12] K. Uddin, S. Perera, W. D. Widanage, L. Somerville, and J. Marco, "Characterising lithium-ion battery degradation through the identification and tracking of electrochemical battery model parameters," *Batteries*, vol. 2, no. 2, p. 13, 2016.

[13] A. Abdelkader, A. Rabeh, D. M. Ali, and J. Mohamed, "Multi-objective genetic algorithm based sizing optimization of a stand-alone wind/pv power supply system with enhanced battery/supercapacitor hybrid energy storage," *Energy*, vol. 163, pp. 351–363, 2018.

[14] A. Lahyani, P. Venet, A. Guermazi, and A. Troudi, "Battery/supercapacitors combination in uninterruptible power supply (UPS)," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1509–1522, 2012.

[15] S. Shili, A. Hijazi, A. Sari, X. Lin-Shi, and P. Venet, "Balancing circuit new control for supercapacitor storage system lifetime maximization," *IEEE Transactions on Power Electronics*, vol. 32, no. 6, pp. 4939–4948, 2016.

[16] H. Shahinzadeh, S. Nikolovski, J. Moradi, and R. Bayindir, "A resilience-oriented decision-making model for the operation of smart microgrids subject to techno-economic and security objectives," in *2021 9th International Conference on Smart Grid (icSmartGrid)*. IEEE, 2021, pp. 226–230.

[17] M. Shaneh, H. Shahinzadeh, M. Moazzami, and G. B. Gharehpetian, "Optimal sizing and management of hybrid renewable energy system for highways lighting," *International Journal of Renewable Energy Research*, vol. 8, no. 4, pp. 1–14, 2018.

[18] M. Moazzami, S. Hosseini, and S. Shahinzadeh, "Optimal sizing of an isolated hybrid wind/pv/battery system with considering loss of power supply probability," *Majlesi Journal of Electrical Engineering*, vol. 11, no. 3, pp. 63–69, 2018.

[19] S. N. Motapon, L.-A. Dessaint, and K. Al-Haddad, "A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1320–1334, 2013.

[20] F. Sanchez, J. Cayenne, F. Gonzalez-Longatt, and J. L. Rueda, "Controller to enable the enhanced frequency response services from a multi-electrical energy storage system," *IET Generation, Transmission & Distribution*, vol. 13, no. 2, pp. 258–265, 2018.

[21] M. Bahloul and S. K. Khadem, "Impact of power sharing method on battery life extension in HESS for grid ancillary services," *IEEE Transactions on Energy Conversion*, vol. 34, no. 3, pp. 1317–1327, Sep. 2019.

[22] H. Ahmed, I. Salgado, I. Chairez, and M. Benbouzid, "Robust gradient estimator for unknown frequency estimation in noisy environment: Application to grid-synchronization," *IEEE Access*, vol. 8, pp. 70 693–70 702, 2020.

[23] N. G. ESO, "System operability framework (SOF)." [Online]. Available: https://www.nationalgrideso.com/insights/system-operability-framework-sof

[24] Y. Kim, V. Raghunathan, and A. Raghunathan, "Design and management of battery-supercapacitor hybrid electrical energy storage systems for regulation services," *IEEE Transactions on Multi-Scale Computing Systems*, vol. 3, no. 1, pp. 12–24, 2016.