Available online at www.sciencedirect.com

SciVerse ScienceDirect

Solar Energy 86 (2012) 867–876

SOLAR ENERGY

www.elsevier.com/locate/solener

Optimization of a linear actuator for use in a solar powered water pump

N.S. Wade [a], T.D. Short [b,*]

[a] School of Engineering and Computing Sciences, Durham University, South Road, Durham DH1 3LE, UK
[b] School of Engineering, University of Liverpool, Brownlow Hill, Liverpool L69 3GH, UK

Received 19 August 2011; accepted 18 December 2011
Available online 16 January 2012

Communicated by: Associate Editor Yogi Goswami

Abstract

A need has been identified for a simply constructed, photovoltaic-powered, water pump to improve the water supply in rural areas of developing countries. The use of a linear actuator to provide the lifting force was investigated as part of a way to meet this need. Substantial challenge was presented in optimizing the system to suit the power characteristic of a photovoltaic panel and the hydraulic requirements of the application. An iterative process combining finite element analysis and analytic expressions was devised to allow comparisons to be made between many geometrical and electrical configurations of the linear actuator. Model predictions achieved close comparison with measured results from an existing water pump. The modelling technique was used to generate an actuator design that will utilize the available power more efficiently in a next generation pumping device.

Keywords: Linear motors; Optimization methods; Actuators; Solar powered water pumps; Finite element methods; Photovoltaic system modelling

1. Introduction

This paper reports on a project looking to design a mechanically and electrically simple, solar (photovoltaic) powered water pump (PVP) that is well suited to use in rural areas of developing countries. In this context, a number of design constraints are present due to both the physical and the socio-economic restrictions of the application. Unlike much other research, therefore, the aim was not to consider a piece of technology in isolation but to design the entire wire-to-water integrated system.

In this work a linear actuator has been selected as a possible mode of providing the lifting force for the pump. The behaviour of the actuator is defined by several parameters, including force, stroke, inductance and resistance. Each of these parameters can be adjusted in isolation to meet a desired specification. However, when the actuator is placed within a system—particularly one that includes photovoltaics and developing countries—the overall performance is determined by a complex interplay between all of the defining parameters. Determining the work done by and efficiency of the complete pumping system is of greatest interest and therefore requires a global optimization of all the parameters, not simply optimization of the individual components.

Developing a new device based around a bespoke electrical machine will always require a design and optimization phase, which may be extensive (Isfahani et al., 2008; Lu et al., 2008). An approach has been found which provides the means to investigate the parameter space bounded by the physical constraints placed on the actuator. Four steps are followed in an iterative process: finite element analysis, analytical model, generation of metrics, evaluation of metrics to feed back into the next iteration. The process is automatic up to the evaluation of metrics, where judgement is required to deal with the potentially unstable results.

* Corresponding author. Tel.: +44 151 794 4821.
E-mail addresses: n.s.wade@durham.ac.uk (N.S. Wade), Timothy.Short@liverpool.ac.uk (T.D. Short).

0038-092X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2011.12.016

This paper therefore presents both the development of a new solar powered water pump and the optimization design process used in the creation of the pump. Section 2 explains the background to the development of this solar water pump. Section 3 outlines the approach that has been taken to engineering design and the characteristics of the resulting device. The modelling techniques that were used to optimize the design are described in Section 4. Section 5 shows experimental results and provides a comparison with the model results. Finally, in Sections 6 and 7 the results are discussed and conclusions are drawn.

2. Application context

Water lifting devices—and PVPs in particular—have been shown to be unreliable in the context of developing countries, due to shortcomings in repair and maintenance procedures (Harvey and Reed, 2006; Kaunmuang et al., 2001; Anderson, 2000). Often, pumps are provided by donors without sufficient thought to the long term sustainability of the system. On the other hand, PVPs have been shown to offer promise in the developing world (Posorski, 1996; Protogeropoulos and Pearce, 2000). It has been proposed that a linear actuator provides the means to construct a simple device that has more in common with a hand-pump than a sophisticated electro-mechanical device (Short and Thompson, 2003). Such a simplification brings the possibility of repair and even manufacture into the reach of workshops in developing countries.

Whilst linear motors have been used and proposed in a variety of applications, such as robotics and energy generation, their use has not spread to borehole water pumps, saving the surface-mounted unit proposed by Perris and Salameh (1995) and further developed by Andrada and Castro (2007). The geometrical constraints on down-borehole use provide significant challenges to pumping systems, similar to (although perhaps not as extreme as), those of Finocchiaro et al.'s artificial heart (2008). Generation of electricity from solar photovoltaic (PV) panels provides the significant benefits of avoiding the need to supply fuel and minimizing operation and maintenance overheads. The difficulty with ownership of a PV panel is the provision of financial services to enable the initial capital investment. These upfront costs are frequently met by development agencies, but there is potential for the private sector to operate a business model which can provide investment.

Solar panels present direct current (DC) at their output terminals with a voltage–current profile dependent on the intensity of solar insolation and temperature. In order to maximize the utilization of energy from a PV panel, it is common practise to use a power electronics stage to match the panel characteristics to the load characteristics. These can be non-trivial circuits that are not straightforward to understand. Furthermore, the electronics are susceptible to damage from either operation beyond the safe stress levels of the components or physical processes such as insect nest building (Short and Oldach, 2003). It is preferable to minimize or eliminate the need for electronics.

Initial experience has shown that a device with a peak power consumption of the order of 100 W is a suitable target. This can be supplied from a single solar panel. Because the pump is based around a piston, the pressure and flow characteristics can be adjusted by changing the diameter of the piston used.

3. Design approach

Since the profile of a borehole is circular, an overall cylindrical shape makes best use of the available space. The diameter of the pump casing is fundamentally constrained by the diameter of the borehole under consideration. So as to fit small boreholes, the maximum allowable casing diameter was set at 100 mm; this sets the most challenging condition, which if able to be relaxed can only lead to improvement.

Materials have been chosen during development to make prototyping straight-forward, but at the same time care has been taken to select materials which are available or can be readily substituted in the end-user countries. The techniques used for manufacturing pump components have been limited to those that can be catered for in any reasonably well equipped mechanical workshop. The use of a lathe and milling machine has been permitted.

Creating a device in which the purpose of each part of the mechanism is readily apparent—in line with Pahl and Beitz's design principle "Principle of the division of task" (Pahl et al., 2007)—is considered to be important to maximize the success of local maintenance. To achieve this there is an implicit need for the pump to be of simple construction.

3.1. Actuator

The use of permanent magnets has been ruled out on the basis of the difficulty of obtaining and working with them. Magnetic flux must therefore be generated by current flowing through turns of wire. The options for arrangement of the magnetic surfaces to produce force are fairly constrained by the requirements for an overall cylindrical shape and DC operation. The choice is between the force/position characteristics of surfaces that are permitted to move normally or tangentially. Actuators operating in the normal configuration exhibit a high force at small openings which rapidly falls away with increasing opening. Tangential forces are much lower than the peak forces in normal configuration but provide a much more uniform magnitude across a wide range of openings. These alternative configurations are presented graphically in Fig. 1.

A pumping device that uses a very simple configuration, purely using the normal force between surfaces, has already been built and tested (Wade and Short, 2006, 2007). Although many of the issues identified for development of a pump in the application context have been addressed in the design of this device, there was thought to be considerable margin for improving the utilization of the available