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A Review of Lithium-ion Battery Capacity Fade Deceleration at Power Fluctuations in Renewable Energy Systems

Isaac Gwayi†, Sarah P. Ayeng'o, and Cuthbert Z.M. Kimambo

Department of Mechanical and Industrial Engineering, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania.

†Corresponding Author: igwayi@mubas.ac.mw; ORCID: 0009-0001-4165-4532

ABSTRACT

Application of lithium-ion (Li-ion) batteries to store energy in renewable energy systems (RESs) is increasing due to their promising properties. Therefore, it is crucial to understand aging behaviours of Li-ion battery during RES life time as this directly affects cost of energy. Li-ion battery aging can be categorised into calendar aging and cycle aging. Calendar aging depends mainly on temperature and state of charge (SoC). In addition to temperature and SoC, cycle aging depends also on charge and discharge current rates and cut-off voltages. Higher current rates lead to faster Li-ion battery aging. It is necessary to identify appropriate battery power control strategies and their configuration to decelerate batteries' aging in RESs. In this paper, a review of effects of power fluctuations on cycle life of Li-ion batteries in RESs has been done. Furthermore, hybrid energy storage systems (HESS), comprising battery system (BS) and supercapacitor (SC), topologies and control strategies are studied. Literature focussing on BS-SC systems in RESs was reviewed aiming at finding commonly used topologies and strategies. It has been found that the most commonly used methods in BS-SC HESS are classical strategies (70%) and full-active converter topology (80%). The study recommends using classical control strategies and full-active converter topology during BS-SC implementation in RESs. Furthermore, the study recommends that future research should focus on evaluating in detail technical and economic factors of the identified control strategies and HESS converter configurations.

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INTRODUCTION

Application of lithium-ion (Li-ion) batteries to store energy in renewable energy systems (RESs) is increasing due to their promising properties. Li-ion batteries are preferred in many other applications as well including transportation, portable electronics and back-up power systems. They are selected mainly due to their higher energy density, power density, efficiency as well as low self-discharge compared to their counterparts such as Nickel Chloride (NiCd) and Lead Acid (Pb-Acid) batteries (Gwayi *et al.*, 2025; Jiang *et al.*, 2014) as evidenced in a Ragone plot shown in Figure 1(a).

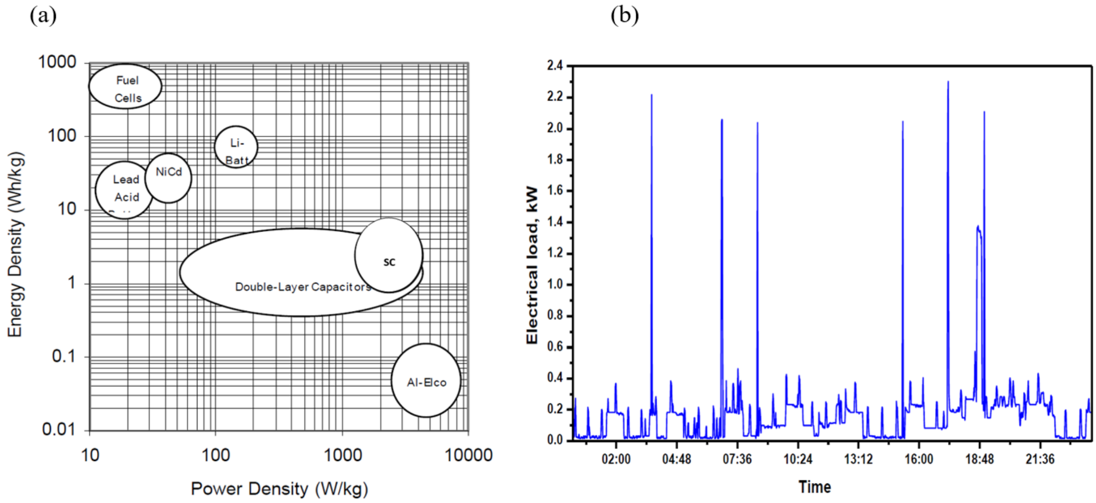
Capacity of Li-ion batteries fade due to aging which is influenced by operation conditions of the battery. The aging of Li-ion battery can be classified into calendric and cyclic (Ayeng'o *et al*., 2018; Groot, 2012). Calendric aging occurs mainly due to the solid electrolyte interface (SEI) formation that takes place in the graphite electrode leading to loss of lithium and increase of resistance. This aging type is mainly influenced by battery temperature and its state of charge (SoC). On the other hand, cyclic aging occurs when the side reactions interact with additional aging phenomena such as the expansion of the electrodes (Schmalstieg *et al*., 2014). The volume changes occurring during repeating intercalation and de-intercalation of the lithium results in mechanical stress in the active material. Cyclic aging is affected by the cycling depth, average SoC, charge and discharge current rates and battery temperature (Schmalstieg *et al*., 2014).

Power supply and demand fluctuates in RESs which results in fluctuations in battery current. The fluctuations are severe in off-grid RESs due to small inertia of the systems as compared to on-grid RESs (Schäfer *et al*., 2017). These fluctuations accelerate cycle aging hence faster battery capacity fade. Accelerated capacity fade increases number of battery replacements within system life time, consequently, increasing cost of energy (COE). Furthermore, more battery replacement within system life time means increased negative environmental effects due to battery production processes as well as disposal (Sayilgan *et al*., 2009). In order to improve Li-ion battery cycle life, hybrid energy storage system (HESS) of Li-ion batteries and Supercapacitors (SCs) have become one of the research focus points concerning energy storage technologies (Sikkabut *et al*., 2016).

In this regard, there is need to identify appropriate battery system (BS)-SC configurations and power control strategies for implementing in RESs to decelerate BS capacity fading due to fluctuations. In this paper, therefore, a review on the effects of current fluctuations on cycle life of Li-ion batteries in RESs and various configurations for interfacing BSs and SC units to direct current (DC) bus in RESs is done. Furthermore, a review of power management strategies in BS-SC HESS configurations is done. Finally, examples from literature are presented and insights are drawn. The paper has presented all this convenient information concisely and in a logical way to assist researchers in Li-ion batteries (and all other batteries) usage cycle life extension to quickly grasp the problem and be able to select appropriate methods to use to extend the batteries' life.

EFFECTS OF POWER FLUCTUATIONS ON LI-ION BATTERY CYCLE LIFE

In off-grid RESs, power produced by energy sources as well as demanded by loads fluctuates. Power fluctuations from energy sources are as a result of intermittent nature of renewable sources, for example wind and solar radiation resources (Hailemariam *et al*., 2013; Jiang *et al*., 2012). Power demand fluctuations by loads are a result of variations of user's needs as a function of time. The demand variations can sometimes be very high, compared to average power demand from the system, but usually in short periods of time. These power demand peaks, appear for short periods of time and are as a result of loads, for example water pumps, grinders, compressors and mills, which need high startup currents. Startup currents for such appliances can be 6 to 10 times greater than their rated currents (Glavin *et al*., 2008; Glavin *et al*. 2009). An example of illustration of such power fluctuations is presented in Figure 1 (b).



(a) Ragone plot (Source: Park *et al*., 2005) (b) Example of load demand power fluctuations (Source: Hassan *et al*., 2022)

Figure 1: A Ragone plot of batteries and supercapacitors and an example of a fluctuating load.

Li-ion batteries, like any other battery type, are efficient at supplying either their rated or lower power (currents) and steady loads (Aravind and Jyothi, 2013). Demand power fluctuation rates have major impact on life span of the battery cells and consequently on the whole BS. Charging or discharging currents' rates affect the number of cycles (cycle life) a Li-ion battery can withstand before reaching its end of life. High current fluctuations (during charge or discharge) reduce its cycle life (Aravind and Jyothi, 2013; Sathishkumar *et al*., 2012). This is so due to fast volume changes occurring during repeating intercalation and de-intercalation of the lithium as a result of current fluctuations, which then results in huge mechanical stress in the active material. These fluctuations also increase internal generated heat which also contributes to capacity fade. Even if these power fluctuations exist for short durations, their impact on battery life cycle is noticeable.

Therefore, how to reduce Li-ion battery capacity fade in off-grid RESs has emerged to be one of the core issues of the energy storage technology. Using HESS technology, where Li-ion battery is combined with SC, is one of the proposed solutions. In SCs, energy storage is through static charge which is different from that of electrochemical process as in batteries; (Camara *et al*., 2008; Lhomme *et al*., 2005). This makes SCs to have higher power densities than BSs as evidenced in Figure 2(a). Furthermore, SCs have lower internal resistance compared to BSs and their cycle life is up to a million times. In BS-SC configurations, the SC, as a device which stores energy on short-term basis, is utilised to handle fast changes in the input or output power. The BS, in this case, which is a long-term energy storage device is used to meet average powers (Camara *et al*., 2008; Lhomme *et al*., 2005). By using the BS together with SC, the charging and discharging currents and internal heat generation of the battery are reduced hence extending Li-ion's battery life time.

BATTERY SYSTEM AND SUPERCAPACITOR SYSTEM CONFIGURATIONS

In general, HESS comprising BS and SC can be configured based on three main topologies, namely: passive topology, semi-active topology, and full-active topology. These topologies are briefly reviewed in Section.

Passive topology

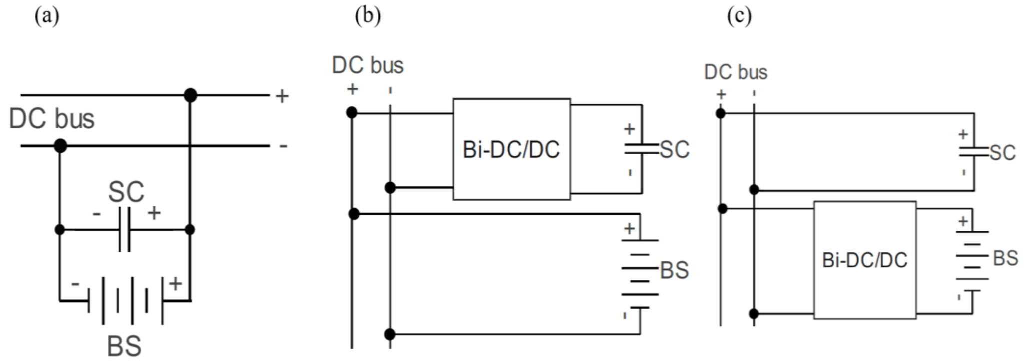
Passive topology is the simplest arrangement (Khaligh and Li, 2010), and it is shown in Figure 2 (a). This topology has no DC-to-DC converters for control, making it light weight, compact size and low cost. In the topology, the BS and SC are connected to the DC bus in parallel, which makes the voltage of the BS and SC consistent with that of the DC bus. The SC mostly works as a low-pass filter due to fast dynamic response, and the filtering effects improve as the capacity of the SC increases (Shin *et al*., 2012). The configuration limits the DC bus voltage to small variations because the bus is directly clamped to the battery. This is a positive feature for the input voltage of the DC to alternating current (AC) converter for AC loads (Guidi *et al*., 2008; Kohler *et al*., 2009). Power flow in this passive configuration is governed by SC's and BS's internal resistances and their voltage characteristics which makes control system to be significantly simple. By virtue of the configuration, the voltage of the SC, BS and DC bus is same. This same voltage prohibits full usage of the SC hence lowering its operational efficiency (Xiong *et al*., 2018). In passive configuration, optimisation of power sharing is not possible because there is no possibility of power management mechanism to govern the power sharing between the battery and SC, since they are directly connected to the bus system.

Semi-active topology

Semi-active topology is further classified as either SC semi-active topology or BS semi-active topology as shown in Figure 2 (b) and Figure 2 (c) respectively. In both topologies, a converter is used to control one of the power storage devices, while the other is connected directly to the DC bus (Song *et al*., 2015). This arrangement makes the HESS to be partially decoupled.

In SC *semi-active topology*, the SC is connected in series with a bidirectional DC-to-DC converter while the BS is connected to the DC bus directly. This makes the SC isolated from the battery as well as the DC bus which makes it take advantage of its wide voltage range (Kouchachvili *et al*., 2018). The arrangement demands the converter to be selected and designed to have the ability to withstand large currents and high voltage fluctuations which increases the cost of the topology.

In BS *semi-active topology*, the BS is connected in series with a bidirectional DC-to-DC converter while the SC is connected to the DC bus directly (Cao and Emadi, 2012). The configuration makes it possible for the battery current profiles to be set to be very smooth by the converter. The SC can absorb high current fluctuations during charging and discharging. The voltage of the DC bus, however, fluctuates because of the direct connection of the SC. To minimise the fluctuations, a very large SC is supposed to be used, making the cost increase for this topology as well (Jing *et al*., 2016).



(a) Passive (b) SC semi-active (c) BS semi-active

Figure 2: BS-SC HESS configuration topologies for reduced battery aging rate.

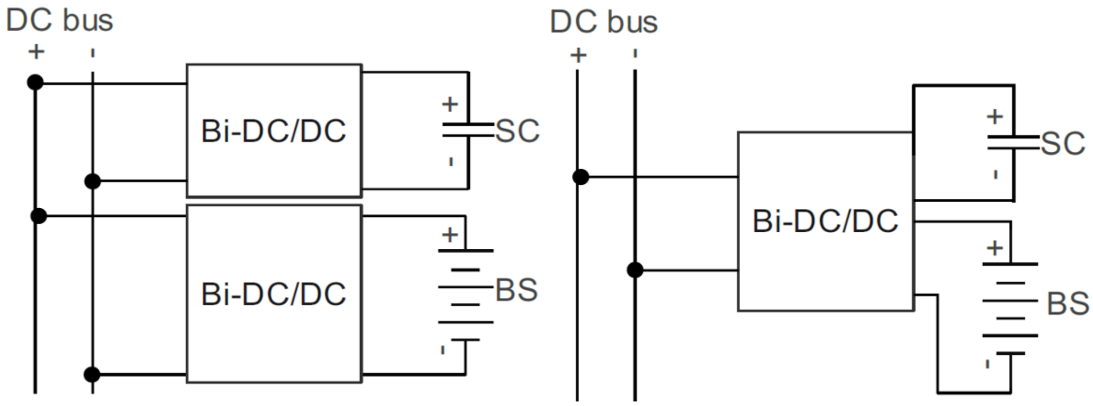
Full-active topology

In full-active topology, both the BS and the SC are connected through DC-to-DC converters (Ju *et al*., 2017). The battery and the SC are totally uncoupled from the DC bus, giving the topology a high degree of controllability. Typical full active topology configurations are as shown in Figure 3. With a proper control system, the BS lifespan can be extended using this topology. The topology has more converters than semi-active topology resulting in a significant increase in the system cost. The full active topology can either be cascaded or parallel or multiple-input. Commonly used ones are parallel and multiple-input topologies.

Parallel full-active topology: In this topology, DC-to-DC converters are used to decouple the battery and the SC from the DC bus. The converters are connected in parallel as represented in Figure 3(a).

Multiple-input full-active topology: In this topology, the DC-to-DC converters are integrated into a multiple-input converter as shown in Figure 3(b) (Yalamanchili and Ferdowsi, 2005). The integration reduces cost and size requirements, however, complicates the energy management strategy.

(a) (b)



(a) Parallel full-active topology (b) Multiple-input full-active

Figure 3: BS-SC full-active hybrid energy storage system topologies.

BATTERY SYSTEM AND SUPERCAPACITOR CONTROL STRATEGIES

Energy and power utilisation of a HESS comprising BS and SC in either semi-active or full-active topology is achieved through control strategies (Chong *et al*., 2016). These control strategies are usually complex and are required to function continuously because of the intermittent nature of the renewable energy sources as well as unpredictability of load demand variations. The control strategies' objective is to ensure optimal HESS system control and performance aiming at improving economic viability of the overall system (Chong *et al*., 2016). In general, from literature shown in Table 1, common aims of the control strategies are to control BS's depth of discharge (DoD), reduce magnitude of charge or discharge BS current, reduce CoE by reducing operational and maintenance cost of the system, stabilise system's DC voltage, control frequency of the system, minimise loss of power supply to load and improve efficiency of the system.

General concept of control strategies is illustrated in Figure 4. The strategy needs states of the system which may include SoC, energy demand/supply, power demand/supply and supply and demand frequency. It then makes a decision on how to distribute power and energy to or from the HESS. The strategy then outputs reference values which are then sent to control circuits linked to bidirectional converters to control power and energy flows. In general, these control strategies are grouped into classical control (rule-based strategies) and intelligent control (optimisation-based strategies).

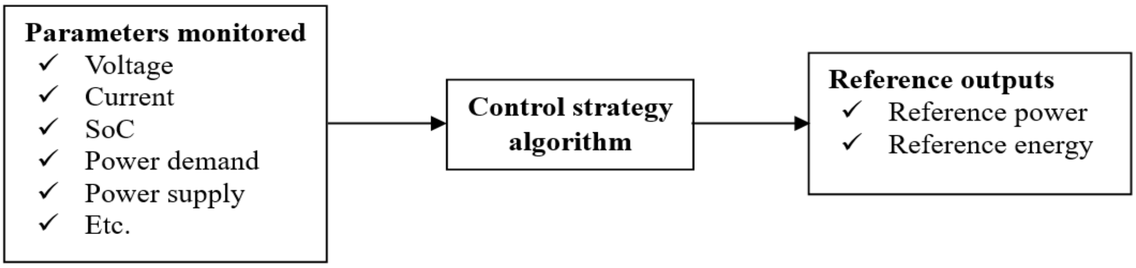


Figure 4: General control strategy concept.

Classical control strategies

Examples of classical control strategies mainly include the following: rule-based control (RBC), filter-based control (FBC) (Oriti *et al.*, 2019), finite state machine (FSM) (Wang *et al.*, 2019b), logic threshold control (LTC) (Wang *et al.*, 2019a), fuzzy logic control (FLC) (Jafari *et al.*, 2019), and sliding mode control (SMC) (Wang *et al.*, 2017). The design of these rule-based strategies is based on experience. The power and energy allocation rules depend on overall characteristics of the source and load. These strategies are advantageous because they are easy to implement in real time system management. However, they are sensitive to the parameter variation and they require an exact model of the system for better performance (Akcayol, 2004).

Intelligent control strategies

Examples of intelligent control (optimisation-based) strategies mainly include the following: genetic algorithms (GA) (Wieczorek and Lewandowski, 2017), particle swarm optimisation (PSO) (Chen *et al.*, 2016), artificial neural networks (ANN) (Huo and Meckl, 2022), model predictive control (MPC) (Hredzak *et al.*, 2014), and dynamic programming (DP) (Li *et al.*, 2019). These optimisation-based strategies can be implemented for robust and efficient control as they do not require an exact model of the system (Akcayol, 2004). They can find optimal power and energy allocation scheme for specific loads. However, most of optimisation algorithms require power and energy allocation method be generated off-line in advance. This means large training data is required to capture all loads characteristics to guarantee optimal performance. Furthermore, optimisation algorithms are not easily implemented in microcontrollers.

BATTERY SYSTEM AND SUPERCAPACITOR TOPOLOGIES AND CONTROL STRATEGIES RESEARCH TREND IN RENEWABLE ENERGY SYSTEMS

Application of BS with SC in RESs using different topologies and strategies is available in literature since many years ago. Researchers have worked on a number of RESs (both on-grid and off-grid) mainly those which use wind and/or photovoltaic (PV) as renewable sources, due to their intermittent nature. In this regard, this paper has compiled some research articles published by different authors. The articles were accessed using different databases including ScienceDirect, Scopus and Lens. Key words used to extract the articles were battery, capacitor, PV, wind and fluctuations. Thereafter, the papers' abstracts were read which resulted into a decision as to whether read the whole paper or not based on relevance to the study.

To appreciate the research status in general, network data extracted from lens database (as an example) was fed into visualisation of similarities viewer (VOSviewer) software tool (Jan and Waltman, 2012). The VOSviewer software is used to create maps which assist in visualising relationships between different areas of research focus. After feeding the data into VOSviewer, the result was the network shown in Figure 5. In the VOSviewer network shown, size of a label and a circle of an item relates to amount of research work/articles put into the item. The higher the work amount the larger the label and circle (Jan and Waltman, 2012). Same colour of these circles means belonging to same cluster and different colours means belonging to different clusters. The lines between these circles represent links between the items. From the map, it is shown, related to RESs, that there has been much research focus on fluctuations, control strategies, microgrids and storage systems for the past years. Furthermore, fluctuations, SCs and HESS are very close to each other which shows close relationship between these items during research in energy systems. Generally, it is interpreted and concluded that fluctuations are taken as a serious issue in RESs and research is ongoing to reduce the impact of the same on battery storage systems.

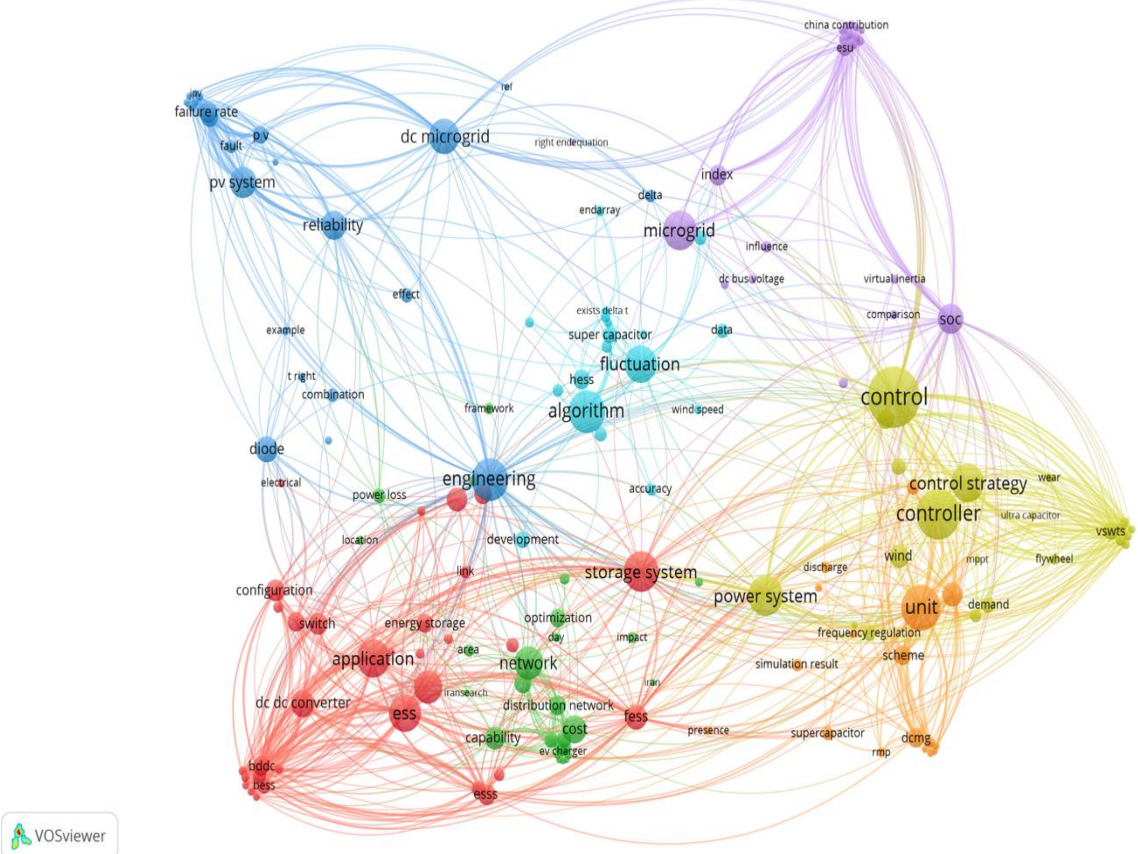


Figure 5: VOSviewer research network visualisation.

After general visualisation using VOSviewer, specific details in the research articles were needed to establish how the actual systems were configured and controlled. Table 1 shows a list of some of the accessed articles in this regard. For brevity's sake, only recent articles, published since a decade ago, have been presented in the table. Included in the Table 1 are control strategy, topology, renewable source (RS), grid connection status and general system performance of the designed systems in terms of meeting design criteria.

From the Table 1, it is shown that common control strategies for RESs comprising either wind or PV or both are rule-based control (RBC) and filter-based control (FBC); the classical control strategies (FBC and RBC have been used in 70% of the systems). These control strategies are preferred to intelligent control strategies due to their ease of implementation in real time systems and low cost. It is also noted from the same table that 16 out of 20 (80%) articles used full-active topology in their configurations. The full-active topology is preferred due to its full capability in controlling both storages (BS and SC). From performance perspective, it is noted that all the designed system showed improved performance in terms of meeting grid set points as well as blocking fluctuations from reaching BS and other set design criteria.

Though the classical control strategies are sensitive to the parameter variation and they require an exact model, but they are cheaper and easy to implement in real time as compared to intelligent methods. On the other hand, full-active DC-DC converters are expensive to implement but they provide highest system flexibility in terms of control and therefore higher efficiencies. Using classical controllers and full-active topology in RESs, as evidenced in literature, strikes a good balance between the two extremes hence resulting into better systems.

During implementation of these classical control strategies together with full-active DC-DC converters, a number of BS and SC models have been used. One of the BS models that incorporates battery capacity and its internal resistance is a modified Shepherd curve fitting model (Tremblay *et al*., 2007). The following Equations 1 and 2 show the charge and discharge models for Li-ion battery using the curve fitting model.

Charging:

$$V_{batt} = E_0 - R.i - K\frac{Q}{it-0.1Q}.i^* - K\frac{Q}{Q-it}.it + Aexp(-B.it) \quad (1)$$

Discharging:

$$V_{batt} = E_0 - R.i - K\frac{Q}{Q-it}.(it+i^*) + Aexp(-B.it) \quad (2)$$

Where V_{batt}: battery voltage (V); E_0: battery constant voltage (V); K: polarization constant (v/Ah) or polarization resistance (Ω), Q: battery capacity (Ah); $it = \int idt$: actual battery charge (Ah); A is exponential zone amplitude (V); B: exponential zone time constant inverse $(Ah)^{-1}$, R: internal resistance (Ω); i: battery current (A); i^*: filtered current (A); $Exp(t)$: exponential zone voltage (V).

For SC systems, equivalent circuit model which mainly consists of the capacitance, equivalent series resistance (ESR), and equivalent parallel resistance (EPR) (Spyker and Nelms, 2000) has been used in some literature. The ESR is a loss term that models the internal heating in the capacitor and is most important during charging and discharging. The EPR models the current leakage effect and impacts long term energy storage performance of the supercapacitor. Equations (3) – (5) describe the model.

$$ESR = \frac{\Delta V}{\Delta i} \quad (3)$$

$$EPR = \frac{-(t_2-t_1)}{\ln\left(\frac{V_2}{V_1}\right)C} \quad (4)$$

$$v_c = ESR.i_c + \frac{1}{C}\int(i_c - \frac{e_c}{EPR})d\tau + V_{c_{init}} \quad (5)$$

where V_2 is the initial self-discharge voltage at t_1, V_2 is the final self-discharge voltage at t_2, C is the rated capacitance, ΔV is change in voltage at turn on of load, ΔI is change in current at turn on of load and i_c is the capacitor current.

The listed examples of BS and SC models given in Equations 1 to 5 have been used to study HESS behaviour in different scenarios. An example of comparison of BS current with and without an SC in an off-grid PV system is shown in Figure 6. It is observed from the graph that inclusion of an SC reduces battery peak current thereby extending its life time.

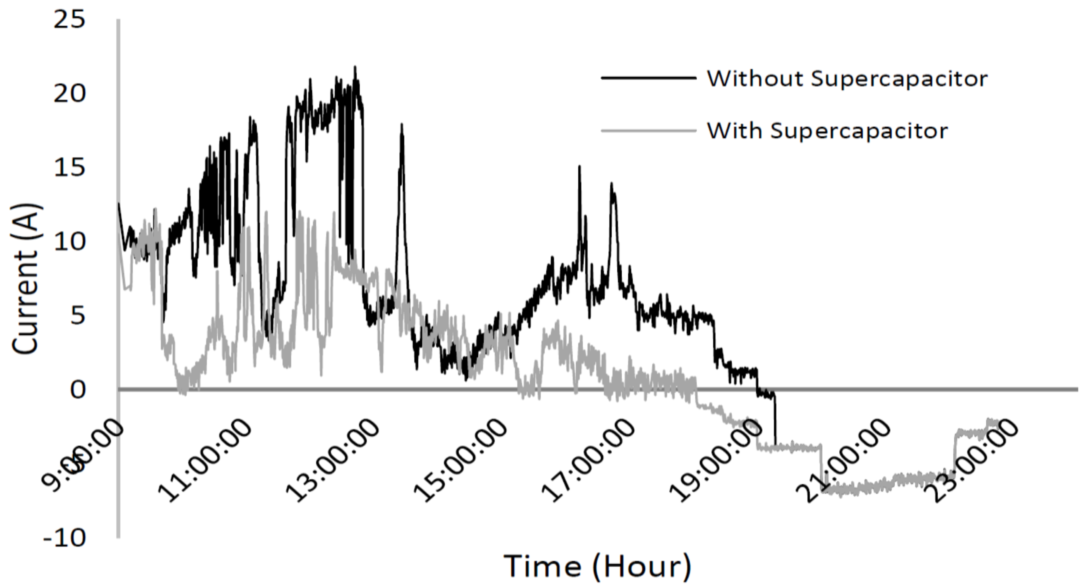


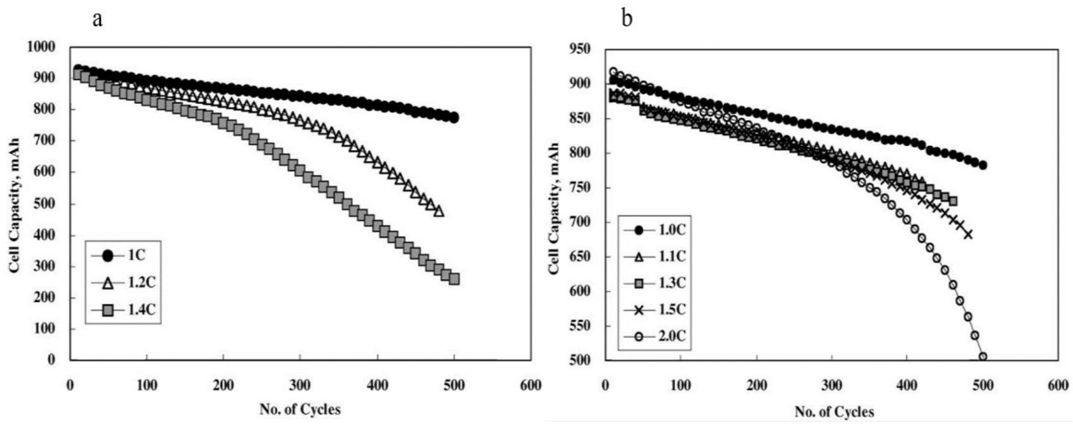
Figure 6: Battery current in off-grid PV system (Source: Fahmi *et al*., 2016).

Determining BS remaining life time is crucial in the studies of impact of power fluctuations. One type of general BS model that represent number of cycle charges as a function of BS current is referred to as equivalent full cycles model (EFCM) (Dufo-López *et al*., 2021). EFCM is capable of estimating BS lifetime as long as specific number of charge and discharge cycles is known (regardless of operating conditions). Equivalent number (Z_N) of full cycles (Z_{IEC}) can be determined by using the following equation:

$$Z_N(t + \Delta t) = Z_N(t) + \frac{|I_b(t)|.\Delta t}{C_N} \quad (6)$$

Where $|I_b(t)|$ is absolute value of battery current, $Z_N(t)$ is the equivalent number of cycles since beginning of operation, C_N is the nominal capacity of the battery (Ah), t is time step and Z_{IEC} number of full cycles from manufacturer's data sheet. When $Z_N = Z_{IEC}$, then BS end of life is reached.

Choi and Lim (2002) performed a number of experiments investigating factors which affect cycle life of Li-ion batteries using estimation models similar to equation (6). The following Figures 7a and 7b illustrate how charge and discharge current rates affected cycle life of BS. It is noted from the figures that increasing charge or discharge rate reduces the number of cycles a battery can withstand before its end of life. Based on the results from literature displayed in Figure 7, it is clearly seen that subjecting BS to higher charge or discharge currents directly affects their cycle life. The currents shown in the figures were controlled in simulation to be at fixed levels as indicated, that is from 1C to 1.4C during charging and from 1 C to 2.0 C during discharging. In real implemented off-grid system, these currents appear as indicated in Figure 6, where the fluctuations are available. It can be concluded that the higher the magnitude of fluctuations, the higher the charge of discharge rate. Therefore, inclusion of SC systems reduces these fluctuations magnitude as shown in Figure 6, which then directly reduces charge or discharge current rates hence extending cycle life of BS as evidenced in Figure 7.



(a) charging **(b) discharging**

Figure 7: Effect of battery current on cycle lifetime during charging and discharging scenarios (Source: (Choi and Lim, 2002).

CONCLUSIONS AND RECOMMENDATIONS

Battery system capacity fade accelerates due to power fluctuations in RESs. This paper presented how the fluctuations specifically affect Li-ion BS which generally also applies to other BSs. It has been noted that to reduce the impact of fluctuations on BSs, SCs are deployed forming HESS together with the BSs. These SCs absorb power fluctuations through usage of control strategies and defined converter topologies. The BS-SC systems can either be passively or semi-actively or full-actively converter configured topologies. These control strategies can either use classical or intelligent. From the review study, it is concluded that classical control strategies, specifically FBCs and RBCs, and full-active topology, have been commonly used in literature for power sharing between BSs and SCs for improved life time of batteries. Furthermore, examples of BSs and SCs models used in literature for life time estimation were presented as well as some graphs displaying impact of currents on BS life time.

Therefore, based on this review study, the following are the recommendations: (1) when designing RESs with BS storages and there is need to deploy SCs to reduce impact of fluctuations on battery life time, use classical based controllers. Also, (2) during integration of the BS-SC storage system in these RESs, use full-active topology. This combination of classical strategy and full-active topology offers a balance between cost and efficiency in RESs.

The study was limited to identifying suitable power control strategies and BS-SC system configuration for RESs based on what is commonly used in literature. It is therefore recommended, that future studies focus on evaluating in detail technical and economic factors of these strategies and configurations. This will assist in implementing the BS-SC HESS in RESs using optimal strategies and configurations. Overall, this will result in further lowering cost of RESs.

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Table 1: Accessed articles focusing on BS with SC systems in RESs

Control strategy	Topology	RS(s)	Grid	Performance	Refs
RBC	Full-active	PV	On-grid	Results showed that PV power output smoothened and SOC of both battery and SC were maintained within defined limits by the proposed system.	Wang *et al*., 2014)
FBC	Full-active	Wind	On-grid	Results showed that the battery life cycle can be prolonged due to battery current smoothing by the capacitor during operation.	Kim *et al*., 2015
FBC	Full-active	Wind	Off-grid	The proposed system reduced battery current which led to increased battery life by approximately 19% compared to battery alone system.	Gee *et al*., 2013
RBC	Full-active	PV	Off-grid	The system managed to divert high frequency components of power to SC and low frequency components to battery. This reduced stress on the battery which could extend battery life time.	Kollimalla *et al*., 2014a
FBC	Full-active	PV	Off-grid	The proposed system is able to divert power surges to the SC system. It controls charge/discharge to reduce stress on battery hence improving its life time.	Kollimalla *et al*., 2014b
FBC	Full-active	PV	Off-grid	The proposed system manages fluctuations of load by supplying them using capacitor while average load demand is supplied by the batteries. This reduced stress on battery system. The system also provided battery dc-link voltage regulation.	Tummuru *et al*., 2015a
RBC	Full-active	PV	On-grid	The configuration and management of battery and supercapacitor handled sudden and average changes in power surges. This resulted in fast DC link voltage regulation and reduced current stress on battery.	Tummuru *et al*., 2015b
FBC and ANN	-	Wind and PV	Off-grid	They proposed support vector machine load predictive system which replaced the need for a bi-directional converter. Results showed that the system was able to maintain battery depth-of-discharge (DOD) and to smoothen the DC voltage and the battery current.	Chia *et al*., 2015
FBC	Full-active	PV	Off-grid	The proposed energy system maintains DC voltage, battery SOC and reduces stress on battery hence improves its life cycle.	Hacini *et al*., 2022
FBC	Full-active	PV	Off-grid	Results showed coordinated power between PV, SC and battery during operation.	Saha and Dey, 2019
-	Full-active	PV and wind	On-grid	The purpose was to increase renewable self-consumption. Results showed that including a capacitor as energy storage device increases self-consumption from 37.01% to 46.65% in PV-battery system and from 33.50% to 49.87% in PV-wind-battery system.	Hassan *et al*., 2022
Control strategy	**Topology**	**RS(s)**	**Grid**	**Performance**	**Refs**

FBC	Full-active	Wind	Off-grid	The purpose was to find optimal battery to capacitor ratio in wind microgenerators. The optimal ratio was found as 1:1500.	Lill *et al*., 2018
FBC	Full-active	PV and Wind	Off-grid	The designed energy management strategy successfully used SC to control charge and discharge rate of the batteries. This reduced stress on batteries in case of high-power supply and demand.	Yasin, 2019
RBC	Semi-active	PV	Off-grid	Purpose was to extend battery life. It was found that the semi-active system reduced battery peak current up to 8.607% thereby prolonging its life. This was compared to battery alone system.	Chong *et al*., 2017
FBC and FLC	Semi-active	PV	Off-grid	Purpose was to reduce battery peak current and power. It was shown that the proposed system reduced battery peak current and power by 16.05% and 15.19% respectively compared to the conventional system with battery-only storage. The system performed better than the one using FBC and RBC strategies.	Chong *et al*, 2016
FBC	Full-active	PV	Off-grid	The proposed system reduced battery peak current, as well as the battery peak power by a significant amount as compared to system without capacitor.	Choudhary and Sharma, 2020
SMC	Full-active	PV	Off-grid	The proposed system sustained desired output voltage in presence of voltage variations.	Dey *et al*., 2018
FBC	Full-active	PV	Off-grid	The proposed systems showed that the supercapacitor can supply peak current demand during day, thereby, preserving the battery state of charge during day for night loads.	Fahmi *et al*., 2014
-	Passive	PV	Off-grid	Results showed reduction in battery peak current during both simulation and experiment.	Fahmi *et al*., 2016
FLC	Full-active	PV	Off-grid	The purpose was to control power flow between BS and SC aiming at reducing battery stress. Results showed that the proposed system successfully controlled the power flow of HESS and increased system efficiency.	Javed *et al*., 2019