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Lithium-ion BESS Integration for Smart Grid Applications - ECM Modelling Approach

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***Abstract*— Lithium-ion battery energy storage systems (BESS) with their present state of technology and economic maturity possess huge potential for catering short-term flexibility requirements in smart grid environment. However, it is essential to model in detail the complexity of non-linear battery system characteristics and control of their adjoining power electronic interfaces. More detailed and accurate modelling of components, enables improved overall power system optimization studies by considering both, component and system level aspects simultaneously. Therefore, this paper develops an equivalent circuit model (ECM) for Lithium-ion battery and Lithium-ion nickel-manganese-cobalt (NMC) battery cell is modelled as a second order equivalent circuit (SOEC), including C-rate, temperature, state-of-charge and age effects. Secondly, detailed controller design methodology for DC/DC- and DC/AC-converter interfaces are developed to enable advanced grid integration studies. Overall, BESS integration design was validated by simulation studies in Simulink Simpowersystems platform.**

***Index Terms*-- Lithium-ion battery; battery energy storage systems; equivalent circuit battery model; flexible energy sources; Smart grids;**

I. INTRODUCTION

Climate change and environmental issues have reinforced the need for large-scale integration of renewable, low emission energy sources at all voltage level, i.e. high, medium and low voltage, in the power system. Integrating such large amount of variable and usually low-inertia renewable energy sources has significant impacts on traditional centralized power systems. Due to these changes and effects there is increasing need for various type of energy storages for applications with different time-scales. For short-term needs, interest in rapidly controllable stationary BESS applications has increased constantly due to their technological advancements and decreasing costs. Ability to react fast, higher energy and power density, longer cycle and shelf life, low rate of self-discharge, high round trip efficiency and improved safety performance have favored Lithium ion based BESSs also for stationary grid applications. Lithium ion (Li-ion) BESSs are capable to act as flexible energy sources and provide multiple technical ancillary services such as frequency support by controlling active power injection, voltage regulation by reactive etc. [1].

Li-ion batteries are intercalation-based ESSs, which operate as a closed system [2] with very few measurable state variables, which makes it difficult to properly monitor the states of the battery and maintain safe operation. Voltage, current and temperature measurements are typically used to determine or estimate all the other parameters of the battery, such as its State-of-Charge (SoC) and State-of-Health (SoH). Therefore, it is required to understand and model precisely the BESS behaviour under various operating conditions, which affect their performance.

Accurate modelling of battery packs for energy storage applications have been minimal where majority of the literature considers battery systems as an ideal DC voltage source [3] or by utilizing mathematical modelling techniques [4]. Math based kinetic battery models (KBM) were first proposed for lead acid batteries. Modified KBMs [5], [6] are widely used to simulate lithium-ion batteries for smart grid simulations. However, KBMs fail to address the non-linear characteristics of Li-ion batteries, which are also affected by various operating conditions such as SoC, temperature, current rate and age. Physics based electrochemical models [7] are suitable to model the internal behavior of the cell involving huge amount of mathematical computations, which makes them practically impossible to be used for smart grid simulations. Integration of ECM has been presented for electrical vehicle propulsion in [8], considering SoC as the only affecting parameter. Most of the ECM models reported for grid related simulations lack in one or several affecting parameters related to the performance of Li-ion batteries.

Power electronics (PE) is one fundamental enabling technology behind BESS growth, utilization and grid integration determined by different grid code and standard requirements. Simultaneously PE based converter is responsible for safe charge/discharge of BESS, operation mode, active (*P*) and reactive (*Q*) power flow as well as current and voltage variations across the battery pack which will affect BESS performance, health and lifetime [9]. Battery design, sizing and converter control design are more likely to succeed when they are based on more accurate BESS models. Hence, this paper aims to establish an ECM for Li-ion battery inclusive of SoC, temperature, current rate and aging effects. Followed by, designing DC/DC- and DC/AC- power converter controllers. Overall methodology was validated by integrating Li-Ion BESS to the MV bus of a power system, enabling them as short-term flexible energy sources for smart grids applications. Methodology for ECM for Li-ion BESS is explained in Section II. BESS integration technique, i.e. power electronic controller design for MV grid integration incorporating accurate BESS model is described in Section III.

II. Li-ion BESS Modelling

Thevenin-based second order equivalent circuit model (SOEC), technique is versatile, as it successfully emulates the model parameters such as multi-variable SoC, C-rate, temperature, hysteresis effects, self-discharge and battery aging. SOEC is considered as the benchmark model for Li-ion batteries, as it depicts the charge transfer, diffusion and solid electrolyte interface (SEI) reactions in the form of resistors and capacitors. SOEC battery model presented in this paper is based on time domain measurements from hybrid pulse power characterization (HPPC) tests in [10], whose performances are affected by SoC, operating temperature, C-rate and age. Therefore, SOEC model developed strikes a perfect balance between the accuracy and complexity of battery modelling.

Fig. 1 shows the proposed dynamic equivalent circuit model for Li-ion battery cell i.e. NMC type. Open Circuit Voltage (*OCV*) is modelled as an ideal voltage source. The internal resistance was modelled as R_i. Two RC combinations are suggested for Li-ion battery cell, so the dynamic behavior is modelled as R_1, C_1, R_2 *and* C_2. The hysteresis effect and polarization effect in the Li-ion cells can be simulated accurately enough with the two RC combinations and the model structure is more simple than with more RC combinations. As the actual behavior of the NMC cells is significantly non-linear, all the parameters vary with SoC, temperature, age and history (number and depth of cycle) of the cell. *OCV*, R_i, R_1, C_1, R_2 *and* C_2, are the parameters obtained from experimental characterization of lithium ion battery cell at various SoC's (100% to 0% with a step of 10%), temperature (15°C, 25°C and 45°C), current rates (1C, 2C and 3C) and cycle age (0, 100, 500, 1000, 1500, end of life). *V* refers to the battery cell terminal voltage.

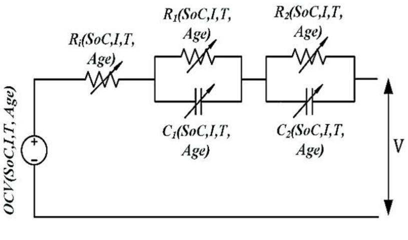

Fig 1. SOEC battery cell model

A closer view of the voltage response from the HPPC profile can be seen in Fig. 2. It shows an immediate voltage drop ($\Delta V0$) when the current pulse is applied. This is the internal resistance of cell, contributed by resistance of active material, electrolyte, and current collector. It can be also observed that there is a time varying voltage ($\Delta V1$ and $\Delta V2$), which can be interpreted as a presence of additional elements such as capacitor in parallel combination with resistance. The time varying voltage part can be divided into short transient and long transient RC elements due to different time constants (t1 and t2) in the voltage profile. The output voltage equation for the 2nd order ECM is shown (1). The mathematical representation of the time constants is shown in (2) and (3). SoC is estimated by coulomb counting method. OCV is evaluated from the voltage response of the HPPC profile at a given SoC interval, at the end of 1 h pause time.

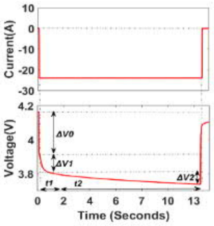

Fig 2. HPPC test response at 100% SoC and 25 °C

A non-linear least-squares solver optimization algorithm lsqcurvefit (Levenberg-Marquardt) was used to minimize the error for each of the analyzed pulses and the optimized parameters R_i, R_1, C_1, R_2 *and* C_2 at each SoC and temperature were obtained. The model was further improvised to incorporate the aging effects, by regularly updating the cell parameters at different cycling intervals.

Fig. 3 provides comparison between simulated and experimental discharge voltages at different aging levels of NMC battery cell, at 25 °C and 3C discharge rate that were recorded as a result of accelerated aging tests. The mean relative error was less than to 2% majority of the discharge cycle and in some cases (especially at higher aging) the error was greater than 5%, towards the end of discharge towards 0% SOC. It is evident that overall discharge capacity reduces with aging which in turn reduces overall discharge time. Modelling aging characteristics of battery is critical for smart grid applications, because the BESS state of energy/power is required in order to consider their capability to provide different kind of active power (*P*) related technical ancillary (flexibility) services like frequency support or peak shaving.

Fig. 4 depicts the evolution of ECM parameters with respect to age and SoC in a 3-dimensional plot. Internal resistance (R_i) of cell, pertaining to $\Delta V0$, in the HPPC voltage response curve is shown in Fig 4(a), its observed to increase with aging, denoting loss of active materials. Values of *OCV* changes are shown in Fig 4(b), whose values decreases over time, predominantly indicating loss of cycleable lithium ions. Figs 4(c)-(d) depict the parameters pertaining to the short transients of the RC branch. It is derived from time varying voltage ($\Delta V1$) and assumed to highlight the dynamics during of charge transfer process of cell operations. Efficiency of charge transfer process reduces with aging, due to increased R_1 and C_1 values. Figs 4(e)-(f) depict the parameters pertaining to the long transients of the RC branch. It was derived from time varying voltage ($\Delta V2$) and assumed to show case dynamics during of diffusion process of cell operations.

$$V_T(t) = V_{OCV} + I(t)R_i + I(t)R_1\left(1 - e^{\frac{-t}{t1}}\right) + I(t)R_2(1 - e^{\frac{-t}{t2}}) \quad (1)$$

$$t_1 = R_1C_1 \quad (2)$$

$$t_2 = R_2C_2 \quad (3)$$

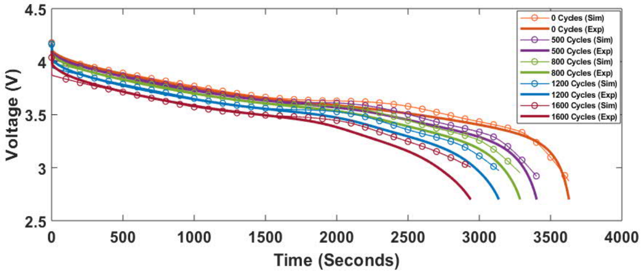

Fig 3. Comparison between simulated and experimental cell discharge voltage with different aging intervals

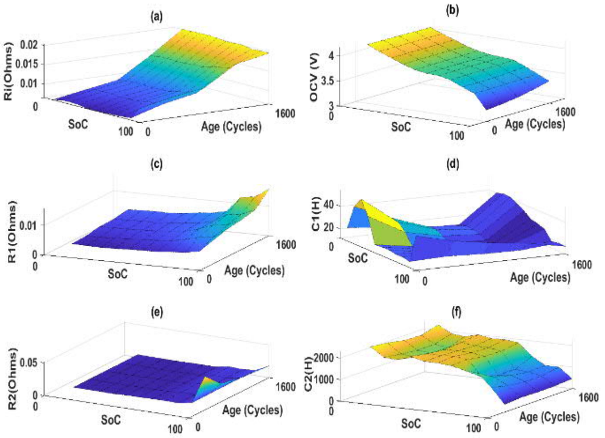

Figure 4. Age dependant ECM Parameters

Cell model was developed in Simscape platform of Matlab/Simulink. Cell model was scaled up to form battery pack model, in order to study it for various purposes in smart grid applications. Multiple cells are connected in series in a battery pack to achieve required voltage levels and multiple strings of serially connected cells have to be added in parallel to boost current level. N_S represents the series cell elements and N_P defines the number of parallel strings for a required battery pack. The interconnecting cable resistance are ignored making it a model with fast simulation response comparatively. Values of N_S and N_P define voltage and current characteristics of the desired battery packs. Developed battery pack model was then integrated into DC/DC buck-boost converter system, which was developed in SimPowerSystems platform.

III. BESS INTEGRATION METHOD

Methodology for BESS integration as short-term flexible energy source, to the MV grid of a power system with an improved ECM based battery pack model and their adjoining power electronics control strategies are explained in this section.

A. BESS Model for MV Grid Integration

Li-ion (LIB) BESS (NMC type) acts as flexible energy resource which can provide short-time energy supply for multiple different technical ancillary services. Li-Ion BESS dynamic characteristics were modelled. BESS is connected to the power system by means of power electronic interface. In this case, DC/DC buck-boost converter will stabilize fluctuating/changing battery voltage. It will also aid in charging and discharging of batteries within its safe operating window. DC/AC -converter will be connected to the high voltage side of the DC/DC -converter, which converts it into 3-phase, 400 V_{RMS}. Voltage will be boosted to MV level by means of 3-phase transformer thereby completing integration of the battery system. Deriving accurate design of the power converter controllers, i.e. DC/AC voltage-source-converter (VSC) and DC/DC BESS buck-boost controllers for optimal operations are explained further. Overall BESS integration design is presented in Fig 5.

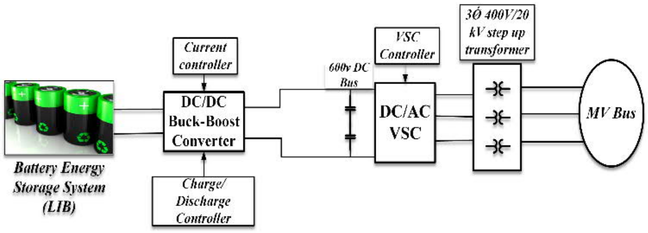

Fig 5. Battery Integration Modelling

B. PE Controller Design for BESS Integration

Design and operation of the controllers for BESS converters are developed in this section and they include DC/AC- VSC and DC/DC- BESS Buck-Boost controller.

1) VSC Controller

Fig. 6 describes the VSC controller methodology i.e. voltage oriented control (VOC) technique [11]. VOC strategy guarantees fast transient response and high static performance through current control loop. *V,abc* and *I,abc* are transformed to *V,dq* and *I,dq* frames. *Id,ref* is obtained by the PI-controller for *V,dc* and the *Iq,ref* reference is provided by the controller designer based on the application demand. Active power output of the converter is controlled by *Id,ref* and *Iq,ref* controls the reactive power output. A cross coupling exists between d- and q- axes components, which shall affect the dynamic performance of the controller. *Vd* feedforward signal is added to the d-component loop. This feedforward signal is crucial for d-component control loop. Feedforward signal can be added to the q-component control loop as well but it is not essential for this application. Both *Id,ref* and *Iq,ref* are limited to ±1.5 p.u. so the VSC should be designed to provide 150% nominal power for certain time period during transients.

2) Battery Charge and Discharge Controller

A single IGBT with anti-parallel diode leg with a switching inductance has been implemented as bidirectional Buck-Boost converter for BESS system [12]. Average model converter is designed to charge and discharge the batteries through/to the VSC DC- bus capacitor. A simple PI-controller is designed to control Buck-Boost converter. Fig. 7 shows Buck-Boost converter control loop. The controller is equal, but the converter can work in either Buck mode or in Boost control loop mode. When it works as Buck converter, the Boost IGBT is blocked and vice versa. The sign (±) of the *Idc,ref* defines in which mode it should work. The DC bus is controlled by VSC d-component control loop so the sign of the PI-controller output defines the active power flow direction therefore, there is no need to add additional voltage control loop in Boost mode (discharging the BESS) to control the voltage level. In both control modes, the PI-controller output provides the duty cycle to the Buck or Boost converter.

Discharge mode works in the range between 20% to 90% of battery SoC, as per the current requirements commanded based on the current required by the converter. For the charging mode, the maximum State-of-Charge (*SoC,Max*), is maintained at 90 %, which typically is achieved by constant current charging alone, eliminating constant voltage (CV) requirements. Battery charge and discharge model is based on SoC of the system and load requirements. Charge controller triggers Buck mode of the converter ON when SoC goes below 20% and turns OFF when it reaches maximum of 90% to maintain battery operation in safe limits. *Idc,ref* is communicated to the BESS Buck-Boost converter controller by upper level control system. Based on sign of this reference current the modality of the Buck-Boost converter and its controller behavior is managed.

IV. CASE STUDY AND SIMULATION RESULTS

Simulation based case study is designed to demonstrate integration of more accurate Li-ion BESSs to the MV grid of a power system. Controllers were designed to charge or discharge the battery as and when the grid commands, considering *P,ref* as the reference for DC/DC- converter stage, which handles battery operations. The use case study was intended to demonstrate the stability of DC/AC- converter and battery charge/discharge controller of the DC/DC-bidirectional buck boost converter, validating their transient and steady state system behavior. It also aids in relevant sizing of BESS for short-term power supply in smart grid applications based on grid current requirements.

Li-ion BESS was sized for a nominal power discharge of 0.334MW at a discharge rate of 1C and peak discharge of 1 MW at 3C. Other battery characteristics are presented in Table 1. DC/DC Buck-Boost converter was rated for 1 MW peak power and DC/AC- inverter was sized for a maximum capacity of 1.5 MVA. Initial battery SoC was maintained at about 50%, where it could accommodate simultaneous charge/discharge operations. Characteristics of new cells, i.e. unaged cells (first-life) are considered for the case study.

Simulations were performed for a time span (TS) of 80 seconds. A set point power reference P_{REF} based on different C-rates of BESS is shown in Table 2, which is variable every 20 seconds, inducing transient instability conditions. During T1, BESS discharges DC power of 0.668 MW (2C), followed by 0.334 MW(1C) in period T2 and 0.167 MW (0.5C) in T3. Finally, during T4, BESS charges from the grid at rate of 0.5C.

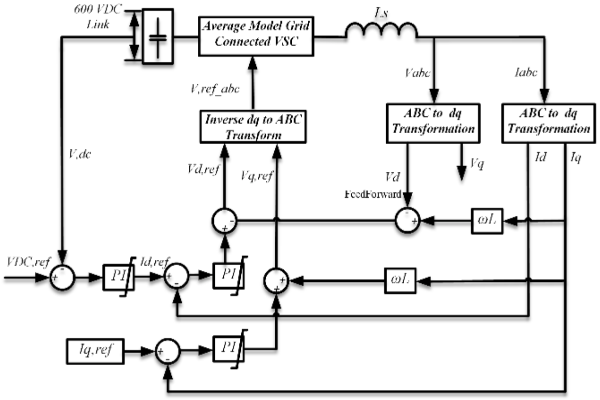

Figure 6. VSC Controller

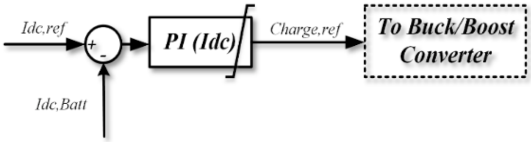

Figure 7. Battery Charge Discharge controller

It was assumed that, BESS shall undergo such cycling characteristics when supporting integration of renewable energy sources such as wind and solar PV, during extreme conditions or changes. In such cases, it is imperative to obtain robust PE converter controller design, as the power output from BESS changes rapidly with alternate charge/discharge pulses, commanded by the grid.

Table I. Li-ion BESS Size and characteristics

Lithium-ion Battery Characteristics	
Nominal DC voltage	311 V
Peak Voltage	353 V
Cut-off Voltage	235 V
Discharge Energy(1C)	334 kWh
Nominal Discharge current (1C)	944 A

Table II- Simulation case details

Time (Secs)	**P_{REF} (MW)**	**BESS Status**
T1 (0-20)	0.668	Discharge
T2 (20-40)	0.334	Discharge
T3 (40-60)	0.167	Discharge
T4(60-80)	-0.167	Charge

Fig. 8 explains the performance of ECM based BESS model and its adjoining PE converters for MV grid integration. BESS charge/discharge current characteristics are shown in Fig 8(a), where magnitude of defined BESS current changes are as per the case study requirements. Fig 8(b) depicts the changes in BESS voltage, based on highly accurate ECM battery model, whose performance characteristics are as close to the real hardware. It is evident that the voltage fluctuations are of considerable magnitude during BESS operation. Capturing such changes accurately provides an important set point for tuning DC/DC- and eventually DC/AC- converter controls. Overall, BESS DC power output is shown in 8(c), where the step change depicts the BESS power dispatch characteristics with a magnitude change based on its C-rate capability. Reason to choose such large step change, is to investigate its effect on the DC bus stability during transient operating conditions of the BESS. BESS SoC behavior is presented in Fig 8(d). DC-

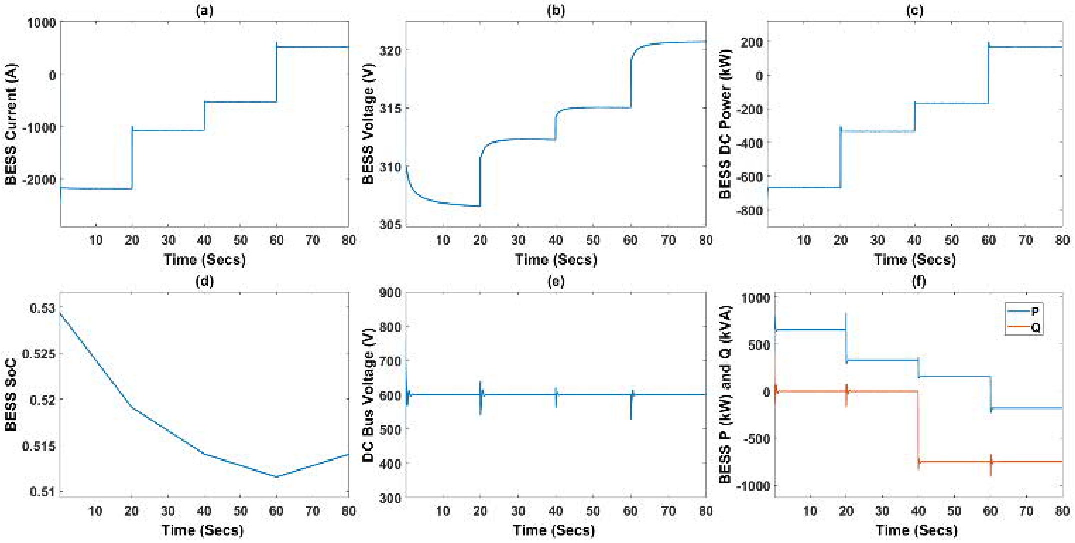

Figure 8. (a) BESS current characteristics (b) BESS Voltage (c) BESS DC power characteristics (d) BESS SoC (e) DC Bus voltage (f) BESS active and reactive power characteristics

bus voltage is constantly maintained at 600V, despite frequent variation of BESS voltage and current rate to the DC/AC-converter stage as shown in Fig. 8(e), thereby, reinforcing robust BESS model and adjoining converter controller design. BESS converter is capable of *P* & *Q* control respectively, which is demonstrated in a period after 40 seconds of the simulation in Fig. 8(f), where converter absorbs reactive power maintaining constant active power output. Henceforth, enabling improvement and management of voltage level or control of reactive power flow between HV and MV network as and when the MV grid (DSO) requires it.

V. CONCLUSION

Li-ion BESSs will play a dominant role as flexible energy sources in the coming decades with their promising characteristics. More detailed modelling of components, like BESS and converter, enables better overall microgrid/smart grid optimization analysis, by considering both component and system level complexities simultaneously. Detailed modelling of BESS and its grid-tied converter in microgrids or larger power systems, also aids to develop better understanding about effect of harmonics in BESS performance, aging etc. Hence, for integration of Li-ion BESS, accurate and detailed design of the DC/DC- and DC/AC- power converters is needed. In this paper, main contribution is the accurate model of Li-ion BESS, which incorporates the dynamic nature of SOEC modelling techniques. And, the design to carefully discharge and charge LIBs within their threshold (DC/DC-converter design) and the converter design and control (active and reactive power), were validated by simulation studies.

In future, role of BESS for multiple applications will be studied considering Sundom Smart Grid (SSG) as a case [13], where short-term and long term planning of BESS are necessary. In such cases, detail battery model with both age and temperature as affecting parameters will play a key role. Also, steady-state and transient stability studies by means of OPAL-RT real-time simulator with the developed new Li-ion battery and converter interface models will be performed.

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