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A systems approach for management of microgrids considering multiple energy carriers, stochastic loads, forecasting and demand side response

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HIGHLIGHTS

- A systems approach is proposed to model energy systems under multiple stochastic loads.
- A state space approach allows the usage of DSR and forecasting with EMS.
- The energy management strategy is the evolution operator in a state space model.
- Novel EMS with DSR and forecasting are proposed that greatly enhance the system performance.

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ABSTRACT

Multi-vector microgrids that utilise several forms of energy storage are becoming popular in smart grid topologies due to their ability to cope with problems induced in the power network from the usage of distributed generation. While these microgrids appear to be pivotal in future energy systems, they impose several problems in the design and operation of the network mainly due to their complexity and the different properties that each energy subsystem has. In this work, we propose a novel, generic and systematic way of modelling the assets in a microgrid including the energy management method that is used to control the operation of these assets under multiple stochastic loads. This gives a unique tool that allows the testing/derivation of multiple energy management methods including demand side response and the usage of forecasting tools to optimise the performance of the system. A thorough study of the proposed method, using data from a real hybrid energy system (built in Greece), proves that the performance and efficiency of the system can be significantly improved while at the same time the requirement for external power supply or the consumption of fossil fuels can be reduced. The main concept is based on a state space modelling approach that transforms the power network into a hybrid dynamical system and the implemented energy management method into the evolution operator. The model integrates structural, temporal and logical features of smart grid systems in order to identify and construct multiple different energy management strategies ~~EMS~~ which can then be compared with respect to their ability to best serve the considered demands. Other than coping with several energy carriers, the model inherently accounts for forecasting, handles multiple random loads with time dependant importance and supports the use of demand side response strategies. Conclusions drawn from numerical case studies are used to demonstrate the advantages of the proposed method. In this work we clearly show that by using 20 different energy management methods and analysing their performance through a multi-criteria assessment approach we obtain non-trivial energy management approaches to support the operation of a multi-vector smart-grid considering variable external demands.

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Nomenclature

Acronyms

DSR	Demand side response
EMS	Energy management strategies
MILP	Mixed integer linear programming
MPC	Model predictive control

Symbols

$a_{i,j}$	weighting coefficient
BAT	battery
DSL	diesel generator
EL	electrolyser
FC	fuel cell
$Flow$	set of flows
FT	fuel tank for hydrogen
$F^{j}_{m\to n}(t)$	flow of j from node m to node n
G	set of EMS
L	logical operator
$H2O$	water
$H2$	hydrogen
OF	objective function
PV	photovoltaic panels
Pow	electrical power
$P_{L_k}(t)$	loads
$P_{R_k}(t)$	probabilities
P_i^j	amount of energy or matter that may be converted by the i^{th} unit
Rs^{Conv}	set of converters
Rs^{Acc}	set of accumulators
S	state space
$SOAcc^{l}(t)$	state of accumulator l
s	state of microgrid
st_j^G	standard deviation of OF
$x^{*}_{i,j}$	scaled OF
$\varepsilon_i(t)$	state of converter i
$\varepsilon_i^{Avl}(t)$	boolean variable that determines the availability of using converter i
$\varepsilon_i^{\text{Req}}(t)$	boolean variable that determines the requirement of using converter i
$\varepsilon_i^{Gen}(t)$	generic condition for converter i
$\varepsilon_i^{LD}(t)$	boolean variable that determines the probability of having high load
μ_j^G	mean value of OF
$\rho_i^{SOAcc^l}$	boolean variable that quantifies a statement for converter i based on accumulator l
Φ	evolution operator

1. Introduction and research hypothesis

1.1. Microgrids and distributed generation

Microgrids that employ hybrid energy storage systems have received significant attention in recent years as a means of exploiting distributed renewable energy sources. They often incorporate multiple types of equipment to transform different types of energy sources into power (e.g. Photovoltaics, Wind generators etc.), while commonly considered storage options include batteries or hydrogen infrastructure, to name but a few [1–4]. Storage is very important in order to enable highly intermittent energy sources to be seen by the grid as dependable power flows. However, together with different energy transformation options they result in the need to combine equipment of heterogeneous technical and temporal operating characteristics. This causes significant complexities pertaining to the selection of the appropriate energy transformation or storage option, of the amount of energy to be transformed or stored and of the appropriate time instant to initiate or terminate the operation of the corresponding equipment [5]. Furthermore, such systems are often required to serve multiple different loads which are driven by variable and often difficult-to-predict demands [6].

To address these challenges, published research includes a wide collection of works on energy management of the power generation [7,8], storage [9,1] and demand side response strategies of such systems [10]. Decisions regarding the equipment and energy carrier to use, the instant of their initiation and the duration of their operation are implemented through Energy Management Strategies (EMS). The employed EMS either result from optimization approaches [10] or from a predetermined but non-trivial set of options [9,1].

1.2. Derivation of energy management strategies

Optimization approaches [11] employ generic models which are able to capture a wide range of connectivity and temporal interactions among different systems and optimize their design (e.g. capacity) or operating characteristics using specific criteria. For example, the works of Parisio et al. [12] and of Arnold et al. [13] employ generic models for non-linear model predictive control of a hybrid system. Chen et al. [14] employ a generic transhipment model in a Mixed Integer Linear Programming (MILP) formulation for the optimum design of hybrid systems. Silvente et al. [15,16] employ a generic representation model for simultaneously planning energy supply and demand in a rolling horizon optimization framework implemented as a MILP. The work is further extended by Silvente et al. [6] to improve the temporal representation so that they can account for both discrete- and continuous-in-time decisions. Zhang et al. [17] propose the optimization of a multi-microgrid system under uncertainty in a bi-level, non-linear optimization formulation. The solution approach employs a sub-problem optimization step, addressing the continuous variables, while for each optimum solution a master problem is solved for the discrete variables. Marzband et al. [18] address performance optimization and scheduling of microgrids using a stochastic optimization algorithm with variation in the load consumption model. These are a few indicative works of generic models used in optimization formulations, whereas an inclusive review is presented in Khan et al. [10]. Such models are clearly very useful as they can identify efficient EMS from numerous options considering economic and operating criteria, while they can also be implemented for short-term decision making in the course of the system operation. However, they also include shortcomings due to the combinatorial complexity and the highly non-linear and often non-convex mathematical models that require increased computational effort in order to reach optimum solutions. Similar issues are highlighted in both Vivas et al. [9] and Parisio et al. [12] who indicate that constraints and options are often omitted, especially in cases of on-line decision making, to facilitate computations.

On the other hand, predetermined EMS are mainly developed based on engineering understanding of the system operation and requirements; they incorporate practical constraints to ensure both efficient and reliable system operation. They have been used widely for optimum design of hybrid systems (e.g. [19,20]) and are chosen particularly in cases of real-time decision-making during system operation [9] as they have no detrimental effects on computations. It is worth noting that among the approximately 100 publications recently reviewed by Olatomiwa et al. [1] there are only 4 that investigate two different EMS [21–24] and 4 more that investigate three different EMS [25–28]. The rest of the publications consider only 1 EMS. Giaouris