Sustainable Energy, Grids and Networks 5 (2016) 114–124

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

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

A controller for single-phase parallel inverters in a variable-head pico-hydropower off-grid network

S.J. Williamson [a,*], A. Griffo [b], B.H. Stark [a], J.D. Booker [a]

[a] *Faculty of Engineering, University of Bristol, Bristol, BS8 1TR, UK*

[b] *Department of Electrical & Electronic Engineering, University of Sheffield, Sheffield, S1 3JD, UK*

ARTICLE INFO

Article history:
Received 9 March 2015
Received in revised form
1 October 2015
Accepted 21 November 2015
Available online 28 November 2015

Keywords:
Parallel inverter control
Pico hydropower
Single-phase
Droop control
Rural electrification

ABSTRACT

The majority of off-grid pico-hydropower systems use a single turbine and generator, connected directly to an AC network resulting in clusters of isolated, power-limited, single failure-prone networks. The use of inverters has been previously proposed in order to decouple the turbine's rotational speed from the network frequency in these remote microgrids. This facilitates the use of multiple generators and the creation of expandable, reliable networks with redundancy. This paper presents an inverter controller for this situation, and addresses a combination of challenges that is specific to expandable pico-hydropower networks in geographically dispersed remote communities. Multiple variable-head turbines are connected to a network, whose individual local hydraulic heads vary due to flow changes over the seasons, and the network has no single generator that dominates and no master controller, but instead identical independent controllers that do not communicate. The controller presented here uses an output voltage and frequency droop controller, with inner synchronous reference frame control loops for the fundamental voltage and current. The control coefficients are automatically adjusted to the available local hydraulic head. Simulation and experimental results show that the power is shared amongst generators, proportionally to the locally available power, in steady and dynamic situations. Harmonic compensation loops are proposed: these reduce the output total harmonic distortion (THD) of a single inverter from 9.53% to 1.45% for a non-linear load. Geographically distributed operation in resistive networks is investigated, and the results show that the controller achieves plug-and-play capability for remote off-grid networks with multiple and different pico-hydropower generators.

1. Introduction

Pico hydropower has been used for many decades as a method of delivering rural electrification. It has been shown to be a cost effective method of off-grid electricity generation, especially in hilly and mountainous regions [1]. A standard pico-hydro system is a stand-alone unit, comprising a turbine driving a generator, a shunt controller, known as an electronic load controller (ELC) regulating either the voltage or frequency output, and a low-voltage distribution system with consumer loads, such as lighting, mobile phone chargers and radios [2,3]. The turbine is designed to operate at a constant speed to generate the grid frequency; the ELC maintaining a constant load on generator. Fluctuations in the environmental conditions, such as a drop in flow rate or head, can cause the system to shut down. Over time, consumer demand on the system increases as they purchase more electrical equipment, up to the point where the increased demand causes severe voltage drop in peak load times and often the circuit breaker at the generator to trip. Therefore, there is a demand for methods to connect multiple hydropower generators and expand the off-grid network as more capital becomes available. A straightforward method is to connect micro-hydro units through synchronizer units directly to the grid. This is implemented in a recent 11 kV off-grid network containing six micro-hydro units, constructed in Western Nepal by the Alternative Energy Promotion Centre [4]. Due to the direct connection of induction generators, power quality and sharing are not controlled, and changes in head strongly affect power sharing, risking a loss of synchronization. A potential solution is to use a power electronic interface per turbine. For example, a rectifier is followed by a DC–DC converter that feeds the DC link of a single-phase inverter. This allows the turbine to operate at its optimal head- and flow-dependent frequency, with grid voltage and power flow regulation performed using techniques similar to those reported for

---

* Corresponding author. Tel.: +44 117 331 5464.
E-mail address: sam.williamson@bristol.ac.uk (S.J. Williamson).

http://dx.doi.org/10.1016/j.segan.2015.11.006
2352-4677/

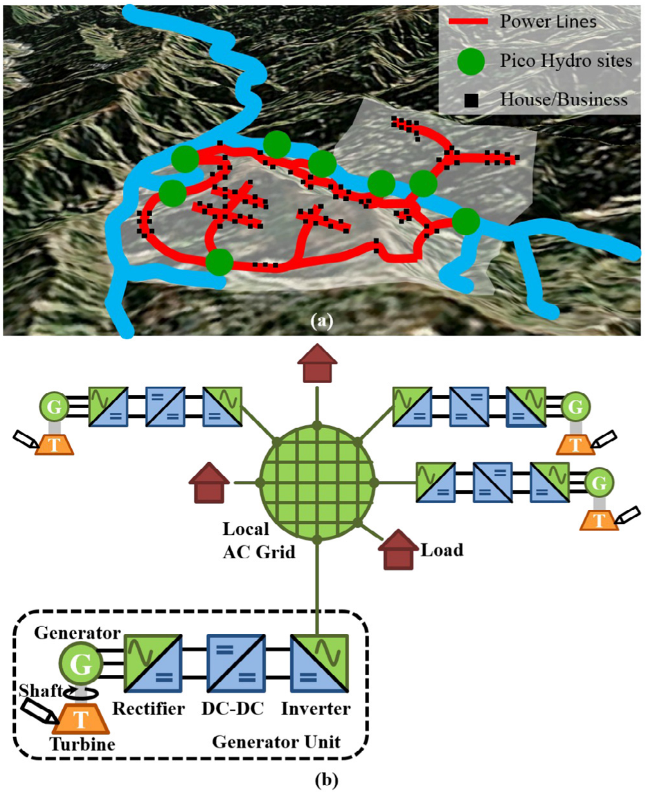

Fig. 1. (a) Example variable head pico hydropower off-grid network implementation. (b) Schematic diagram of the off-grid network and energy conversion system.

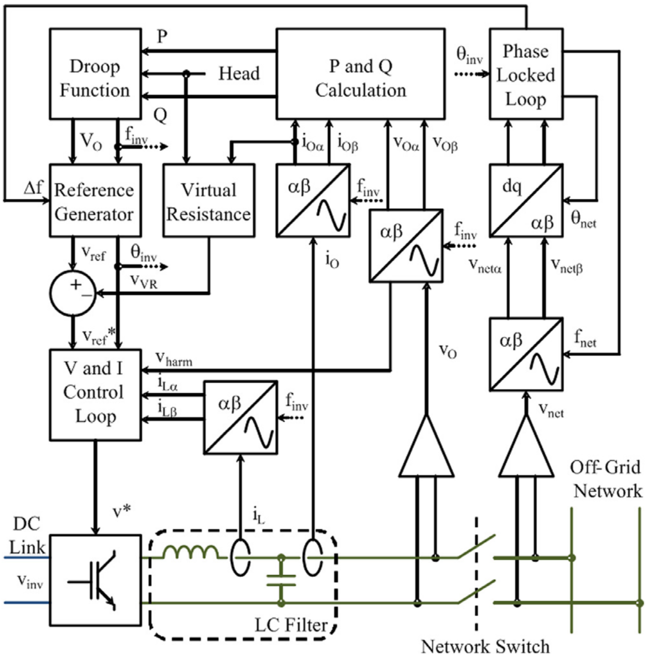

Fig. 2. Control system structure.

grid-connected and off-grid microgrids. An example system implementation in a rural off-grid network is shown in Fig. 1(a), with the schematic system diagram shown in Fig. 1(b).

This paper proposes the controller for the single-phase inverter interface. The main aim is to enable a pico-hydro network with an arbitrary number of turbines, each with an identical controller with no master controller or communication between controllers. The main differentiators to the literature are that the controller adapts to seasonally and spatially varying hydraulic conditions, and it does not require the network to be grid-connected or have a generator that dominates supply. This controller provides an essential component for a pico-hydro network that can be interconnected and expanded to increase capacity and redundancy.

Parallel inverter control has 5 basic requirements [5]: voltage and frequency regulation; power sharing between units; output power quality; synchronization; and fault and islanding protection. The first 4 requirements are examined in this paper. Controlling parallel inverter interfaces without communication requires the closed-loop regulation of voltage and frequency using local measurement of voltage and current. This is normally achieved through droop control [6–12], emulating the response of a synchronous generator connected to a grid. There are alternative methods proposed in the literature, such as augmenting the control with an average power control technique [13] or controlling the inverter to behave as a synchronous machine [14,15]. A secondary control loop can also be used to restore the network voltage or frequency to its nominal levels [16].

Utilizing droop control requires a trade-off between the voltage and frequency regulation and the power sharing capability of the system [7]. In the approach reported on here, loose regulation is required to achieve power sharing between geographically-dispersed generators on a low-voltage (resistive) network. Power sharing between units with different input power can be improved by adjusting the droop coefficients [8] and virtual impedance [9] with the input power. The output power quality can be controlled using a single virtual impedance [16] or set of band-pass filters in the virtual output impedance [7] or through a series of harmonic droop controllers [17]. Synchronization between parallel inverters has been achieved through using a large variable physical [10] or virtual [7] impedance or a phase-locked-loop [18]. There are many examples in the literature of parallel inverter control schemes, such as those in the references above, but none that have been interfaced with a variable-input-power pico-hydro system.

The paper is structured as follows: Section 2 develops the control system, derives the inner current, voltage and harmonic controller transfer functions, and shows respective bode plots. The section also addresses: automated adjustment of droop coefficients and virtual output impedance as a function of the available turbine power; power sharing proportional to each unit's available power; plug-and-play capabilities enabling interconnection of additional units, each capable of working in load sharing or grid forming mode; and compensation of harmonic distortion caused by nonlinear loads. Section 3 demonstrates the controller performance by simulation. Section 4 describes the experimental test facility, and finally Section 5 presents scale experimental results for voltage quality and power sharing ratios with unequal transmission line length and source power.

2. Control system design

The design of the control system is discussed in the following section, with the 4 functions of the parallel inverter controller discussed in detail. An overview of the control system is shown in Fig. 2.

2.1. Voltage and frequency regulation via droop control

Droop control adjusts the output voltage and frequency of an inverter in order to establish a desired relationship between supplied active and reactive power and measured local voltage and frequency. The relationships depend on the line and inverter output impedances [10]. Typically, transmission lines are considered to be inductive, e.g. in [6], however the network considered here