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Energy-efficient three-phase bidirectional converter for grid-connected storage applications

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ABSTRACT

Grid connected energy storage systems are expected to play an essential role in the development of Smart Grids, providing, among other benefits, ancillary services to power grids. It is therefore crucial to design and develop control and conversion systems that represent the key instrument where intelligence for decision-making is applied, in order to validate and ensure its optimal operation as part and parcel of the electrical system. The present research describes the design and development of a battery energy storage system based on an AC-DC three-phase bidirectional converter capable of operating either in charge mode to store electrical energy, or in discharge mode to supply load demands. The design is modelled with MATLAB® Simulink® environment in order to evaluate the performance during load variations. Moreover, the assessment is complemented by a global sensitivity analysis for variations in the operating parameters set by the transmission system operator. The effectiveness of the simulation is confirmed by implementing the system and carrying out grid connection tests, obtaining efficiencies over 98% for values over the 30% of the bidirectional converter rated power.

1. Introduction

2015 United Nations Climate Conference (COP21) [1] reinforced that a rapid and global transition to Renewable Energy Sources (RES) offers a realistic means to achieve sustainable development and avoid catastrophic climate change. One key action that must be addressed in order to enable the significant scale-up of RES is to introduce greater flexibility into energy systems and accommodate the variability of these resources [2].

When the intermittent RES share in the generation mix is lower than 15–20% of the overall electricity consumption, the Transmission System Operator (TSO) is able to compensate the intermittency. Nevertheless, when the share exceeds 20–25%, intermittent RES need to be curtailed during the low consumption periods in order to avoid grid perturbation and grid congestion [3].

The vision for the future Smart Grids includes a significant scale-up of clean energy and energy efficiency that balances environmental and energy goals with impacts on consumer costs and economic productivity. The adoption of technology for the bidirectional flow of energy and communications would open up access to information, participation, choice, and empower consumers with options from using electric vehicles to producing and selling electricity [4].

In this regard, Energy Storage Systems (ESS) represent a promising key solution to provide ancillary services, essential to facilitate the current and future needs of electricity grids [3,5–7] playing, therefore, a relevant role in the development of the smart grids [8–11]. Regarding this issue, several studies have been conducted about storage technologies (Table 1), identifying their technical characteristics and most appropriate applications [12–17].

A widely-used approach for classifying EES is the determination according to the form of energy used. In this sense, ESS are classified into mechanical, electrochemical, chemical, electrical and thermal energy [18]. Throughout the supply chain, ESS can be implemented into large-scale energy storage (GW), such as reversible hydro (pumped storage) or thermal storage; storage in grids (MW), like batteries, capacitors and superconducting coils and flywheels; and finally, at an end user level (kW), such as batteries, superconducting coils and flywheels.

In particular, electrochemical ESS offer the flexibility in capacity, sitting, and rapid response required to meet application demands over a much wider range of functions [19], such as grid integration, offering versatility as well as high energy density

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Nomenclature

Acronyms

AC	alternating current
BESS	Battery Energy Storage Systems
CC	current control
COP21	21st conference of the parties
DC	direct current
EPRI	Electric Power Research Institute
ES	electric system
ESS	Energy Storage Systems
EU	European Union
HB	hysteresis band
IGBT	Insulated Gate Bipolar Transistor
ITER	Instituto Tecnológico y de Energías Renovables, S.A.
LHB	lower hysteresis band
PEI	Power Electronic Interface
SPWM	Sinusoidal Pulse Width Modulation
RES	renewable energy systems
RTU	Remote Terminal Unit
RMS	root mean square value
SCADA	Supervisory Control and Data Acquisition
SOC	state of charge
TSO	Transmission System Operator
UHB	upper hysteresis band
VSI	voltage source inverter

Parameters

$i_{a,ref}$	reference current in the phase a (A)
$i_{b,ref}$	reference current in the phase b (A)
$i_{c,ref}$	reference current in the phase c (A)
i_a	measured current in the phase a (A)
i_b	measured current in the phase b (A)
i_c	measured current in the phase c (A)
v_a	measured voltage in the phase a (V)
v_b	measured voltage in the phase b (V)
v_c	measured voltage in the phase c (V)
ε_a	error signal in the phase a
ε_b	error signal in the phase b
ε_c	error signal in the phase c
S_a	signal for commanding the transistor base drives in the phase a
S_b	signal for commanding the transistor base drives in the phase b
S_c	signal for commanding the transistor base drives in the phase c
$\bar{v}$	voltage vector
$\bar{i}$	current vector
$\bar{a}$	bidimensional vector
I_{max}	peak current
θ	angle between the voltage vector and real axis
$i_{a,up}$	upper current band in the phase a (A)
$i_{a,low}$	lower current band in the phase a (A)
$i_{b,up}$	upper current band in the phase b (A)
$i_{b,low}$	lower current band in the phase b (A)
$i_{c,up}$	upper current band in the phase c (A)
$i_{c,low}$	lower current band in the phase c (A)
h	hysteresis band limit
v_{DC}	Terminal voltage of the battery bank (V)
ω	angular velocity (rad/s)
v_{ag}	ground-to-line voltage in the phase a (V)
v_{bg}	ground-to-line voltage in the phase b (V)
v_{cg}	ground-to-line voltage in the phase c (V)

and efficiency [20] and providing a wide range of services, including voltage control, power flow management, system restoration, energy and ancillary markets, commercial and regulatory framework and grid management [7,21–26].

Experience so far demonstrates that technological progress is not sufficient to boost storage deployment [27–29]. The integration of grid-connected Battery Energy Storage Systems (BESS) within electrical power systems has been hampered by technology costs, limited deployment experience, existing electricity market and regulatory structures and complex value chains which increase investment risk [9]. This means that technological development should actively complement an adequate regulatory environment, industrial acceptance and progress on different issues still needing regulatory support and research and development funding [29,30]. In particular, the integration of ESS in grids requires designing topologies and special converters, for virtually each case [21].

Power Electronic Interfaces (PEI) associated to grid-connected BESS are responsible for exchanging power between battery units and loads or the AC-side source [31,32]. These PEI systems must be bidirectional converters with the capability to operate in both charging and discharging modes [31]. When implementing PEI, one of the major challenges is the design parameters, depending upon the ESS and their implementation.

Voltage source inverters (VSI) are PEI traditionally operated as voltage sources where the controller generates gate pulses for obtaining an output voltage with a particular fundamental

Table 1
Performance of storage technologies [16].

Storage type	Power (MW)	Discharge time	Efficiency (%)	Lifetime (yr)	Overall storage cost (USD/MW h)	Capital cost (USD/kW)
Pumped hydro	250–1000	10 h	70–80	>30	50–150	2000–4000 (100–300)[b]
Compressed air energy storage (CAES)	100–300 (10/20)	3–10 h	45–60	30	–150	800–1000 (1300–1800)[c]
Fly wheels	0.1–10	15 s–15 m	>85	20	na	1000–5000[d]
Supercapacitor	10	<30 s	90	$5 \cdot 10^4$ cycles	na	1500–2500 (500)[d]
Vanadium redox battery (VRB)	0.05–10	2–8 h	75/80DC 60/70AC	5–15	250–300[d]	3000–4000 (2000)[d]
Li-ion battery	–5	15 m–4 h	90DC	8–15	250–500[d,e]	2500–3000 (<1000)[d,e]
Lead battery	3–20	10 s–4 h	75/80DC 79/75AC	4–8	na	1500–2000
NaS battery	30–35	4 h	80/85DC	15	50–150[d]	100–2000[d]
Superconducting magnetic energy storage (SMES)	0.5+[d]	1–100 s/h[d]	>90	>$5 \cdot 10^4$ cycles	na	na

[a] All figures are intended as typical order of magnitude estimated based on available sources and information, often with wide ranges of variability.
[b] Hydro power plant upgrading for storage service.
[c] Small systems (10–20 MW).
[d] Projected/estimated.
[e] Large Li-ion cells.