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Energy efficiency evaluation of a stationary lithium-ion battery container storage system via electro-thermal modeling and detailed component analysis

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HIGHLIGHTS

- A holistic model for stationary battery systems is developed.
- In total 18 energy loss mechanisms in the system are analyzed and modelled.
- The model is parametrized based on an existing prototype battery system.
- Different grid applications are simulated for estimation of real-world performance.
- A detailed analysis of the battery system energy efficiency is given.

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ABSTRACT

Energy efficiency is a key performance indicator for battery storage systems. A detailed electro-thermal model of a stationary lithium-ion battery system is developed and an evaluation of its energy efficiency is conducted. The model offers a holistic approach to calculating conversion losses and auxiliary power consumption. Sub-models for battery rack, power electronics, thermal management as well as the control and monitoring components are developed and coupled to a comprehensive model. The simulation is parametrized based on a prototype 192 kWh system using lithium iron phosphate batteries connected to the low voltage grid. The key loss mechanisms are identified, thoroughly analyzed and modeled. Generic profiles featuring various system operation modes are evaluated to show the characteristics of stationary battery systems. Typically the losses in the power electronics outweigh the losses in the battery at low power operating points. The auxiliary power consumption dominates for low system utilization rates. For estimation of real-world performance, the grid applications Primary Control Reserve, Secondary Control Reserve and the storage of surplus photovoltaic power are evaluated. Conversion round-trip efficiency is in the range of 70–80%. Overall system efficiency, which also considers system power consumption, is 8–13 percentage points lower for Primary Control Reserve and the photovoltaic-battery application. However, for Secondary Control Reserve, the total round-trip efficiency is found to be extremely low at 23% due to the low energy throughput of this application type.

1. Introduction

The majority of human-induced carbon dioxide emissions come from fossil fuels that today still provide 80% of global primary energy demand [1]. Climate change requires a transition to a low-carbon energy supply, which often includes the intensified use of renewable energy sources such as wind and solar [2]. As wind and solar are volatile energy sources, the issue of decoupled production and demand load arises. Flexibility options such as variable generation, demand-side management, and grid expansion can support the reduction of unbalanced production and load. For a stable energy supply with high shares of volatile renewable energy sources, energy storage at large-scales for short and long-term is a technically possible option [3–5].

Recently, lithium-ion batteries have achieved significant cost

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Nomenclature

Abbreviations

AC alternating current
AirC air conditioning
C & M control & monitoring
DC direct current
IGBT insulated-gate bipolar transistor
OCV open circuit voltage
PCR primary control reserve
PE power electronics
PV-B photovoltaic-battery
RMS root mean square
SCR secondary control reserve
SOC state of charge

Parameters & variables

ΔU battery overvoltages
ΔT temperature difference in thermal network
$\eta_{\mathrm{Conversion}}$ round-trip conversion efficiency
η_{Total} round-trip total efficiency
ϕ_i relative losses of mechanism i
τ_t temporal utilization of system
τ_Q charge-based utilization of system
A interface area in thermal network
$c_{p,\mathrm{Air}}$ specific heat capacity of air
$c_{p,\mathrm{Cell}}$ specific heat capacity of cell
C_{Nom} nominal capacity of battery
$C_{\mathrm{th,Block}}$ heat capacity of cell block
$C_{\mathrm{th,Cell}}$ heat capacity of cell
COP coefficient of performance for cooling/heating
$E_{\mathrm{Charge,AC}}$ total system energy input (grid-side)
$E_{\mathrm{Discharge,AC}}$ total system energy output (grid-side)
energy loss of mechanism i
E_{Nom} nominal energy of battery
E_{Off} turn-off energy of IGBT
E_{On} turn-on energy of IGBT
E_{Rec} recovery energy of diode
$E_{\mathrm{System\ Consumption}}$ total system energy consumption for auxiliary components
f_{Grid} grid frequency
f_{Switch} switching frequency
i_{C} collector current
i_{CE} collector-emitter current
i_{F} forward current
i_{Grid} grid-side current of LCL-filter
I battery current
$\dot{m}_{Air,Module}$ air mass flow rate in the battery module
$m_{\mathrm{Air,PE}}$ air mass in power electronics zone
$m_{\mathrm{air,Sys}}$ air mass in battery zone
m_{Cell} battery cell mass
$m_{\mathrm{Connector,Block}}$ battery cell block connector mass
P_{AirC} power consumption air conditioning
$P_{\mathrm{C\&M,Batt}}$ power consumption C & M battery
$P_{\mathrm{C\&M,PE}}$ power consumption C & M power electronics
$P_{\mathrm{C\&M,Sys}}$ power consumption C & M system
$P_{\mathrm{Fan,Nom}}$ nominal power fan
$\overline{P}_{\mathrm{Loss,Block}}$ average experimental power losses in cell block
$P_{\mathrm{Loss,Diode,Cond}}$ conduction losses in diode
$P_{\mathrm{Loss,Diode,Switch}}$ switching losses in diode
$P_{\mathrm{Loss,IGBT,Cond}}$ conduction losses in IGBT
$P_{\mathrm{Loss,IGBT,Switch}}$ switching losses in IGBT
$P_{\mathrm{Loss,Interface}}$ losses in interface module
$P_{\mathrm{Loss,LCL,Cond}}$ conduction losses in LCL-filter
$P_{\mathrm{Loss,LCL,Core}}$ core losses in LCL-filter
$P_{\mathrm{Loss,PE}}$ conversion losses power electronics
$\dot{Q}_{\mathrm{AirC}}$ heat flow of air conditioning unit into ventilation duct
$\dot{Q}_{\mathrm{Batt\text{-}Sys}}$ (overall) heat input from battery rack to battery zone
$\dot{Q}_{\mathrm{Block}}$ heat input from cell operation into cell block
$\dot{Q}_{\mathrm{Block\text{-}AmbMod}}$ heat exchange of cell block to air in battery module
$\dot{Q}_{\mathrm{Cell}}$ heat input from cell operation into cell
$\dot{Q}_{\mathrm{Cond,PE\text{-}Sys}}$ conductive heat flow from power electronics zone to battery zone
$\dot{Q}_{\mathrm{Cond,AmbOutd\text{-}Sys}}$ conductive heat flow from ambient outdoor to battery zone
$\dot{Q}_{\mathrm{Conv,AmbOutd\text{-}Duct}}$ convective heat flow from ambient outdoor to ventilation duct
$\dot{Q}_{\mathrm{Conv,Duct\text{-}Batt}}$ convective heat flow from ventilation duct to battery rack
$\dot{Q}_{\mathrm{Conv,Duct\text{-}PE}}$ convective heat flow from ventilation duct to PE zone
$\dot{Q}_{\mathrm{Conv,Duct\text{-}Sys}}$ convective heat flow directly from ventilation duct to battery zone
$\dot{Q}_{\mathrm{Conv,PE\text{-}Sys}}$ convective heat flow from PE zone to battery zone
$\dot{Q}_{\mathrm{Conv,PE\text{-}AmbOutd}}$ convective heat flow from PE zone to ambient outdoor
$\dot{Q}_{\mathrm{Conv,Sys\text{-}AmbOutd}}$ convective heat flow from battery zone to ambient outdoor
$\dot{Q}_{\mathrm{Conv,Sys\text{-}Duct}}$ convective heat flow from battery zone to ventilation duct
$Q_{\mathrm{Throughput}}$ charge-throughput of battery
$Q_{\mathrm{Throughput,theoretical\ max}}$. theoretical maximum charge-throughput of battery
R_{i} battery resistance cell model
R_{th} thermal heat transfer resistance
$R_{\mathrm{th,Block\text{-}AmbientMod}}$ thermal heat transfer resistance cell block to ambient air in module
R_{Contact} electrical contact resistance
$R_{\mathrm{DC10s,Exp}}$ experimental battery resistance derived from 10 s pulse
$R_{\mathrm{DC10s,Scaled}}$ calculated battery resistance derived from 10 s pulse
$R_{\mathrm{LCL,total}}$ total inductor resistance of LCL-filter
s battery self-discharge rate
S battery entropy
SOC state of charge
$t_{\mathrm{Operation}}$ total time of system in operation
$t_{\mathrm{Simulation}}$ total duration of simulation
$T_{\mathrm{Air,Duct}}$ air temperature ventilation duct
$T_{\mathrm{Air,PE}}$ air temperature PE zone
$T_{\mathrm{air,Sys}}$ air temperature battery zone
$T_{\mathrm{AmbientMod,Row}k}$ air temperature in module in row k
T_{Block} cell block temperature
T_{J} junction temperature
T_{Ref} reference temperature battery model
U_{CE} collector-emitter voltage in IGBT
U_{DC} blocking voltage in IGBT
U_{F} forward voltage diode
U_{Grid} grid voltage
U_{Hys} battery hysteresis voltage
U_{Max} maximum battery voltage
U_{Min} minimum battery voltage
U_{Nom} nominal battery voltage
U_{OCV} open circuit battery voltage
$U_{\mathrm{OCV,Ref}}$ open circuit battery voltage at reference temperature
U_{T} terminal battery voltage
$\dot{V}_{\mathrm{Fan}}$ fan volumetric flow rate
$V_{\mathrm{Fan,Nom}}$ nominal fan volumetric flow rate