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Multi-objective three stage design optimization for island microgrids

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HIGHLIGHTS

- An enhanced multi-objective three stage design optimization for microgrids is given.
- Use of an optimal control problem for the calculation of the optimal operation.
- The inclusion of a detailed battery model with CC/CV charging control.
- The determination of a representative profile with optimized number of days.
- The proposed method finds its direct application in a design tool for microgids.

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ABSTRACT

Hybrid off-grid energy systems enable a cost efficient and reliable energy supply to rural areas around the world. The main potential for a low cost operation and uninterrupted power supply lies in the optimal sizing and operation of such microgrids. In particular, sudden variations in load demand or in the power supply from renewables underline the need for an optimally sized system. This paper presents an efficient multi-objective model based optimization approach for the optimal sizing of all components and the determination of the best power electronic layout. The presented method is divided into three optimization problems to minimize economic and environmental objectives. This design optimization includes detailed components models and an optimized energy dispatch strategy which enables the optimal design of the energy system with respect to an adequate control for the specific configuration. To significantly reduce the computation time without loss of accuracy, the presented method contains the determination of a representative load profile using a k-means clustering method. The k-means algorithm itself is embedded in an optimization problem for the calculation of the optimal number of clusters. The benefits in term of reduced computation time, inclusion of optimal energy dispatch and optimization of power electronic architecture, of the presented optimization method are illustrated using a case study.

1. Introduction

The increase of fuel prices and the worldwide rise of energy demand up to 53% by 2035 [1] poses additional demands for sustainable energy generation. In particular, microgrids comprising of diesel generators, storage devices and renewable sources present an effective approach for an economic energy supply to rural areas. They operate autonomously, either in parallel with an existing utility grid, or as a stand-alone island grid, dependent on their field of application [2]. An overview of different research projects concerning microgrids, the challenges, and developments is given in [3]. The integration of renewable resources into these energy systems is of high importance to achieve a low cost operation although it places additional requirements on the power management of the microgrid. The discontinuity in the generation of renewables and sudden variations in their power output emphasize the need for an enhanced control and optimal system design. The steady increase in the usage of stand-alone hybrid energy systems consequently puts the focus on their layout optimization and dimensioning of components. Related work focusing on microgrids can be found in [4] for the optimal design using particle swan optimization (PSO) methods and a decentralized agent based control for the operation of the microgrid. In [5], an agent based demand response control method for a simultaneous sizing of the microgrid components is presented. The type of microgrid considered in this paper presents an island energy system including diesel generators, photovoltaics (PV), power electronics (PoE), and a battery module. The focus of the optimal design lies on economic as well as environmental aspects while aiming for an uninterrupted power

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Nomenclature

Variables & functions

C	capacity [Ah]
$C(\cdot)$	cost function [\$/kWh]
δ_{off}	diesel generator off time
δ_{state}	diesel generator on/off state
$\delta_{u/d}$	start up/shutdown of diesel generator
δJ	state transition cost
η	efficiency [%]
f	function including one objective
F	objective function of multi-objective optimization
f_d^t	discount factor
G	all irradiations on the solar penal [W/m^2]
I	current [A]
J	objective function
N	number
N_{days}	number of days in representative profile
P	output power [kW]
P_{gen}	generated energy over system lifetime
P_{sp}	spinning reserve [W]
$\dot{Q}$	heat transfer [kg m^2/s^3]
$\dot{Q}_{rad}$	the radiation heat transfer to and from the panel [kg m^2/s^3]
$\dot{Q}_{conv}$	the convection heat transfer to and from the panel [kg m^2/s^3]
R	resistance [Ω]
T	temperature [K]
T_{STC}	temperature of standard test conditions [K]
$\mathbf{u}$	input vector of optimization
V	voltage [V]
V_{diode}	voltage across the diode [V]
V_{OC}	open circuit voltage [V]
V_t	the terminal voltage [V]
x	optimization variable
$\mathbf{x}_C$	state vector of variables of optimal control problem
$\mathbf{x}_L$	state vector of variables of design optimization problem
$\mathbf{z}$	cluster center
Z	number of profiles in cluster

Indices

$(\cdot)_b$	index for energy storage system
$(\cdot)_{cap}$	all variables of the capital cost
$(\cdot)_{cl}$	cluster
$(\cdot)_{Cell}$	index for battery cell
$(\cdot)_{dg}$	index for diesel generator
$(\cdot)_{el}$	electric
$(\cdot)_{fuel}$	index for fuel consumption
$(\cdot)_i$	index for diesel generators
$(\cdot)_k$	index of time
$(\cdot)_{load}$	index for load demand
$(\cdot)_{max}$	index for maximal value
$(\cdot)_{min}$	index for minimal value
$(\cdot)_{mod}$	index for photovoltaic module
$(\cdot)_{O\&M}$	all variables of the O&M cost
$(\cdot)_{pe}$	index for power electronics
$(\cdot)_{pv}$	index for photovoltaic
$(\cdot)_{real}$	subscript for real values
$(\cdot)_{ref}$	index for reference trajectories form first level
$(\cdot)_{rep}$	all variables of the replacement cost
$(\cdot)_{sal}$	all variables of the salvage cost

Abbreviations

CAPEX	capital expenditure
CC/CV	constant current/constant voltage
CID	cluster dispersion indicator
DDP	discrete dynamic programming
GA	genetic algorithm
LCOE	levelized cost of energy
MIA	mean index adequacy
MINLP	mixed integer nonlinear problem
MPC	model predictive control
NOMAD	Nonlinear Mesh Adaptive Direct Search Method
O&M	operation and maintenance
PV	photovoltaic
PoE	power electronics
SOC	state of charge

supply. Such systems can for example be found in remote areas to power small villages. The diesel generator usually acts as a primary or backup power supply and is defined by a high operation cost mainly resulting from the fuel consumption. The integration of a storage system, here a lead acid battery, renders more flexibility by storing additional energy and providing it when it is needed. Its main task is to balance the load demand and power generation in the microgrid [6]. An investigation of different storage system technologies and benefits of their inclusion into microgrids are discussed in [7]. Photovoltaics are particularly attractive for remote communities since they offer a clean source of power in locations that cannot be economically served by means of grid extension. PV integration reduces the system cost but poses additional challenges on the system due to the intermittency and unpredictability of renewables.

The design, control and optimization of these hybrid systems are usually very complex tasks. Recently considerable notice is being given to the improvement of microgrid layouts and component sizing with the use of advanced algorithms. A common approach is the use of meta-heuristic and heuristic optimization approaches as the PSO. The approach presented in [8] considers the multi-objective design optimization of an energy system with underlying rule based operation strategy applying PSO in combination with an ϵ-method. In [9], a stand alone photovoltaic–wind–bat tery system is modeled as mixed integer problem and optimized using PSO. A comparison of PSO, a genetic algorithm (GA), and the planning tool Homer for the optimization of an energy system, which include a cycle charging strategy for the calculation of the energy dispatch, is presented in [10]. The work in [11] focuses on a modified PSO algorithm for the optimization of off-grid as well as grid connected systems to improve the convergence speed. Further methods are the ant colony in combination with the artificial bee algorithm [12], neural network and adaptive neuron fuzzy interference [13], a hybrid simulated annealing-tabu search method [14] or GA. In [15], a GA is used for the optimal design of the storage system by the use of fuzzy expert methods for the energy management. The multi-objective optimization problem in [16] is solved using the NSGA-II [17], which will also be used in this paper. The models included in the problem formulation in [16] are given on a power and efficiency based level where the system is operated using a rule based dispatch strategy. The use of GA for the optimization of autonomous energy systems, including three different rule based optimization modes, can be found in [18]. A GA also finds its application for the multi-objective