Renewable Energy 95 (2016) 433–448

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Power grand composite curves shaping for adaptive energy management of hybrid microgrids

Damian Giaouris [a, d], Athanasios I. Papadopoulos [a, *], Panos Seferlis [a, c], Spyros Voutetakis [a], Simira Papadopoulou [a, b]

[a] Chemical Process and Energy Resources Institute, Centre for Research and Technology Hellas, Thermi-Thessaloniki, Greece
[b] Department of Automation Engineering, Alexander Technological Educational Institute of Thessaloniki, Thessaloniki, Greece
[c] Aristotle University of Thessaloniki, Department of Mechanical Engineering, Thessaloniki, Greece
[d] Newcastle University, School of Electrical and Electronic Engineering, Newcastle Upon Tyne, UK

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form
28 March 2016
Accepted 16 April 2016
Available online 27 April 2016

Keywords:
Energy management
Power pinch analysis
Grand composite curves
Hybrid renewable energy systems
Process integration

ABSTRACT

This work proposes a systematic approach for the adaptive identification and implementation of efficient power management strategies (PMS) in the course of operation of hybrid renewable energy microgrids. The approach is based on the temporal evolution of the system power grand composite curve (PGCC), which is adaptively shaped on-line and within short-term time intervals to form a sequence of decisions indicating the instant and duration of activation of different subsystems. It builds on from previous work where the potential for system performance enhancement could not be exploited through pre-specified PMS identified off-line. More specifically, it involves a stored energy targeting step that exploits the PGCC to identify the desired operational profile of an accumulator during a prediction horizon in order to satisfy the system operating goals. The identified energy targets are subsequently enforced through a sequence of control actions that enable the exact matching of the PGCC hence resulting in a new PMS. The method is elaborated graphically for multiple potential operating goals and is supported by a formal mathematical model that captures system structural and temporal characteristics. It is implemented on an actual hybrid microgrid considering multiple RES-based energy generation and storage options for expected and unexpected weather conditions.

1. Introduction

Micro grids based on renewable energy sources (RES) are receiving increased attention worldwide as they are required to support isolated and non-grid connected applications. To address the intermittent nature of largely unpredictable environmental phenomena, such systems transform RES into dependable energy flows by simultaneous utilization of different types of conversion equipment and storage media (e.g. PV panels, wind generators, chemical energy accumulators, hydrogen and so forth). The resulting infrastructures combine multiple subsystems of heterogeneous characteristics that need to operate efficiently while satisfying power demands based entirely on RES. The complex synergies and interactions that emerge among such components raise the need for efficient decision making as potential operating alternatives unravel simultaneously with an increasing number of diverse components that become involved in the operations of the system. This decision making is generally addressed through power management strategies (PMS) [7] which represent a complex sequence of actions offering efficient utilization of resources and equipment to meet specific targets. Such actions account for decisions regarding the appropriate instant to activate/deactivate different subsystems, the duration of operation of a particular subsystem, the amount or type of energy carrier to use (e.g., electricity, hydrogen in high or low pressure, water) and so forth. They also depend on several criteria involving the availability of power from RES with respect to the demand (lack or excess), the availability of energy carriers in storage and the previous state of operation of different sub-systems [11], to name but a few. Such diverse characteristics give rise to a large number of potential PMS. Efficient operation depends on the selection of the PMS that best satisfies the demands of the targeted application in view of RES variability, while maintaining a smooth system operation and

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* Corresponding author.
E-mail address: spapadopoulos@cperi.certh.gr (A.I. Papadopoulos).

http://dx.doi.org/10.1016/j.renene.2016.04.028
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Nomenclature

BAT	battery
BF	low pressure (buffer) storage tanks
C_l	capacity of accumulator *l*
CMP	compressor
DSL	diesel generator
EL	electrolyser
$F^j_{m\rightarrow n}(t)$	state of the flow *j* between the nodes *m* and *n*
FC	fuel cell
FT	long-term storage tank
H	overall time span
H2HP	hydrogen in high pressure
H2LP	hydrogen in low pressure
H2O	water
L	logical operator
LD	load
$Lo_i^{SOAcc^l}$	lower desired limit for accumulator *l*
MOES	maximum outsourced energy supply
N_c	number of steps in control horizon
N_p	number of steps in prediction horizon
OES	outsourced energy supply
P_i^j	amount of energy or mater per time unit of the flow *j* that may be produced or consumed by a converter *i*
PGCC	power grant composite curve
PMS	power management strategy
POW	electrical power
PV	photovoltaic panels
Q	set of all available PMS
RES	renewable energy sources
Rs	set of resources
$SOAcc^l$	state of accumulator *l*
T	end of time interval
t_{Lo}	instant when $SOAcc^l$ reaches the value of the limit *Lo*
$t_{\min}$	instant when $SOAcc^l$ reaches the minimum value of $SOAcc^{l,q_k}$ in interval *k*
t_0	beginning of time interval under study
$Up_i^{SOAcc^l}$	upper operating limit for accumulator *l*
WG	wind generator
WT	water tank

Greek symbols

ΔT	duration of time interval
$\varepsilon_i(t)$	binary variable that represents the state of converter *i*
$\rho_i^{SOAcc^l}$	binary variable associated with temporal conditions in accumulator *l*

Subscripts/superscripts

Acc	accumulator
Avl	available
Conv	converter
i	index of converter or accumulator
Gen	general
j	flow for a converter or accumulator
k	time interval
l	accumulators as part of the set of Resources
Mat	materials
max	maximum
min	minimum
n, m	resources (converters or accumulators) indicating the type of equipment employed to perform conversion and accumulation tasks $m, n \in Rs, m \neq n$
Nrg	energy

protecting the individual components from malfunctions due to over- or under-utilization. This is clearly a non-trivial task requiring the use of systematic approaches to identify targets of efficient operation which can be subsequently interpreted as appropriately fitted operating realizations.

The recently proposed power Pinch concepts (grand composite curves [1] and composite curves [27]) represent one such approach, allowing the investigation of complex energy systems based on the identification of insights pointing towards optimum decisions. Such methods have been inspired from the well-known heat Pinch [17] and evolved to sophisticated tools [25] that allow for the analysis of complex energy systems [26]. A major advantage of these methods is their implementation in the form of intuitive and easy to develop graphical interfaces (e.g., grand composite curves), whereas the underlying principles are often efficiently represented using rigorous mathematical tools (e.g., flexible process models combined with optimization algorithms). Regardless of the realization, Pinch methods allow the user to easily identify, review, and analyse potentially useful design and operating options [15]. A recent overview of Pinch analysis and mathematical programing for process integration is presented in Ref. [14].

Focusing on electrical systems, Pinch-based analysis methods utilize composite or grand composite curves similarly to the traditional heat Pinch; however, the associated sink and source streams are plotted in power versus time diagrams. In this context, a method proposing the identification of energy recovery targets using the grand composite curves (GCC) analysis approach was reported in Ref. [1] addressing the optimal sizing of power generation systems in the form of an optimization problem. Priya and Bandyopadhyay [24] also proposed an approach for power systems planning considering a Pinch-based analysis for emissions targeting. Work presented in Ref. [27] proposed the power Pinch analysis (PoPA) method to determine the minimum electricity targets for systems comprising hybrid renewable energy sources. The graphical power Pinch analysis method takes the form of numerical tools in Ref. [20] such as the power cascade analysis (PoCA) and storage cascade table (SCT) in order to facilitate the precise allocation of power and electricity targets in power generation systems. Work presented in Ref. [21] extends the numerical power Pinch method by additionally considering power losses during conversion, transferring, and storage including sizing considerations [28]. The method is applied in the optimization of a pumped hydro-storage system in Ref. [22] that is further extended in Ref. [23] to address the optimal sizing of hybrid power generation systems. Recent work presented in Ref. [29] proposed the outsourced and storage electricity curves (OSEC) to visualize the required minimum outsourced electricity and the current storage capacity at each time interval during startup and operation of hybrid power systems. Methods for load shifting that may lead to further reductions of the maximum storage capacity and the maximum power demand in hybrid systems are also proposed in Ref. [19] using power Pinch analysis, whereas combined load shifting and design is proposed in Ref. [8]. Work presented in Ref. [9] proposed the stand-alone hybrid system, power Pinch analysis method (SAHPPA), which is a graphical tool employing new ways of utilizing the demand and supply through composite curve methods. Recently, work presented in Ref. [10] adapted the power Pinch concept in the electricity system cascade analysis (ESCA) approach to optimise