Energy 116 (2016) 1051–1064

Contents lists available at ScienceDirect

Energy

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

Discrete cogeneration optimization with storage capacity decision support for dynamic hybrid solar combined heat and power systems in isolated rural villages

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ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form
9 August 2016
Accepted 8 October 2016

Keywords:
Numerical optimization
Solar cogeneration
Control automation
Intelligent energy
Smartgrid
Storage optimization

ABSTRACT

Pre-packaged cogeneration systems are popular as lead supply in distributed and isolated energy systems aimed at empowering remote off-grid communities and in supporting eco-villages in nature reserves. Energy cooperatives and independent power producers deploy cogeneration systems in community shared microgrid configurations as building blocks in smart localised multi-carrier energy grids. Small-scale renewable energy and distributed energy resources in the energy mix of multi-carrier combined heat and power microgrids call for the development of intelligent control automation solutions. This paper describes a multi-objective optimization solution where hierarchical digital microgrid control is integrated into solar powered micro-cogeneration. The control solution includes an integrated cost-competitive economic and environmental optimization algorithm customized around the needs of small off-grid isolated village settlements. A secondary stage optimization loop functions as a storage capacity decision support system, to alert the community when operating costs can be reduced through an investment into increased storage capacity for the village microgrid. This cost-aware control optimization algorithm is tested in a rural village microgrid by using parametric computer simulation models of a hybrid residential solar cogeneration system. Digital simulation experiments evaluate the operational plans and operational cost performances of energy management for different storage scenarios at an isolated remote rural location in Africa.

1. Introduction

Smart villages are seen as a concept to spread affordable renewable energy systems for the benefit of humanity. Therefore, the Smart Village Initiative and its partners around the world are calling for the development of new technologies, control processes and business models to bring clean technology and community microgrids to off-grid areas as an energy replacement for paraffin, fuel-wood and candles [1]. In smart villages, contributions from renewable energy has the potential to improve the living conditions in low income households, especially in developing countries [2]. Shared community solar systems are showing particularly good potential for fuel transitions towards improving livelihoods and sustainability in small rural villages [3]. This approach will be valuable with village power systems in developing economies where it can support sustainable housing in rural areas that operate independent from municipal utilities [4].

Hybrid concentrating solar cogeneration plants are of particular interest since they have the ability to achieve high levels of energy efficiency. Moreover, these cogeneration systems have the ability to produce both electricity and heat from the same device by way of recovering energy that would otherwise have gone to waste [5]. These attributes make cogeneration units well suited for district energy systems in remote off-grid areas, especially in isolated rural villages, nature reserves and eco-estates where sustainable off-grid living strives towards zero-carbon footprint electrification [6,7]. The increasing popularity of solar cogeneration in autonomous power solutions are therefore inspiring various developers to manufacture packaged cogeneration systems [8]. The design of packaged cogeneration systems place significant emphasis on functional controller design since an intelligent cost-aware controller will make the economics of cogeneration more

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http://dx.doi.org/10.1016/j.energy.2016.10.026
0360-5442/

attractive. Pragmatic low-complexity cost/fuel optimal control solutions will further increase the marketability of these systems as it would help create new pathways for early adopters in rural markets of developing countries. Control automation in smart villages and smart home energy management systems therefore focus on suitable system configurations and scheduling coordination strategies customized around society needs [9].

Functional control and scheduling optimization designs are generally developed as part of energy poverty reduction and grid modernization in microgrid platforms [1]. Smart energy system thinking in microgrids powered by renewable energy resources rely on smart controllers to help manage operational costs and assist in mitigating the impact of intermittent renewable energy resources [10]. In this regard, widespread communications infrastructure should provide access to advanced online optimization solutions that implement adaptive control strategies for cogeneration controllers in a cloud-computing environment [11]. An example is the self-optimizing Distributed Energy Resources Customer Adoption Model (DER-CAM) developed by Lawrence Berkeley National Labs. This centralised cloud-based microgrid optimizer ensures web-integrated economic and environmental impact optimization in automated buildings and microgrids [12]. Online teaching and learning based optimization methods have also been used in solving the optimal power flow control problem in multi-carrier energy systems remotely [13]. Advanced web-based control schemes have further been developed for time-of-use optimization of microgrid operational costs through market-based control signals based on economic auction and price-based scheduling schemes such as transactive control [14].

However, control optimization for packaged cogeneration systems that operate as autonomous stand-alone powerpacks in eco-villages or at isolated rural sites in Africa do not always have access to wideband wireless and cellular communications infrastructure. This leaves many of the existing online optimization solutions beyond communication reach of rural village control electronics. Isolated power systems further rely heavily on battery energy storage systems that operate in strict power budget constraints. This aspect requires special attention in the optimization of operational planning in support of smart microgrid distributed generation and energy distribution functions [15]. Village microgrid applications therefore require novel storage-aware and cost-aware control automation solutions with a closer integration between energy cogeneration control and microgrid distribution automation. This offers the opportunity to develop custom designed localised intelligent hierarchical control solutions that are able to integrate instantaneous primary device control with higher level smart microgrid control strategies [16]. It also calls for new research to deliver cost-aware autonomous smart microgrid automation solutions that would better serve these microgrids in off-grid applications where resources may be limited and where cellular, mobile or fixed-line communication infrastructure may be unreliable or completely absent. The inherent resilient nature of the proposed control and energy storage optimization strategy might also find application in dynamic-microgrid distributed control automation solutions. Control strategies in dynamic microgrids are presently in high demand in cooperative and utility grid-edge coastal areas, where microgrids are prone to isolation risks as a result of natural disasters and utility grid damage in super storms [17].

The contribution of this paper is to the field of knowledge centres around control optimization for packaged cogeneration systems through integration into autonomous multi-carrier smart microgrid solutions. This village energy management system design has the goal of powering Africa's economic growth with decentralized energy and distributed intelligence [18]. The solution is novel in that it proposes digital optimization algorithms for cost-aware and storage-aware dynamic control automation that ensures closer integration between renewable energy cogeneration control, microgrid energy storage control and microgrid energy distribution automation. The proposed hierarchical automation solution is able to better serve isolated microgrids in off-grid applications where storage resources, fuel resources and communication infrastructure are limited.

The focus of this paper is on integrated on-board control and optimization methods for local off-grid residential village supply generation to accomplish load demand balancing within certain cost and communication constraints. Section 2 introduces a custom designed packaged hybrid solar micro-cogeneration system prototype. The model based control design and optimization method for the integrated residential solar cogeneration and embedded microgrid system is detailed in Sections 3 and 4. The storage capacity optimization support procedure is described in Section 5. Section 6 evaluates the control solution in a scenario-based case study simulation approach, with conclusions in Section 7. Experimental results demonstrate control optimization and cost outcomes under different microgrid storage capacity scenarios.

2. Solar cogeneration control application

Governments in developing countries are interested in rural energization solutions that offer multi-stream energy with high microgrid viability and high replication potential [19]. The technical choice for a community based solar cogeneration system was inspired by parabolic dish micro-cogeneration technology such as the Innova Trinum/Turbocaldo system and the Qnergy Infinia system [20]·[21]. These micro-cogeneration power plants, in addition to electricity generation, offer hot water solutions suitable for renewable energy programs meant to support sustainable village housing in isolated rural areas. Micro-cogeneration based village power systems may also help to overcome load congestion in off-grid rural village settlements where PV microgrids suffer blackouts when dealing with heavy loads such as heating water [19].

The prototype for the solar micro-cogeneration system includes a dynamic mechatronic platform and parabolic dish combination, configured as a stand-alone packaged cogeneration unit (rated capacity $P_t = 3$ kWh, $P_e = 1$ kWh). The system was designed to be installed by unskilled support personnel and acts as a plug-and-play village power and hot water generation system for remote rural areas. The benefits of the technical choice for this particular micro-cogeneration configuration have been demonstrated in computer simulation models for various rural village locations in Africa [22]. An optimal low-complexity control and energy management method is now sought for this hybrid solar micro-cogeneration system, to make it more suitable for the electrification of rural areas in developing countries [4].

In this design, the solar receiver feeds a combined heat and power type Stirling engine manufactured by Migrogen Engine Corporation [23]. This unit can operate in both a solar-operation-mode and a gas-hybrid-mode, which makes it suitable for domestic micro-cogeneration in community solar projects. To accommodate the gas-hybrid-mode, the system includes an external gas-fired generation unit that allows the use of burner flames using liquefied petroleum gas (LPG) as fuel. When used in the gas-hybrid-mode, the unit uses a fixed thermal energy source to generate electricity at 1 kW and thermal energy at 3 kW, at the prevailing gas $ costs [23]. These features make this system especially suitable for small-scale cogeneration applications that require electric power of capacities around 1 kW and thermal energy of around 3 kW (residential hot water supply, 1500 l storage in this case).