

Solar photovoltaic water pumping system using a new linear actuator

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Abstract. In this paper a photovoltaic solar pumping system using a new linear actuator is presented. This linear actuator is a double-sided flat two-phase variable-reluctance linear stepper motor that moves a piston-type water pump with the help of a rope, a pulley and a counterweight. The entire actuator pump ensemble is controlled by a simple electronic unit that manages the electric power generated by a photovoltaic array. The proposed system is suitable for rural communities in developing countries because it is reliable, affordable and easy to maintain.

Keywords

Solar photovoltaic energy, water pumps, electric linear actuator, stepper motor, power converter.

1. Introduction

Salt water accounts for 97.5% of all of the Earth's water. Of the remaining 2.5% of fresh water, approximately 70% is frozen in the polar ice caps and the other 30% is mostly soil moisture or lies in underground aquifers. In all, less than 1% of the world's fresh water is readily accessible for direct use.

While water is readily available in developed countries, in developing countries more than 1.2 billion people do not have access to a safe and adequate water supply. One billion people make a three-hour journey just to collect water and 14,000 people die every day from water-related illnesses. As the world's population grows, pressure on the available water supply increases.

Groundwater is an important source of water and the dominant source for domestic supply in many areas, especially in dry areas where surface water is scarce and seasonal.

Water pumping has a long history and many methods have been developed. These have utilized a variety of

power sources, including human, animal, wind, hydro and solar power, and fossil fuels.

Solar photovoltaic (PV) water pumping has been recognized as suitable for grid-isolated rural locations in poor countries where there are high levels of solar radiation. Solar photovoltaic water pumping systems can provide drinking water without the need for any kind of fuel or the extensive maintenance required by diesel pumps. They allow people to devote more time to productive activities and thus improve life style, health and economic conditions. Additionally, they create new jobs in remote rural areas of the country. The drudgery of bringing water from afar can be reduced significantly. Although the cost of solar photovoltaic water pumping systems is initially high, they demand virtually no maintenance, require no fuel and thus save on foreign exchange. They are easy to install and operate, highly reliable, durable and modular, which enables future expansion. They can be installed at the site of use, rendering long pipelines unnecessary [1]-[3].

Solar photovoltaic water pumping systems are very simple. They are composed of a photovoltaic solar array, a controller, a motor, a pump and a reservoir. The presence of a controller depends on the type of motor pump combination and whether or not maximum power point tracking is required. The use of a reservoir precludes the need for a battery. The installations must be safe in two respects: they must be as immune as possible to external events, such as lightning strikes, and hazard-free.

These systems may be configured in different ways, depending on the type of pump employed. The most common types of pumps are submerged centrifugal motor pumps, submerged pumps with surface motors, reciprocating positive-displacement pumps, floating motor pumps and surface suction motor pumps.

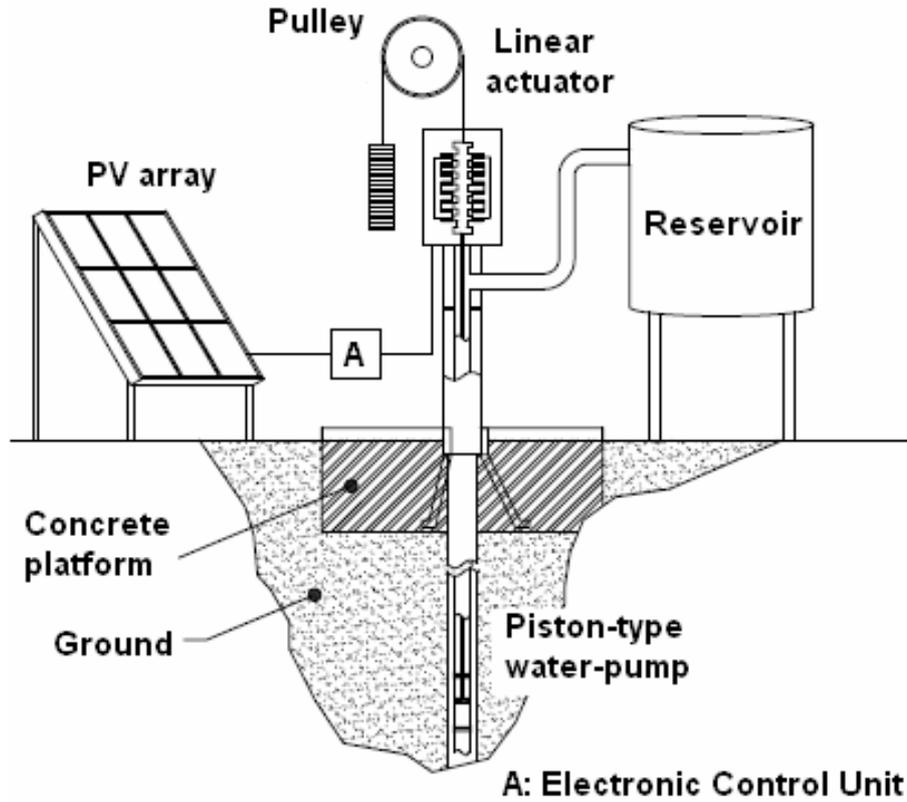


Fig. 1. Proposed solar PV water pumping system

In developed countries, submerged centrifugal motor pumps, in which an induction three-phase squirrel cage motor is controlled by an inverter, are most common. However, solar photovoltaic pumping systems operating in rural communities in developing countries must be cheap, reliable and maintainable by persons with limited formal education. Reductions in cost and gains in reliability can be obtained by reducing the complexity of the controller and motor pump.

In accordance with these arguments, in this paper we present a solar PV water pumping system using a new linear actuator. A two-phase variable-reluctance linear stepper motor [6] moves a piston-type water pump and is controlled by a simple electronic unit. The proposed system is suitable for rural communities in developing countries, because it is reliable, affordable and easy to maintain. To date, few authors have discussed systems of this type, although a design study of a fully submerged linear electromagnetic actuator has been proposed by T.D. Short and M.A. Mueller [4], whilst C. Perris and Z. Salameh [5] have presented a proposal that involved replacing a rotary motor and gearbox with a linear DC motor system controlled by a four-quadrant chopper, positioned at ground level and coupled to the pump via a long connecting rod.

2. Description of the proposed solar PV water pumping system

A solar PV water pumping system suitable for rural communities in developing countries is designed. The proposed system consists of a piston-type water pump, a two-phase variable-reluctance linear stepper motor [6] mounted onto the piston rod that drives the pump with the help of a rope, a pulley and a counterweight. The actuator pump ensemble is controlled by a simple electronic unit that manages the electric power generated by a photovoltaic array. The system is completed by a water reservoir, as shown in Figure 1.

A single-acting reciprocating positive-displacement piston or plunger pump was chosen, because this type of pump is highly suited to high head and low flow applications. Piston pumps comprise a cylinder with a reciprocating plunger inside it. The piston forces water from the inlet side to the outlet side of the pump. In a single-acting pump the working cycle is completed with two strokes of the piston: a downward stroke and an upward stroke. The force required to pump the water can be estimated by

$$F_H = d g \gamma A H_{ef} \text{ (N)} \quad (1)$$

where d is the density of water, g is the acceleration of gravity, γ is the leakage coefficient (≈ 0.9), A is the piston surface and H_{ef} is the effective height.

The linear actuator allows the piston to move between its extreme positions at constant speed. A variable-reluctance linear stepper motor is proposed because it can operate as an open loop system, it is mechanically robust, its control is straightforward and it can be manufactured in developing countries. The double-sided flat two-phase variable-reluctance linear stepper motor (Figure 2) was selected because of its simplicity and because, ideally, no net normal force is exerted on the mover.

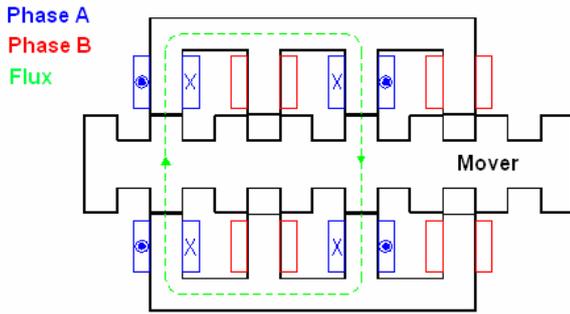


Fig. 2. Longitudinal cross-section of the linear actuator

Because of the salient nature of both the stator and mover poles, the inductance of each phase varies with the mover's position. The operating principle of the linear actuator is based on the minimum reluctance rule. Thus the thrust, if saturation is disregarded, takes the form:

$$F_{ac} = \frac{1}{2} i^2 \frac{dL}{dx} \text{ (N)} \quad (2)$$

The motor has four air gaps per phase. The stator pole width and the mover pole width are equal and are half the stator slot width. Therefore, its average thrust is determined by the following equation:

$$F_{ac} = 4(B_{\delta} \Delta) K_V \left(1 - \frac{\lambda_{na}}{\lambda_a} \right) b_s^2 w \text{ (N)} \quad (3)$$

where B_{δ} is the flux density in the air gap, Δ is the current density, K_V is the slot fill factor, λ_{na} is the permeance per unit of length in the unaligned position, λ_a is the permeance per unit of length in the aligned position, b_s is the stator pole width and w is the normal length.

The displacement of the mover equals the downward and upward strokes of the piston; therefore, a power converter must sequentially energize the phase windings of the motor and reverse the sequence each time the end positions of the mover are reached. Because simplicity was one of our main goals, we chose a unipolar power converter with only one switch per phase and a freewheeling diode (Figure 3).

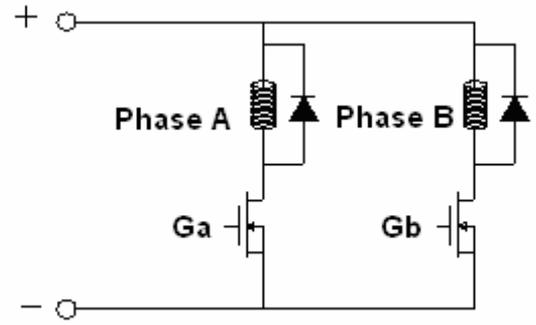


Fig. 3. Unipolar power converter

Each phase must be turned on at around the point at which its own inductance increases, $\frac{dL}{dx} > 0$. Thus, a device such as a logic sequencer that is able to consistently send the right commutation signals to the gates of the power switches is required (Figure 4).

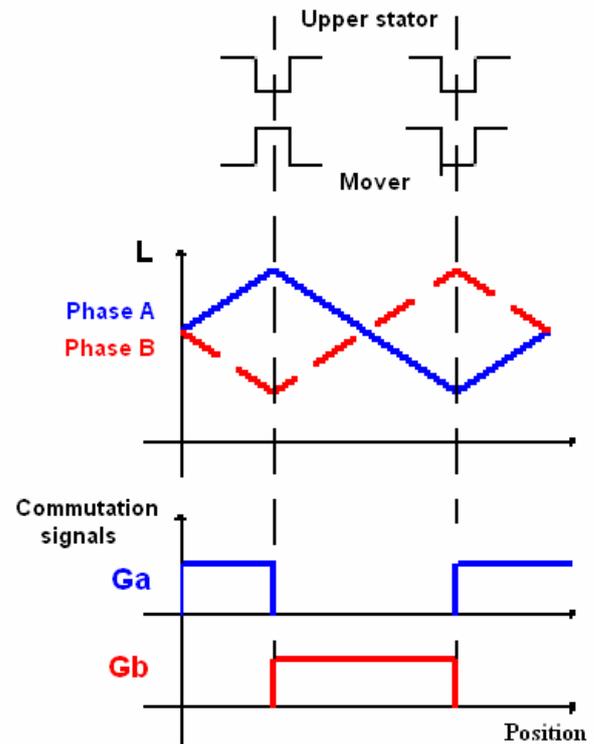


Fig. 4. Variation of phase inductances and commutation signals

The linear actuator is coupled with the pump rod and is linked to a pulley and a counterweight. This solution reduces the size and cost of the linear actuator and the power required from the photovoltaic array. The counterweight equalizes load requirements during a complete cycle, i.e. the force generated by the linear actuator when it is moving upwards must be almost equal

to the force generated when it is moving downwards. Therefore, the final thrust of the actuator is given by

$$F_{ac} = \frac{1}{2} F_H \text{ (N)} \quad (4)$$

and the mass of the counterweight is

$$M_{cb} = \frac{1}{g} \left(\frac{F_H}{2} + F_r \right) \text{ (kg)}, \quad (5)$$

F_r being the weight of the rod, piston and mover.

The PV array is made using commercial PV panels. The configuration and disposition of the PV array depends on its location and on the pumping specifications. Given that the PV array exhibits nonlinear current-voltage characteristics and its maximum power point varies with solar irradiation and temperature, it is usually necessary to employ a device that is able to provide the voltage and current required by the actuator at all times. Nevertheless, in this case the electrical variables of the actuator and the PV array outputs can be adapted by combining the logic sequencer with a current control stage.

Finally, adverse weather conditions or faults in the system must be taken into account when the reservoir's water capacity is designed. A reasonable choice would be to consider a capacity of at least five times the daily water flow forecast.

3. Case study

The solar PV water pumping system proposed was projected for a specific rural community of a developing country, located near the town of Asela in the Rift Valley in Ethiopia [7]. The location is 1669 m above sea level and its coordinates are latitude $7^\circ 30'$ N and longitude $38^\circ 30'$ E. The average annual insolation on a horizontal surface is $6.69 \text{ kWh/m}^2/\text{day}$, and the average maximum and minimum annual temperatures are respectively 21°C and 16°C . The monthly average is 12 hours of daylight per day; however, irradiance is more than 400 W/m^2 for only 8 hours per day.

At the site, water is typically found around 15 m below the surface; thus, an effective height of 18 m is considered in the following calculations. A water flow of 12.5 m^3 per day is sufficient to cover the needs of a small rural community of about 250 people. The force required to pump the water, F_H , is equal to 500 N, considering that the weight of the rod, piston and mover is about 200 N and the counterweight has a mass, M_{cb} , of 46 kg.

The pump selected—because it satisfied all these requirements—was an India Mark III $2\frac{1}{2}$ " , a piston-type water pump commonly used in deep-well, hand-pump installations (Figure 5). Several modifications had to be made to adapt it. The piston and the riser pipe diameter were $2\frac{1}{2}$ ". Between upward and downward strokes, the piston traveled 125 mm.

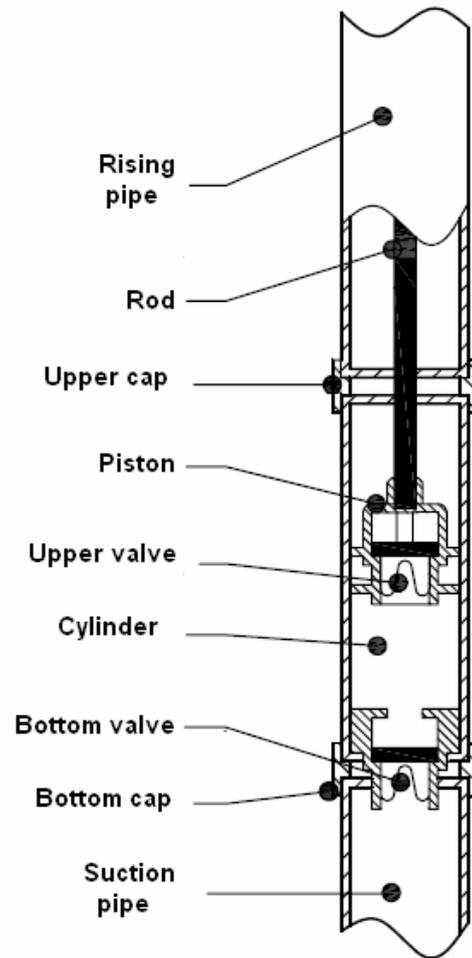


Fig. 5. Cross-section of the single-acting reciprocating positive-displacement piston pump

TABLE I. Summary of linear actuator parameters

Parameter	Value
F , average thrust (N)	250
U , voltage (V)	48
I , current (A)	4.39
v , speed (mm/s)	150
m , no. of phases	2
N_m , no. of stator poles	4
B_δ , flux density in the air gap (T)	1.5
Δ , current density (A/mm^2)	3.58
b_s , stator pole width (mm)	25
b_r , mover pole width (mm)	25
w_s , stator slot width (mm)	50
w_r , mover slot width (mm)	25
h_s , stator pole height (mm)	50
h_r , mover pole height (mm)	18.75
w , normal length (mm)	75
δ , air gap (mm)	1.5
K_v , slot fill factor	0.4
N_p , no. of turns per pole	409
d , conductor diam. (bare) (mm)	0.9
c , no. of conductors in parallel	2

The variable-reluctance linear stepper motor had to be designed according to the parameter values summarized in Table I. The linear reluctance stepper motor was analyzed using the Finite Element Method [8]. The flux distribution is given in Figure 6 for the case in which phase A is excited by a current of 4.39 A. The inductance vs. the position of each phase is obtained from the aforementioned analysis, as shown in Figure 7, and the evolution of instantaneous thrust with respect to the position is shown in Figure 8.

The PV array is composed of two rows connected in parallel; each row consists of two panels connected in series. The PV array is south-oriented and its inclination is 12°. The panels used are PW 1250-135 W and their main parameters are given in Table II.

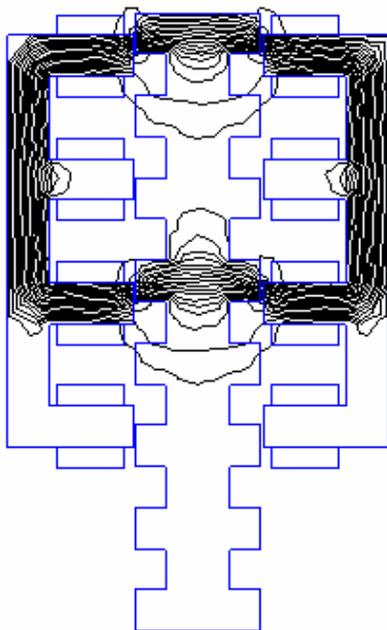


Fig. 6. Flux distribution obtained by FEM analysis

TABLE II. Summary of PW1250 parameters

Parameter	Value
Number of cells	54
Typical power (W)	135
Voltage at typical power (V)	26.4
Current at typical power (A)	5.1
Length (mm)	1237
Width (mm)	822
Depth (mm)	38
Weight (kg)	12.5

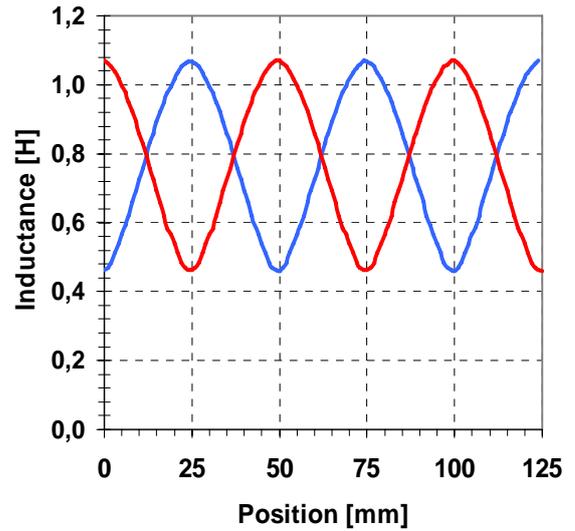


Fig. 7. Inductance vs. position, Phase A (blue), Phase B (red)

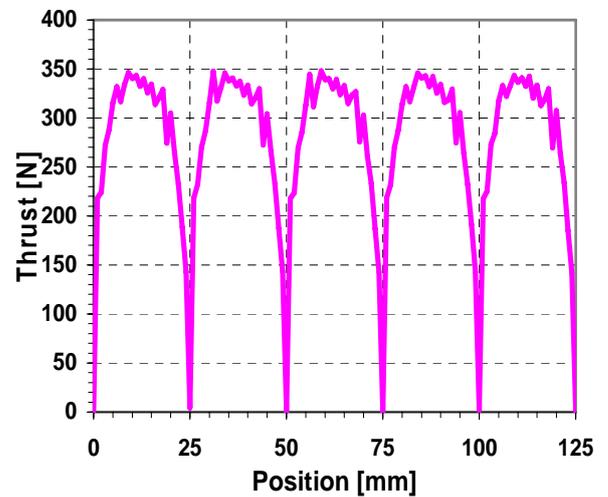


Fig. 8. Thrust vs. position

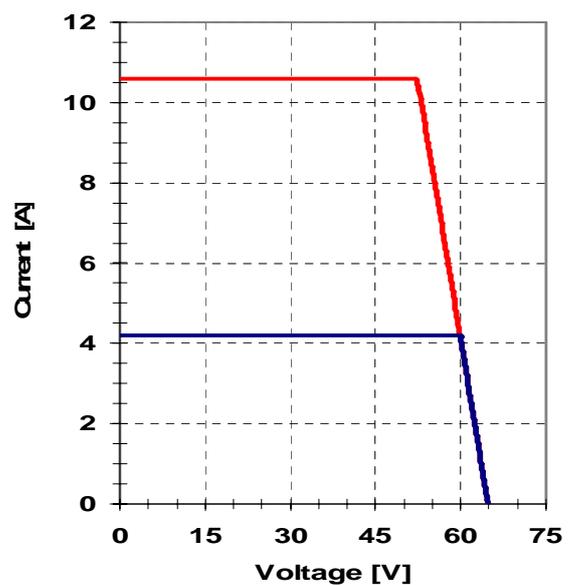


Fig. 9. Current-voltage characteristics of the PV array for different levels of irradiance, 1000 W/m² (red), 400 W/m² (blue)

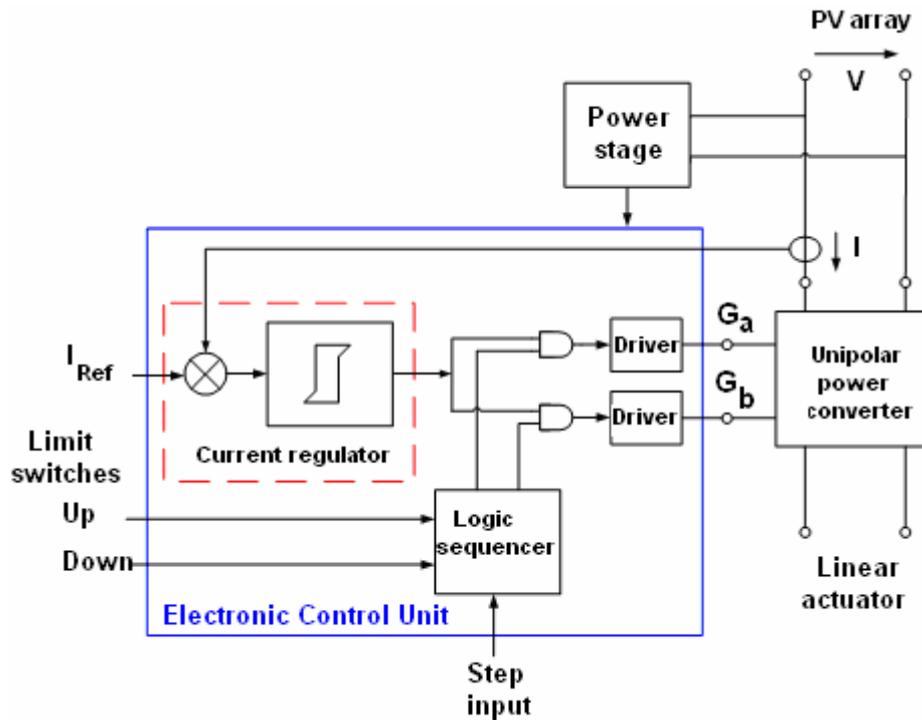


Fig. 10. Block diagram of the electronic control unit

The PV array current-voltage characteristics, for different levels of irradiance, are shown in Figure 9. The complete system must be able to work with a threshold irradiance of 400 W/m^2 ; thus, under these conditions the phase currents must hold the thrust of the linear actuator. As a result, the current is regulated, at each instant and at the reference value, by means of a simple hysteresis controller that uses just one Hall-effect current sensor. The output signal of this controller is logically combined with the output signals of the logical sequencer in order to generate the commutation signal that turns the power switches on and off. The direction in which the actuator moves, which is either up or down, depends on the sequence of phase excitation that is determined according to the state of two limit switches, one placed in the uppermost position and the other in the lowest position that the mover can reach. The electronic control unit is fed through a regulated power stage from the PV array output. A block diagram of the electronic control unit is shown in Figure 10.

4. Conclusions

A solar PV water pumping system using a new double-sided flat two-phase variable-reluctance linear stepper motor suitable for developing countries was proposed. The system consists of a piston-type water pump, a linear motor mounted onto the piston rod that drives the pump with the help of a rope, a pulley and a counterweight. The actuator pump ensemble is controlled by a simple electronic unit that manages the electric power generated by a photovoltaic array. A water reservoir completes the installation. The system was projected for a specific rural

community near the town of Asela in the Rift Valley in Ethiopia. The proposed system is suitable for rural communities in developing countries because it is reliable, affordable and easy to maintain; in addition, most of its parts can be manufactured in developing countries.

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