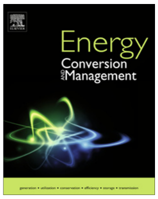
Energy Conversion and Management 91 (2015) 405–415

Contents lists available at ScienceDirect

Energy Conversion and Management

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



On battery-less autonomous polygeneration microgrids: Investigation of the combined hybrid capacitors/hydrogen alternative

George Kyriakarakos [a,*], Dimitrios D. Piromalis [b], Konstantinos G. Arvanitis [a], Anastasios I. Dounis [b], George Papadakis [a]

[a] Agricultural University of Athens, Department of Natural Resources and Agricultural Engineering, 75 IeraOdos Street, GR 11855 Athens, Greece
[b] Technological Education Institute of Piraeus, Department of Automation, 250, P. Ralli&Thivon Str., Egaleo 122 44, Greece

ARTICLE INFO

Article history:
Received 1 October 2014
Accepted 10 December 2014
Available online 31 December 2014

Keywords:
Hybrid capacitors
Polygeneration
Microgrid
Hydrogen

ABSTRACT

The autonomous polygeneration microgrid topology aims to cover holistically the needs in remote areas as far as electrical power, potable water through desalination, fuel for transportation in the form of hydrogen, heating and cooling are concerned. Deep discharge lead acid batteries are mostly used in such systems, associated with specific disadvantages, both technical and environmental. This paper investigated the possibility of replacing the battery bank from a polygeneration microgrid with a hybrid capacitor bank and more intensive utilization of a hydrogen subsystem. Initially commercial hybrid capacitors were tested under laboratory conditions and based on the respective results a case study was performed. The optimized combination of hybrid capacitors and higher hydrogen usage was then investigated through simulations and compared to a polygeneration microgrid featuring deep discharge lead acid batteries. From the results it was clear that it is technically possible to exchange the battery bank with a hybrid capacitor bank and higher hydrogen utilization. From the economic point of view, the current cost of the hybrid capacitors and the hydrogen components is high which leads to higher overall cost in comparison with deep discharge lead acid batteries. Taking into account, though, the decreasing cost prospects and trends of both the hybrid capacitors and the hydrogen components it is expected that this approach will become economically competitive in a few years.

1. Introduction

The autonomous polygeneration microgrid (APM) topology aims to holistically cover the needs of communities in remote areas [1]. The products of such polygeneration microgrids can include power, fuel for transportation, pumped and desalinated water, space heating and cooling, and refrigeration. This topology has been investigated and proved to be both technically feasible and economically viable [1]. Various approaches have been used for their energy management [2,3]. Finally an intelligent demand side energy management system has been created [4]. This topology has been also deployed in a real world microgrid in the Sahara desert in Egypt [5].

For an autonomous microgrid to operate, energy storage is essential. The most commonly used energy storage approach is battery banks, most often in the type of deep discharge lead acid batteries [6–9]. This type of batteries can reach efficiencies of about 85% in market available solutions, are simple to operate and are readily available [10]. On the other hand though, lead acid batteries present specific disadvantages. Practice has shown that they have low operational lifetimes [10], they cannot be fully discharged and are also delicate to handle after their operational lifetime has ended because they contain toxic elements [11]. Because of these specific disadvantages, efforts have been made in order to minimize lead acid battery usage in renewable energy systems in favor of hybridized storage approaches [12].

In an effort to minimize battery usage there have been many examples were ultracapacitors (double layer electrochemical capacitors) are introduced in a hybridized energy storage system both for mobile and stationary applications [12–15]. Ultracapacitors have specific advantages like round-trip efficiencies of about or above 95% and are optimally used in applications where higher power density is needed. On the other hand, though, they present

---

Abbreviations: APM, autonomous polygeneration microgrid; CF, cost function; FCM, Fuzzy Cognitive Map; FM, Flow Matrix or Incidence Matrix of the Petri Net; NPC, Net Present Cost; PSO, Particle Swarm Optimization; RO, reverse osmosis.

* Corresponding author. Tel.: +30 210 5294046; fax: +30 210 5294032.
E-mail address: gk@aua.gr (G. Kyriakarakos).

http://dx.doi.org/10.1016/j.enconman.2014.12.027
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

C_n	*n* concept of the Fuzzy Cognitive Map (–)
eta	efficiency of the hybrid capacitor (%)
H^{TANK}	volume of stored hydrogen in the hydrogen storage tank (N m^3 H$_2$)
I_c	capacitor current (A)
P_{ES}	energy storage penalty (€)
P_{H2}	hydrogen penalty (€)
P_{TANKS}	tanks penalty (€)
P_w	water penalty (€)
SOC	State of Charge (%)
SOCL	set point of battery SOC from which and below the fuel cell should be turned on (%)
SOCM	set point of battery SOC from which and above one or both the consumptions should be turned on (%)
V_c	capacitor voltage (V)
W_{ij}	weight of FCM concept (–)
W^{3D}	desalinated water needed in order to cover the needs for 3 days (m^3)
W^{TANK}	volume of stored desalinated water in the desalinated water tank (m^3)

low energy densities [16]. Another type of capacitors is the hybrid capacitors, which are manufactured with one electrode being a double layer material and the other electrode being of a pseudo-capacitance material [16], which in many cases is a lithium ion electrode [17,18]. Their performance lies between an ultracapacitor and a battery. These devices present higher energy densities in comparison with ultracapacitors and could look attractive in completely replacing batteries in specific applications like the autonomous polygeneration microgrid, since ultracapacitors can supply power bursts with ease, but cannot store much energy [19]. In a polygeneration microgrid the maximum total power can be observed for constant periods of time up to hours – there are no loads presenting power peaks for some seconds, if any load is activated, the needed power is going to be constant until they are deactivated. In literature hybrid capacitors are also named hybrid supercapacitors and hybrid ultracapacitors.

In the autonomous polygeneration microgrid topology a hydrogen subsystem is used both for the production of on-site fuel, and for medium to long term energy storage. Also long-term energy storage can take place in the form of desalinated water [1]. Various devices used in this topology are not "instant on". For example a reverse osmosis (RO) desalination unit starts producing water, after about a minute or in some cases even more until the needed pressure is reached in the system and acceptable salinity water is produced. Also it is not advisable to turn on and off an RO desalination unit in a matter of minutes. In the same manner hydrogen components like electrolyzers and fuel cells need a time period of some seconds up to minutes until they have completed their self-checks and are operating. This means than an energy buffer with adequate capacity to cover the various needs for at least some minutes is needed. Hybrid capacitors have the potential to fit into this scheme by substituting the battery bank and being able to cover the needed energy buffer for the time period needed until a consumer like the desalination unit or the electrolyzer is activated when it becomes full and the fuel cell can be activated in the case that the buffer is getting empty. Apart from this, the hybrid capacitors have much extended expected lifetime. Currently commercially available hybrid capacitors are advertised with lifetime from 10,000 charging/discharging cycles up to 50,000 cycles depending on the company. In comparison deep discharge batteries can only present usually about 1800 charging/discharging cycles at 50% depth of discharge before the capacity drops below 80% and the battery needs to be replaced [20]. It has to be noted that the lifetime of deep discharge batteries can considerably decrease when operating above 25 °C; at 45 °C the flooded electrolyte batteries can present severe levels of corrosion and the gelled electrolyte batteries can present considerable lifetime decrease [21]. On the other hand commercially available hybrid capacitors have temperature operating ranges of −40–60 °C allowing for better system integration in most remote areas around the world. Finally, the round trip efficiency of the hybrid capacitors in literature is found to exceed 98% in some cases [17], in comparison to efficiencies of about 86% for deep discharge batteries [20].

Another important aspect in order to accomplish a combined hybrid capacitors/hydrogen alternative is the needed energy management and control algorithms [22,23]. Without an intelligent energy management system the benefits of a hybrid energy storage system cannot be harvested. Different approaches have been proposed and investigated in literature for the management of hybrid energy storage systems [24–27]. The approaches that have already been developed for the energy management in a polygeneration microgrid can also be utilized [2,3], after their operational variables have been optimized for this configuration.

This paper presents the investigation of the possibility of exchanging the battery bank in the APM topology with the combination of a hybrid capacitor bank and higher utilization of the hydrogen subsystem. The investigation was planned to be realized in two steps. The first step would include the experimental testing of market available hybrid capacitors and the second step was planned to comprise of a techno-economic comparison of an APM based on deep discharge batteries and an APM based on the combined hybrid capacitors/hydrogen approach through a case study based on simulations.

Initially a market research took place and three manufacturers that offer hybrid capacitors were identified. Samples for each of these manufacturers were procured and laboratory testing took place in order to investigate their ability to operate as energy buffers in the polygeneration microgrid topology. Further experiments took place for the chosen hybrid capacitor in order to measure its real world energy storage capabilities and round-trip efficiency. Using these experimental results, a comparison between an optimized polygeneration microgrid utilizing the new approach and an optimized polygeneration microgrid utilizing deep discharge batteries took place through simulation.

2. Experimental investigation of the hybrid capacitors

2.1. Selection of hybrid capacitors for testing and choice of tests

A market investigation took place world-wide trying to identify commercial hybrid capacitors. The result of this investigation was three companies that all offer hybrid capacitors at different capacities. Samples of the model of the hybrid capacitor with the highest capacity offered by each manufacturer were gathered in the laboratory. Fig. 1 presents these hybrid ultracapacitors.

The technical characteristics of the considered capacitors are given in Table 1. The most notable differences between them are in their capacity, rated voltage, and physical dimensions. Companies A and C state that they use lithium ion material for the pseudo capacitance electrode.