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Integrated solar pump design incorporating a brushless DC motor for use in a solar heating system

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ABSTRACT

Most solar thermal hot water heating systems utilize a pump for circulation of the working fluid. An elegant approach to powering the pump is via solar energy. A "solar pump" employs a photovoltaic module, electric motor, and pump to collect and convert solar energy to circulate the working fluid. This article presents an experimental investigation of a new integrated solar pump design that employs the stator of a brushless DC motor and a magnetically coupled pump that has no dynamic seal. This design significantly reduces total volume and mass, and eliminates redundant components.

The integrated design meets a hydraulic load of 1.7 bar and 1.4 litres per minute, equal to 4.0 watts, at a rotational speed of 500 revolutions per minute. The brushless DC motor and positive displacement pump achieve efficiencies of 62% and 52%, respectively, resulting in an electric to hydraulic efficiency of 32%. Thus, a readily available photovoltaic module rated 15 watts output is suitable to power the system.

A variety of design variations were tested to determine the impact of the armature winding, pump size, pulse width modulation frequency, seal can material, etcetera. The physical and magnetic design was found to dominate efficiency. The efficiency characteristics of a photovoltaic module are such that oversizing is wasteful.

The integrated design presents a robust, efficient package for use as a solar pump. Although focus has been placed on application to a solar thermal collector system, variations of the design are suitable for a wide variety of applications such as remote location water pumping.

1. Introduction

The use of a photovoltaic (PV) module, electric motor, and pump constitute a zero-emission and effective method to cause fluid flow for pumping purposes. The collected solar radiation undergoes conversion to electricity, mechanical (rotating shaft), and finally hydraulic form. Such a "solar pump" may suit a variety of purposes, but is often limited due to the power density of solar radiation and the cost of the PV module. Two common applications of solar pumps are remote water pumping and the circulation of fluid through solar thermal (ST) collectors. The former application usually derives from the lack of access to alternatives (economical or technical) and may be used to supply water for both personal consumption and irrigation purposes [1–4]. The latter application results in an autonomous thermal energy collection system entirely supported by solar energy.

ST systems are an alternative to conventional heating devices that are powered by fossil fuel energy sources, and may be used to incorporate renewable energy into buildings for purposes such as space or hot water heating. Most ST systems located in moderate to cold climates rely on collectors that are separate from the storage or the direct end-use, thereby eliminating the night-time heat loss associated with integrated collector-storage units [5]. This necessitates a linkage, usually accomplished via a working fluid. Solar pumping is particularly well suited for circulating the fluid through an ST system because the active periods of the collector and solar pump are identical. Fig. 1 shows an example of such a system involving a solar pump.

Solar pumps employ a PV module and any of a variety of motor and pump component combinations. Motors are typically brushed direct-current (DC) or single-phase alternating current (AC) and pumps are typically positive displacement (PD) or centrifugal. Each combination has specific advantages and disadvantages related to the characteristics of the components and the load requirements (e.g. high pressure and low flow rate, or vice versa). It is evident from the literature that there is a range of electric motor types for solar pumping: AC induction, switched reluctance, separately excited and brushed DC, and brushless DC (BLDC) [6–13]. The use of a brushed DC motor with permanent magnets (PMs) is common in solar pump circulator applications due to its low cost and the ability

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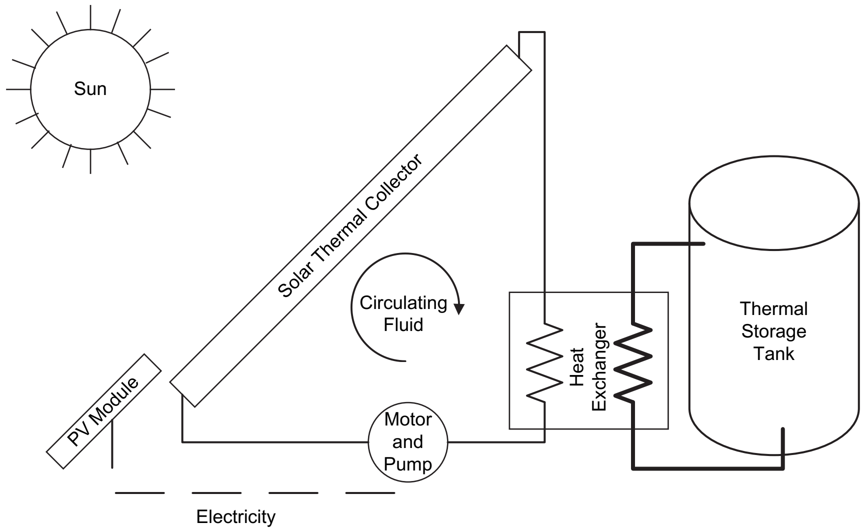

Fig. 1. Typical solar thermal collector system.

to be powered directly by the PV module. However, the brushed DC motor suffers from increased maintenance issues due to wear items such as the commutator and brushes. The BLDC motor type has seen recent interest due to a continued reduction in power electronics and controller costs.

Ongoing development in ST systems is focused on increased system efficiency and reliability, and decreased cost. This article presents a new design and experimental test results of a PV powered, integrated BLDC motor and pump, that is intended to increase efficiency and reliability, and decrease cost primarily through the reduction of components.

2. Solar pump design evolution

The following gives a general description of two solar pump generations which have been researched and developed at Dalhousie University over the last 25 years. These solar pump designs are intended for household ST systems and rely on brushed DC motors and PD pumps.

2.1. A first generation solar pump design

A first generation solar pump design of the 1980's used a brushed DC motor directly connected to the input shaft of a PD pump. This simple design had two significant drawbacks: i) a mismatch of motor voltage requirements and PV module operating voltage that led to low efficiency [14], and ii) the dynamic pump seal surrounding the input shaft is prone to leakage.

Silicon PV cells have a voltage-current relationship that results in an operating point which produces maximum power. This point is termed the maximum power point (MPP) and is achieved by operating the cell at the MPP voltage. By examining any typical silicon PV cell manufacturer's datasheet (e.g. [15]) it may be determined that the MPP voltage strongly depends on cell temperature and weakly depends on the level of solar insolation. A fixed voltage of approximately 0.42 V/cell is sufficient to operate the PV cell efficiently (i.e. near the MPP) in temperate climates. In contrast, the terminal voltage of a motor is a function of torque and speed, which varies significantly as a function of available power from the PV module. If the PV module is connected directly to the motor terminals, it is typically operating at a position different than the MPP, resulting in less than maximum efficiency.

In the first generation solar pump design the rotational mechanical power is transmitted from the motor to the pump via a shaft. The shaft passes through and rotates within a dynamic seal that prevents the working fluid from leaking. As a consequence of wear at the dynamic interface of the seal and shaft, the dynamic seal is prone to leakage. Dynamic seal wear is a function of many issues including: damage due to edges or assembly, deposits, debris, grooving, and temperature [16]. Such leakage may be rectified by replacing the seal, although this usually involves the separation of the motor and pump, and the removal of the pump from the fluid loop.

2.2. A second generation solar pump design

To mitigate both the voltage and leakage issues, components were added at the expense of size and cost to the second generation solar pump. A simple step down DC/DC converter was added between the PV module and the motor terminals. The DC/DC converter transforms the high voltage and low current electricity of the PV module, to low voltage and high current electricity for the motor. The control algorithm of the DC/DC converter seeks to increase the PV module current while maintaining the voltage near the MPP voltage, allowing the PV module to operate near the MPP.

The dynamic seal may be eliminated by a magnetic coupling as shown in Fig. 2. Brennen provides a succinct overview of magnetic drive pump technology, materials, and considerations [17]. An interior magnet is placed on the input shaft of the pump. A seal can is placed over the interior magnet and is sealed to the pump housing using a static O-ring. The dynamic seal is no longer required and the interior magnet functions while surrounded by the working fluid. An exterior magnet is mounted to the motor shaft and positioned to surround the seal can, resulting in a magnetic, non-contact coupling that is capable of transmitting rotational mechanical power. The replacement of the dynamic seal with a static seal dramatically reduces the potential of a working fluid leak.

3. New design

Taking advantage of the MPP and magnetic coupling techniques employed in the second generation solar pump, a new design has been developed that reduces volume and mass, and increases integration and utilization of components. Taking advantage of advances in power electronics and microcontrollers, a BLDC stator