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An optimal control strategy for standalone PV system with Battery-Supercapacitor Hybrid Energy Storage System

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HIGHLIGHTS

- The proposed control strategy comprises low pass filter and fuzzy logic controller.
- Membership functions of fuzzy logic controller are optimized by PSO.
- The dynamic stress and peak current of the battery are greatly reduced.
- The level of utilization of supercapacitor are significantly increased.

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ABSTRACT

This paper proposes an optimal control strategy for a standalone PV system with Battery-Supercapacitor Hybrid Energy Storage System to prolong battery lifespan by reducing the dynamic stress and peak current demand of the battery. Unlike the conventional methods which only use either filtration based controller (FBC) or fuzzy logic controller (FLC), the proposed control strategy comprises of a low-pass filter (LPF) and FLC. Firstly, LPF removes the high dynamic components from the battery demand. FLC minimizes the battery peak current demand while constantly considering the state-of-charge of the supercapacitor. Particle swarm optimization (PSO) algorithm optimizes the membership functions of the FLC to achieve optimal battery peak current reduction. The proposed system is compared to the conventional system with battery-only storage and the systems with conventional control strategies (Rule Based Controller and FBC). The proposed system reduces the battery peak current, battery peak power, maximum absolute value of the rate of change of power and average absolute value of the rate of change of power by 16.05%, 15.19%, 77.01%, and 95.59%, respectively as compared to the conventional system with battery-only storage. Moreover, he proposed system increases the level of supercapacitor utilization up to 687.122% in comparison to the conventional control strategies.

1. Introduction

Batteries are commonly implemented in standalone PV power systems to fulfill the power mismatch between the PV power generation and the load demand. Generally, a battery would encounter frequent deep cycles and irregular charging pattern due to the varying output of PV and the intermittent high power demand of the load. These operations would shorten the battery lifespan and increase the replacement cost of the battery [1–3]. Battery-Supercapacitor Hybrid Energy Storage System (HESS) is thus a practical solution to minimize the battery stress, battery size and the total capital cost of the system [4]. The technical characteristics of battery and supercapacitor (SC), such as specific power, specific energy, response time and durability, are complementary.

A control strategy is essential for the HESS to optimize the energy utilization and energy sustainability to a maximum extent as it is the algorithm which manages the power flow of the battery and SC. One of the common aims of HESS implementation is to prolong the battery lifespan by reducing the peak current demand and the dynamic stress of the battery. Battery peak current reduction would reduce the internal voltage drop in the battery and improve the battery efficiency [4,5]. Reduction in battery dynamic stress minimizes the heating and the internal losses of the battery [5,6].

Table 1 summarizes that Rule Based Controller (RBC) [7–12] and Filtration Based Controller (FBC) [13–18] that are commonly

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Nomenclature

$\lvert Ah\rvert_{SC}$	Absolute value of accumulated ampere hours of supercapacitor (Ah)
$\lvert\Delta P\rvert$	Absolute value of the rate of change of power (W s^{-1})
$\lvert\Delta P\rvert max$	Maximum $\lvert\Delta P\rvert$ (W s^{-1})
$\lvert\Delta P\rvert mean$	Mean $\lvert\Delta P\rvert$ (W s^{-1})
Δt	Time Step (s)
ANN	Artificial Neural Network
dP	Power Deficit between P_{PV} and P_{load} (W)
$f(x)$	Fitness Function
FBC	Filtration Based Controller
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
Gbest	Global Best Value
H	High
HESS	Hybrid Energy Storage System
HPF	High Pass Filter
HSS	Hydrogen Storage System
ib1	Battery Current Threshold 1
ib2	Battery Current Threshold 2
I_{batt}	Battery Current (A)
I_{batt_peak}	Battery Peak Current Demand (A)
i_L	Inductor Current (A)
K1	Gradient 1
K2	Gradient 2
L	Low
LPF	Low Pass Filter
M	Medium
MF	Membership Function
mf	Number of Membership Functions
n	Number of Input Variables
NH	Negative High
NL	Negative Low
P(t)	Power at time t (W)
P(t-Δt)	Power at time t−Δt (W)
P_{batt}	Battery Power (W)
pbest	Personal Best Value
PH	Positive High
P_H	Peak Power Demand (W)
P_{HF}	High Frequency Power Demand (W)
PL	Positive Low (W)
P_{LF}	Low Frequency Power Demand (W)
P_{load}	Load Demand (W)
P_{PV}	PV Output Power (W)
P_{sc}	Supercapacitor Power (W)
Psc^*	Supercapacitor Reference Power (W)
P_{sc}'	Converted Supercapacitor Power (W)
PSO	Particle Swarm Optimization
P_{batt_peak}	Battery Peak Power Demand (W)
RBC	Rule Based Controller
REPS	Renewable Energy Power System
SC	Supercapacitor
SOC	State-of-Charge (%)
SOC_{batt}	State-of-Charge of Battery (%)
$SOC_{batt\_average}$	Average State-of-Charge of Battery (%)
SOC_{batt_final}	Final State-of-Charge of Battery (%)
SOCsc	State-of-Charge of Supercapacitor (%)
SVM	Support Vector Machine
WCA	Water Cycle Algorithm
Z	Zero
α	Power Sharing Ratio
η_{dcdc}	Efficiency of Bidirectional DC-DC Converter (%)

Table 1
Summary of literature [7–18] showing analysis on the type of RE sources, and control strategy for system with Battery-Supercapacitor HESS only.

Ref.	RE source(s)	HESS	Control strategy	Optimization
[7]	PV	Battery/SC	RBC	–
[8]	PV	Battery/SC	RBC	–
[9]	Wind	Battery/SC	RBC	–
[10]	PV	Battery/SC	RBC	–
[11]	PV	Battery/SC	RBC	–
[12]	PV	Battery/SC	RBC	–
[13]	Wind & PV	Battery/SC	FBC & ANN	–
[14]	Wind	Battery/SC	FBC	–
[15]	Wind	Battery/SC	FBC	–
[16]	PV	Battery/SC	FBC	–
[17]	Wind	Battery/SC	FBC	–
[18]	PV	Battery/SC	FBC	–
This Study	PV	Battery/SC	FBC & FLC	PSO

employed in renewable energy power system (REPS) with Battery-Supercapacitor HESS. Despite RBC being simple to implement, it is rigid and incapable of adapting to real-time system condition as it has pre-defined thresholds, rules and operations [30]. In Refs. [9] and [27], both studies implemented RBC for off-grid REPS with HESS. In these studies, the output power of the renewable energy sources is free of fluctuation with the utilization of filtered wind speed and solar irradiation profiles. This is not realistic as the output power of renewable energy sources would fluctuate in real life due to the varying weather condition.

FBC decomposes the power demand into high and low frequency components by utilizing a filter and it is excellent in smoothening the battery current. In Ref. [16], the authors implemented a low pass filter (LPF) based FBC to reduce the charge/discharge rate of the battery. However, the SOC of the energy storage systems was considered as trivial in the control strategy. In fact, FBC is not effective in minimizing the peak power demand of the battery as it can only process the frequency of the power demand.

Table 2 shows that fuzzy logic controller (FLC) is commonly employed in REPS with hydrogen storage system (HSS)-battery HESS. However, there has been little discussion about the

Table 2
Summary of literature [19–29] showing analysis on the type of RE sources, and control strategy for system with HESS.

Ref.	RE source(s)	HESS	Control strategy	Optimization
[19]	Wind	Battery/HSS	RBC	–
[20]	Wind & PV	Battery/HSS	Neuro-fuzzy	Neuro-fuzzy
[21]	Wind & PV	Battery/HSS	RBC & FLC	–
[22]	Wind	Battery/SMES	FLC	GA
[23]	Wind & PV	Battery/HSS	FLC	WCA
[24]	Wind & PV	Battery/HSS	ANN	–
[25]	Wind	Battery/HSS	FLC	PSO & SFL
[26]	Wind & PV	Battery/HSS	FLC	PSO
[27]	Wind & PV	Battery/HSS	RBC	–
[28]	PV	Battery/HSS	RBC	–
[29]	Wind & PV	Battery/HSS	RBC	–
This Study	PV	Battery/SC	FBC & FLC	PSO