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Sizing of hybrid energy storage system for a PV based microgrid through design space approach

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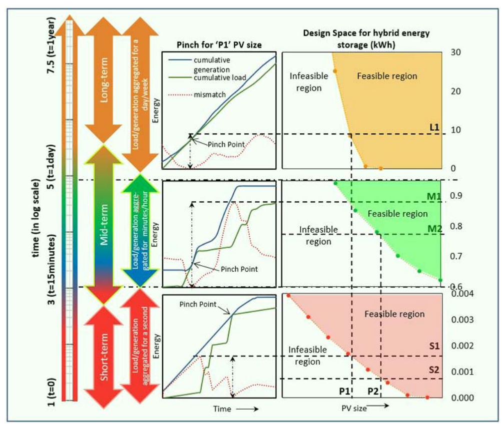
HIGHLIGHTS

- Generic sizing methodology for hybrid storage system.
- Correlating the supply–demand variability with discharge time of storage.
- Pinch analysis and design space approach to hybrid energy storage.
- Design curve fitted with quadratic equation and solved as an optimisation problem.
- Optimal sizing based on minimal life cycle costing.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy storage plays a crucial role in ensuring reliable power supply in a renewable microgrid. The supply and demand variability is found in different time scales (i.e., instantaneous, diurnal, and seasonal). The nominal discharge duration of multiple storage options can be matched effectively for variability in all relevant time scales. An optimum mix of storage options is important to design a cost-effective system.

This paper proposes a generic sizing methodology using pinch analysis and design space for hybrid energy storage in a PV-based isolated power system. Pinch analysis utilises a time series simulation of the system where generation should always exceed the load. The methodology defines the design space as feasible combinations of short, medium, and long-term storage size and PV array rating for the given loads. These design space curves are approximated by quadratic equations and the correlations are used as constraints to determine the optimal mix of supply and storage that minimise the life cycle cost.

Four different practical cases in Indian context —a remote village, telecom tower, welding shop, and a standby system for a lift load – are analysed to illustrate the sizing method. As an example, the optimal size for a PV based microgrid supplying a remote telecom tower with an average load of 72 kWh/day is 40 kW_p of PV, 5 m^3 of hydrogen storage and 58 kWh of battery. The proposed methodology extends the design space approach to obtain an optimal minimum cost solution.

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Nomenclature

A	PV array area, m^2
a_1,b_1,c_1	curve fitting coefficients for long-term storage
a_2,b_2,c_2	curve fitting coefficients for mid-term storage
a_3,b_3,c_3	curve fitting coefficients for short-term storage
AC_{fuel}	annualised fuel cost, ₹
$AC_{O\&M}$	annualised cost of operation and maintenance, ₹
$ALCC$	annualised life cycle costing, ₹
B	battery storage capacity, kWh
C	storage capacity, kWh
C_0	initial investment, ₹
COE	cost of energy, ₹/kWh
CRF	capital recovery factor
d	discount rate, %
D	load demand, kW
DoD	depth of discharge
E	Electrolyser size, kW
E_d	annual energy delivered, kWh
FC	fuel cell size, kW
G	power generated by renewables, kW
G_{ref}	actual generation from renewable, kW
H	hydrogen storage capacity, kWh
I	solar insolation, kW/m^2
L_{H_2}	hydrogen storage capacity, kWh
n	component life, years
n_B	battery life, years
n_H	hydrogen storage life, years
n_P	PV array life, years
n_S	supercapacitor life, years
P	PV array rating, kW
P_{HT}	pressure of hydrogen tank, atm
P_{L1},P_{L2}	bounds of PV rating on long-term storage, kW
P_{M1},P_{M2}	bounds of PV rating on mid-term storage, kW
P_{S1},P_{S2}	bounds of PV rating on short-term storage, kW
Q_s	stored energy in storage devices, kWh
S	supercapacitor storage capacity, Wh
T	time horizon
t	time step
$t_{H_2 storage}$	time step for hydrogen storage, h
V_{HT}	volume of hydrogen tank, litres

Greeks

Δt	time step for simulation
η_{st}	round trip efficiency of the storage device
η	PV array efficiency

Abbreviations

BoS	balance of system
GCC	grand composite curves
HESS	hybrid energy storage system
PV	photovoltaics
O&M	operation and maintenance
SMES	superconducting magnetic energy storage
SOC	state of charge
VRLA	valve regulated lead acid battery

1. Introduction

Microgrids are decentralised grids that use distributed generators to cater to the local demand [1]. These decentralised grids can be operated in grid connected mode or stand-alone mode. Energy storage is needed in PV based microgrids to cater to the supply and demand variability. Batteries, hydrogen storage, pumped-hydro, flywheel, compressed air storage, supercapacitor, and superconducting magnetic energy storage (SMES) are storage options proposed for microgrids [2–12].

An important decision factor in the design of a renewable microgrid system is the sizing of its components as it affects the cost. An oversized energy storage system leads to high cost and will not perform to its full potential while an undersized energy storage device degrades and may result in loss of load [13]. Different storage options have different characteristic discharge durations. Combinations of storage options (hybrid storage) are likely to be more cost effective than a single storage technology. The main goal of this paper is to propose a design methodology to size different components of a microgrid, namely the distributed generator and the hybrid storage options based on the available resource and load profile.

Table 1 summarises the previous literature related to the sizing of hybrid storage in microgrids. The conventional approach is to meet the peak load through a high power density device and the average load through a high energy density storage device [14–16]. This size of hybrid storage components may not be optimal.

Jallouli et al. [17] report sizing of a battery and a reversible fuel cell for a PV based residential off-grid system. The battery capacity is computed for the maximum monthly average load power in a year for one day of autonomy whereas hydrogen storage is based on the supply demand energy balance. Similarly, Martin et al. [18] integrate a fuel cell and a supercapacitor to supply the variability in wind and PV generation for the microgrid at the University of Navarre, Spain. The

Table 1
Summary of literature on sizing of hybrid storage.

Ref.	Author, Year	Hybrid storage	Supply	Sizing Criteria
[20]	Onar, 2006	Supercapacitor and hydrogen storage	Wind energy converter	Peak load and average energy
[21]	Maclay, 2007	Battery and supercapacitor	PV and grid	Peak load energy
[22]	Li CH, 2009	Battery and hydrogen storage	PV	Minimal cost configuration
[23]	Gee, 2010	Battery and supercapacitor	Wind energy converter	Peak load energy and average energy
[24]	Glavin, 2012	Battery and supercapacitor	PV	Mismatch between load and generation and peak load energy
[17]	Jallouli, 2012	Battery and hydrogen storage	PV	Monthly average load and energy balance
[18]	Martin, 2013	Supercapacitor and hydrogen storage	PV, wind, and grid	Mismatch between load and generation and peak load energy
[19]	Masih-Tehrani, 2013	Battery and supercapacitor	IC engine	Based on battery degradation cost
[25]	Zhou, 2014	Battery and supercapacitor	PV and wind	Based on energy balance
[26,27]	Song, 2014,2015	Battery and supercapacitor	IC engine	Based on battery degradation cost
[28]	Li J, 2016	Battery and SMES	Wave energy converter	Peak load energy and energy balance
[29]	Destro, 2016	Battery and pumped hydro	PV	Based on power balance
[30,31]	Esfahani, 2015, 2016	Battery and hydrogen storage	PV, wind, and biomass	Based on power balance using pinch analysis
[32,33]	Li B, 2017	Battery and hydrogen storage	PV	Based on operating strategy optimal size selected using genetic algorithm