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Effective mitigation of the load pulses by controlling the battery/SMES hybrid energy storage system

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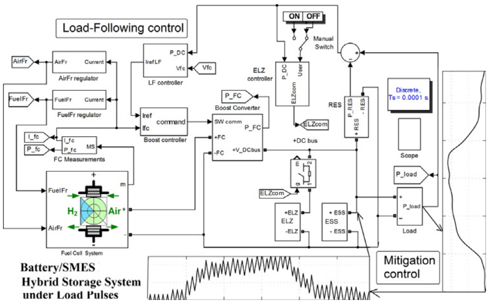
HIGHLIGHTS

- The mitigation control of the load pulses is designed for SMES converter.
- The Load-Following (LF) control applied to Fuel Cell allows reduced battery capacity.
- LF control attenuates load dynamics and the variability of renewable energy.
- The LF control loop is validated in different scenarios considered.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper it is analyzed the behavior of a battery/Superconducting Magnetic Energy Storage (SMES) hybrid Energy Storage Systems that can be used in a Fuel Cell/Renewable Energy Sources (RESs)/Hybrid Power System under an unknown load profile and variable RES power, which uses the Fuel Cell System as Auxiliary Energy Source. In general, the load demand profile includes large and sharp pulses, especially requested for space and military equipment, communication, and high-tech applications. The sizing and control of the battery/SMES Hybrid Power System under pulsed load are validated by simulations. The variability of the load demand and RES power is mitigated by using the Load-Following control for Auxiliary Energy Source of the RES Hybrid Power System. Thus, if the load power is higher than the RES power, then the battery will operate in charge-sustaining mode due to using the Load-Following control for Auxiliary Energy Source. Otherwise, the battery will operate in charge-increasing mode if the Hybrid Power System does not use an electrolyzer to be supplied with this excess of power. So, a reduced capacity is needed for battery operating in charge-sustaining mode due to use of the Load-Following control. However, the load pulses with large and sharp profile must be mitigated by the appropriate control of the SMES in order to protect the Fuel Cell system. So, the capacity of the SMES to generate (or to absorb) such pulses is analyzed in this paper. The simulation results illustrate the capacity of the SMES to generate different shapes of pulses. Thus, an effective mitigation of the load pulses is proposed here by

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Abbreviations: AES, Auxiliary Energy System; AirFr, air flow rate; AV, average value; BESS, Battery Energy Storage Systems; BPF, band-pass filter; CAES, Compressed Air Energy Storage; CSS, chemical storage system; EcSS, electro-chemical storage system; ELZ, electrolyzer; ESS, energy storage system; FC, Fuel Cell; FES, Flywheel Energy Systems; Fuel$_{eff}$, fuel consumption efficiency; FuelFr, fuel flow rate; HPF, high-pass filter; HPS, Hybrid Power System; HSS, Hybrid Storage Systems; Li-ion, lithium-ion; LF, Load-Following; LPF, low-pass filter; MAFC, metal air fuel cell; MFC, microbial fuel cell; MSS, mechanical storage system; PEMFC, proton exchange membrane fuel cell; PHS, Pumped Hydroelectric Storage; PWM, pulse width modulation; RFC, Regenerative Fuel Cell; RES, Renewable Energy Source; SMES, Superconducting Magnetic Energy Storage; SOC, State-of-Charge; sFF, Static Feed-Forward; TSS, Thermal Storage System; UC, ultracapacitor; YBCO, Yttrium Barium Copper Oxide; η_{sys}, FC system efficiency

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controlling the SMES converter. Also, the design of the battery/SMES Hybrid Power System under dynamic load is presented.

1. Introduction

In the last decade, the storage technologies have become varied but the most used are still the Battery Energy Storage Systems (BESS) due to the advanced technologies proposed recently [1,2], besides the Flywheel Energy Systems (FES) [3], the Pumped Hydroelectric Storage (PHS) systems [4], hydrogen Fuel Cell (FC) systems [5], Superconducting Magnetic Energy Storage (SMES) systems [6], Compressed Air Energy Storage (CAES) [7], and other Hybrid Storage Systems (HSS) [8].

The hybridization of the BESS with power storage devices such as ultracapacitors (UC), small SMES devices, and high-speed FES could be viable storage solutions for smart grids integrating renewable energy sources [9], and other stationary [10] and transport applications [5,11], avoiding some of BESS disadvantages related to efficient operation (through hybridization using HSS in vehicles [12] and excavators [13]), maintenance [14,15], and potential environmental hazards [16].

SMES devices have recently attracted the attention of researchers for equipment loaded with pulses requested by different applications for space missions [17], communication [18] and military [19,20], besides their current use for energy storing [21], power energy system stabilization [22,23], black start and uninterruptible power supply [24], Renewable Energy Sources (RESs) integration in smart grids [25], and so on [26,27].

For example, the EmDrive propulsion for spacecraft is based on Yttrium Barium Copper Oxide – (YBCO) superconducting cavities incorporated into the thrusters [19], being an advanced propulsion system based on recent superconductivity research [20]. An excellent state-of-the-art on SMES applications is made in [23]. The SMES integration in RES - based smart grids is approached in [22,25], and experimental results for high-temperature SMES in pulsed power supply is shown in [26], considering the time delay effect in the secondary side of the transformer. Note that pulse power technology is a challenging research field for military and high-tech applications [27,28]. The SMES advantages to ensure the energy spinning reserve, including legislative and economic aspects, are mentioned in [29]. A droop control algorithm for a battery/SMES HSS used to maintain the power system stability is proposed in [30] based on the average model of the power system during the switching period. The SMES based Shunt Active Power Filter topology is proposed in [31] to compensate the impulse load demands in the power system. Both Refs. [30,31] propose new methodologies to optimally design battery/SMES HSS, which will be used in this paper to design the HSS considering specific pulses on the load demand.

The main objectives of this study are as follows:

- To perform a review of the HSSs applications under dynamic load including pulses in order to identify the best candidates for pulse applications;
- To efficiently control the FC system from the RES/ELZ Hybrid Power System (HPS) using the Load-Following (LF) technique based on the power gap on the DC bus (the load power minus the RES power) in order to ensure the charge-sustaining mode of the battery even if the load has an unknown profile and the RES power is variable;
- To control the SMES converter in order to generate different shapes of pulses (such as large and sharp pulses and low frequency pulses generated by different equipment (robots, communication satellites, electromagnetic launcher, laser weapons, etc.) supplied by the HPS);
- To size the battery/SMES HSS and validate the design through the

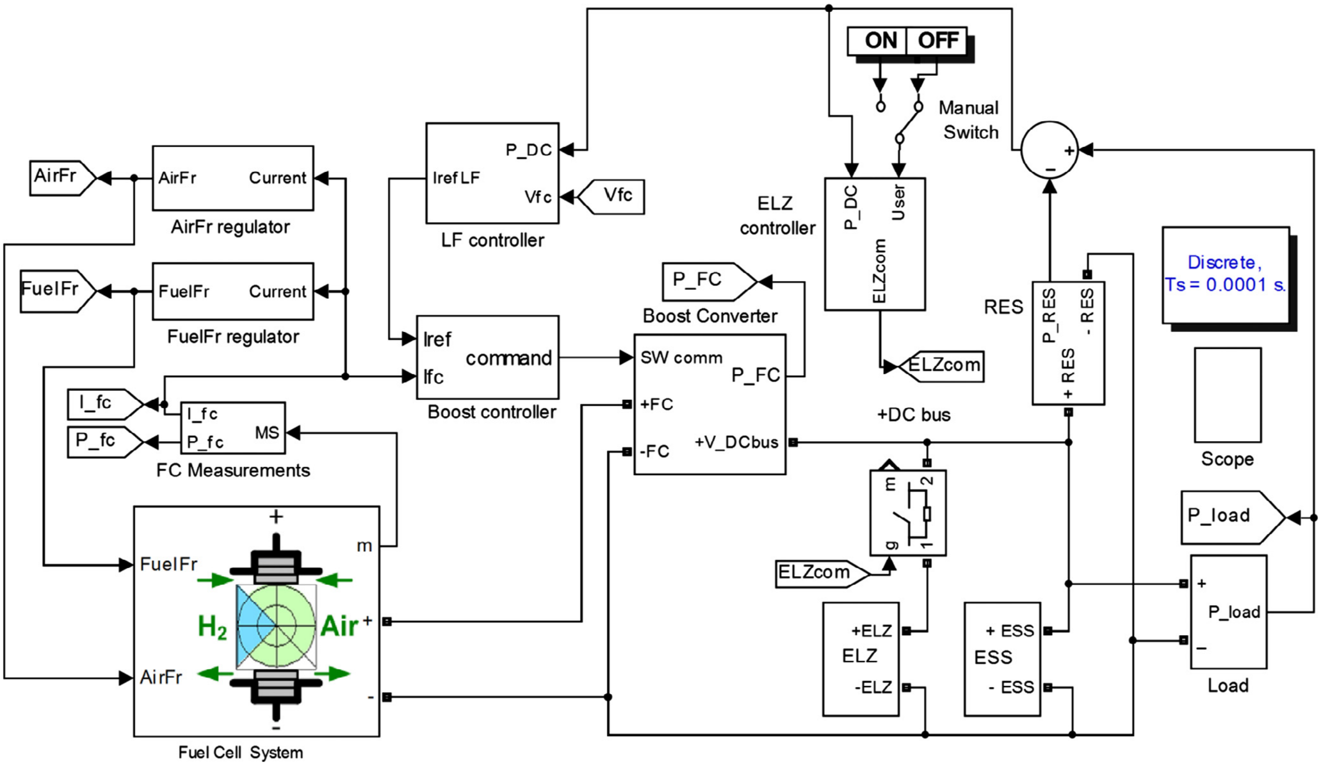

Fig. 1. FC/RES/ELZ Hybrid Power System.