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Practical Representation of a Water Pump With a Linear Electric Motor

***Abstract**. Solar photovoltaic water pumping (SPVWP) is an economically viable system in developing countries and remote areas of developed countries. The economy and reliability of solar power made it an excellent choice for remote pumping of water. Despite numerous significant advantages of the SPVWP system, there are also many problems associated with it, especially in operation and maintenance. This article discusses some aspects that affect the economic efficiency of the SPVWP system in developing countries. Also, a photovoltaic solar pumping system with the use of a linear drive (actuator) is presented in this paper. This linear actuator represents a two-phase linear stepper motor with variable resistance that moves a piston water pump using a rope, pulley, and counterweight. The entire drive pump ensemble is managed by a simple electronic unit that controls the electrical energy generated by the photovoltaic grid. The proposed system is suitable for rural communities in developing countries, as it is reliable, affordable, and easy to maintain.*

Streszczenie.** Pompowanie wody za pomocą fotowoltaiki słonecznej (SPVWP) jest ekonomicznie opłacalnym systemem w krajach rozwijających się i odległych obszarach krajów rozwiniętych. Oszczędność i niezawodność energii słonecznej sprawiły, że jest to doskonały wybór do zdalnego pompowania wody. Pomimo wielu istotnych zalet systemu SPVWP ma również wiele problemów, szczególnie w eksploatacji i konserwacji. W artykule omówiono niektóre aspekty wpływające na efektywność ekonomiczną systemu SPVWP. W artykule przedstawiono również fotowoltaiczny solarny układ pompowy z wykorzystaniem napędu liniowego (siłownika). Ten siłownik liniowy reprezentuje dwufazowy liniowy silnik krokowy ze zmiennym oporem, który porusza tłokową pompę wodną za pomocą koła pasowego i przeciwwagi. (Pompa wodna z liniowym silnikiem elektrycznym zasilanym ze źródła fotowoltaicznego**)

Keywords: solar energy, water pumps, electric drive (actuator), stepper linear motor, power converter.
Słowa kluczowe: pompa wodna, zasilanie fotowoltaiczne, silnik liniowy.

Introduction

About 97.5% of the water on our planet is not potable due to high salinity. The remaining water reserves are freshwater, of which about 70% are contained in polar ice caps, and the remaining 30% are mainly moisture in the soil or lie in groundwater. In general, less than 1% of the world's freshwater is suitable for direct drinking purposes.

Though water is easily accessible in developed countries, over 1.2 billion people do not have access to a safe and sufficient water supply. One billion people must travel three hours to take on water, and 14,000 people die every day from water-related diseases. As the world population grows, the pressure on available water supplies increases.

Groundwater is an important source of fresh water and the dominant source of household water supply in many areas, especially in arid areas where surface water is scarce and seasonal.

Water pumping has a long history, and many water supply methods were developed. They used various sources of energy, including human, animal, wind, hydro, and solar energy, as well as fossil fuels.

Studies have shown that in developing countries and remote regions with electricity supply issues, the use of *SPVWP* systems for water supply is the most optimal way. Solar photovoltaic water pumping systems can provide drinking water without using any fuel and do not require complicated maintenance as in the case of diesel pumps. They allow people to devote more time to other activities and thus improve their lifestyle, health, and economic conditions. Besides, the application of such systems provides new working possibilities in remote rural areas of the country. The hard efforts of women and children who otherwise deliver water from far away can be significantly reduced. Although the cost of solar photovoltaic water pumping systems is initially high, they require virtually no maintenance, no fuel, and, thus, become more profitable to use permanently. These systems are very reliable and durable, as well as easy to install and operate, and their modular design allows for easy improvements in the future. They can be installed at the place of use, which makes long pipeline routing unnecessary [1-3].

Solar photovoltaic water pumping systems are very simple. They consist of a photovoltaic solar panel, controller, motor, pump, and reservoir. The availability of the controller depends on the type of motor pump combination and whether the maximum power point needs to be monitored. The use of a reservoir eliminates the need for a battery. Installations should be safe in two ways: they should be as safe and irresponsive to external factors such as lightning strikes to the maximum extent.

These systems can be configured differently depending on the type of pump used. The most common types are submersible centrifugal motor pumps, submersible pumps with surface motors, piston pumps, and submersible pumps with floating impellers.

In developed countries, submersible centrifugal motor pumps, in which an asynchronous three-phase short circuit motor is controlled by an inverter, are the most common. However, solar photovoltaic pump systems operating in rural communities in developing countries need to be low-cost, reliable, and maintenance-free for highly specialized personnel. Cost savings and reliability improvements can be achieved by reducing the complexity of the controller and motor pump.

Following the aforementioned, this paper presents a solar photovoltaic water pumping system using a linear actuator. A two-phase linear stepper motor with variable resistance [4] moves a piston water pump and is controlled by a simple electronic unit. The proposed system is suitable for rural communities in developing countries due to its reliability, affordability, and ease of maintenance.

Literature review

Solar photovoltaic water pumping systems (SFPVWS) have been used for almost three decades. The analysis of the economic aspects of SFPVW systems can be divided into two categories: developed and developing countries.

These systems proved to be financially beneficial for remote locations in developed countries [5-6]. Operation and maintenance at the local level improve the SFPVWS life cycle and reduce the costs of their maintenance and exploitation. However, the cost of SFPVW systems installation is quite high for the majority of rural residents in developing countries. At present, SFPVW systems are not a suitable and affordable alternative to traditional power systems or diesel generators in developing countries [7-9]. For the SFPVW system to be cost-effective in developing countries, Purohit offers government subsidies [8], which is not an ideal long-term solution. In developing countries, a manually driven pump is often used in combination with the SFPVW system to supply drinking water. The hand-operated pump can be used in small villages to supply drinking water, but for irrigation purposes, it requires constant physical labor, making it unsuitable. During the dry season, the water level drops, and the manual pump can hardly meet the need for drinking water. On the other hand, a solar-powered water pump works autonomously and supplies water while the sun shines. Using an autonomous diesel generator following the five steps described in [10-11], the SFPVW systems can be economically competitive. In developed countries, the main application of SFPVW systems is water supply for livestock and wildlife in remote areas.

The long-life cycle of SFPVW systems depends on proper maintenance and availability of spare parts in the local market. Some reliability assessment reports for 10 years of operation were published in [7,9]. In Thailand between 1995 and 1998, 489 SFPVWSs were examined. Out of 489 systems, 220 units (45%) failed and stopped pumping water, 88% of them failed within 7 years. The main causes of malfunctions were water tap failure of 30%, motor/pump failure of 27%, pipeline leakage of 18% and inverter failure of 17%. Pipeline and pump failures are caused by clogging due to water plants and precipitation entering the system [9].

Cota-Espericueta et al. [7] provided the results on the work of 46 systems in Mexico to assess the reliability and rationality of SFPVW systems after 10 years of their operation. Out of 46 systems, 18 systems (39.13%) were not in operation and 26 failures of system components were documented. The causes of failure were 54.2% pump/motor failure, 20.8% controller/inverter failure, 16.7% well pollution, and 8.3% system damage.

Between 1991 and 2002, the University of Wyoming's Engine Testing and Upgrading Center monitored the installation of 15 SFPVW systems. Also, in 2005-2006, this Research Center installed an additional 80 SFPVW systems. A report on the operation of the systems installed between 1991 and 2002 has been provided, and the information is available for 11 of these systems. One system (9%) out of 11 is not functioning as the well has dried up. Information was recorded on 16 failures: 10 (62.5%) pump/motor failures, 4 (25%) controller failures, 1 (6.25%) pipe failure, and 1 (6.25%) electrical cable failure. All malfunctions were corrected by replacing the respective components with spare parts.

By analyzing the above failure scenarios, it can be concluded that most SFPVW systems can be recovered and continue to operate by simply replacing the pump/motor, controller, and other components. Technical knowledge and availability of spare parts play an important role in the successful operation of these systems. In this aspect, developed countries have great advantages over developing countries due to already developed social, economic, and technical infrastructure.

Task setting

In areas where the network power supply is not available (remote areas are separated from urban facilities), SFPVW systems are directly connected to local communities. If any technology is used in remote areas, it must be reprocessed according to the socio-economic structure of the particular area. Schumacher agrees with the views of Dann [10], arguing that ignoring training and organizational factors during the project design stage will only cause economic loss and destruction. The positive impact of technology in developed countries will not necessarily manifest itself in developing countries. The technology must be adapted in order to comply with the environment. Here are some of these principles and criteria for the corresponding technology.

Main objectives:

I. Improve the living standards of local residents.
II. Utilize renewable resources.
III. Create job opportunities for the local population.

The selected targets should consider the following factors:

- Human Resources.
- Available material resources.
- Financial resources of the local region.
- Local culture.
- Needs of the local population.

The main needs of the community are food, water, clothing, housing, health care, hygiene, sanitation, education, and vocational training. All these items are directly related to clean water. The SFPVW system can ensure an uninterrupted supply of freshwater while meeting the above five criteria. Developed and developing countries have their perspectives to meet different needs. Therefore, the main task of this article was to study and evaluate the reliability of the SFPVW system.

Materials and methods

The photovoltaic system is based on semiconductor technology that converts sunlight into electricity. It is a proven technology, although it is more expensive than other methods of electricity production, such as power plants generating electricity from fossil resources (gas, coal, oil) and traditional hydroelectric conversion methods. Figure 1 shows the schematic diagram of the solar water pumping system.

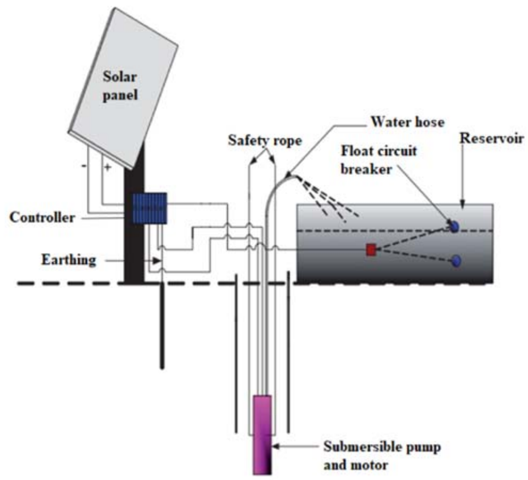

Fig.1. Principal scheme of the solar water pumping system [12]

Photovoltaic matrices serve as the source of electrical energy for SFPVW systems. Each photovoltaic array has its own (I-V) characteristics. The maximum power point of the photovoltaic grid depends on several factors, including solar radiation in a particular area, temperature, and connected load. For a specific output power, the size of the array depends on the efficiency of the cell. Solar cells are divided into three categories depending on the type of crystalline material used in manufacturing, namely, monocrystalline, polycrystalline, and amorphous. The efficiency level currently available is about 7%, 15%, and 17% for amorphous, polycrystalline, and monocrystalline silicon respectively.

An important part of SFPVW systems is a water pump, which the pumps can be divided into three types depending on their use: surface, floating, and submersible. Surface pumps are used for pumping water from small wells (rivers, lakes, springs), submersible pumps are used for deep wells, and floating pumps are used for tanks with changing water levels. The pumps are also divided into several categories according to their pumping principle.

Centrifugal pumps in which the fluid is sucked in by the centrifugal force created by the rotor wheel, and the body directs the fluid to the discharge port when the wheel rotates. Liquid exits at a higher speed and pressure than the at pump inlet. *Screw pumps*, where a screw picks up liquid on the suction side of the pump body and directs it to the discharge port. *Piston pumps* where the movement of the piston draws water into the chamber with the inlet valve and pushes it out to the discharge port with the outlet valve.

The choice of the right pump for a solar pumping system depends only on the place of use or, for example, the purpose of water use and water quality.

Pump motor. Currently, there are several types of motors available on the market, such as: with a variable or permanent magnet, brush or brushless, synchronous and asynchronous, with variable resistance, etc. The photovoltaic matrix can be directly connected to the motor if a DC motor is used. When using an AC motor, an inverter (usually called a controller) must be installed between the photovoltaic matrix and the motor. The motor and pump are depleted in the case of submersible and floating systems. In this case, the consumer is not able to select them separately. In a surface system, the pump and motor separately can be selected, and their performance can be evaluated together with the controller and panel.

The controller is necessary if an AC motor is used. The controller effectively isolates the photovoltaic matrix from the pump motor system for greater safety and provides the pump motor with the optimal voltage/current for specific local conditions. The controller also protects the pump motor from dry running and saves water by turning off the system when the tank is full. However, the controller is a vulnerable component in solar photovoltaic water pumping systems as its electronics components are sensitive to the external environment.

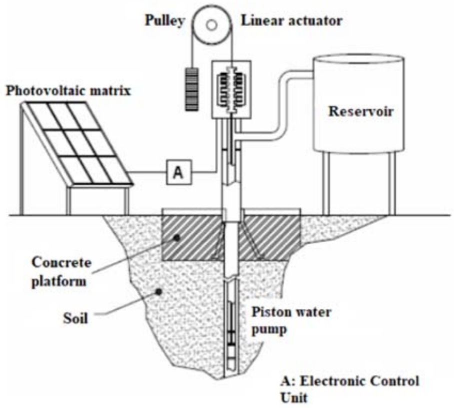

Fig.2. Scheme of solar photovoltaic pump system [13]

Results

A solar photovoltaic pump system, suitable for rural communities in developing countries, has been developed. The proposed system consists of a water pump of the piston type, a two-phase linear stepper motor with variable resistance [5], mounted on the piston rod and driving the pump using a rope, pulley, and counterweight. The drive pump ensemble is controlled by a simple electronic unit which controls the electrical power generated by the photovoltaic battery. The system is equipped with a water reservoir as shown in Fig. 2.

In this work, either a conventional plunger pump or a single-acting plunger piston pump have been chosen. The latter is well suited for operating under high pressure and low consumption. Piston pumps consist of a reciprocating plunger cylinder inside. The piston pumps water from the inlet to the outlet side of the pump. In a single-acting pump, the operating cycle is completed by two piston strokes: downward and upward. The force required to pump the water can be estimated by the following formula:

(1) $$F_H = dg\gamma AH_{ef}$$

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

The linear actuator allows the piston to move between its end positions at a constant speed. Also, the linear stepper motor with variable inductance has been chosen as it can operate as an open-loop system, is mechanically reliable and simple to control, and can be manufactured in developing countries.

Due to the noticeable characteristics of the stator and motor poles, the inductance of each phase varies depending on the motor position. The principle of the linear actuator operation is based on the rule of minimum resistance. Thus, the traction, if saturation is not taken into account, is as follows:

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

The engine has four air gaps per phase. The width of the stator pole and the width of the motor pole are equal to each other and are half the width of the stator slot. Therefore, its average traction is determined by the following equation:

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

where $B\delta$ is the flow density in the air gap, Δ is the current density, K_V is the slot filling factor, λ_{na} is the relative permeability per unit of length in the non-aligned position, λ_a is the permeability per unit of length in the aligned position, bs is the stator pole width, and w is the normal length.

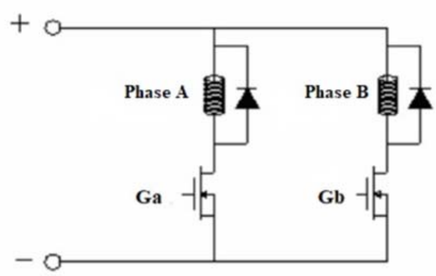

Fig.3. Unipolar power converter

The displacement of the motor is equal to the stroke of the piston downward and upward. Therefore, the power converter must sequentially feed the motor phase windings and change the sequence every time the motor reaches the end positions. Since simplicity was one of our main goals, we chose a single-pole power converter with a single switch per phase and a free-running diode (Fig. 3).

Each phase must be activated approximately at the point at which its own inductance increases. Thus, a device such as a logic sequencer is required to consistently send the correct control signals to the circuit breaker gates (Fig. 4).

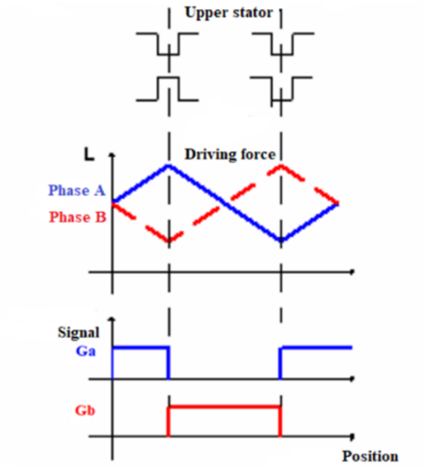

Fig.4. Change of phase inductances and switching signals

The linear drive is connected to the pump stem, pulley, and counterweight, which reduces the size and cost of the linear actuator, as well as the power required from the photovoltaic matrix. The counterweight equalizes the load requirements for the full cycle, that is, the force created by the linear actuator when it moves upward should be almost equal to the force created when it moves downward. Consequently, the final thrust of the actuator is determined by

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

and counterweight weight

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

Fr is the weight of components (rod, piston).

The photovoltaic matrix is manufactured using commercial photovoltaic panels. Configuration and location of the photovoltaic grid depend on its location and pump specifications. Since the photovoltaic array has nonlinear volt-ampere characteristics and its maximum power point varies with the solar radiation and temperature, a device that can provide the required voltage and current at any time is usually required. In this case, the electrical variable drives and outputs of the photovoltaic matrix can be adapted by combining a logical sequencer with a current control stage.

Also, when designing the reservoir capacity, the weather conditions, and time for repairing the breakdowns are required. The optimal choice would be a capacity five times higher than the predicted daily water consumption.

Discussion

The solar photovoltaic pump system described above was used by a rural community in a developing country near Asella city in Rift Valley, Ethiopia [8]. The village is located at an altitude of 1669 m above sea level, and its coordinates are 7 ° 30' north latitude and 38 ° 30' east longitude. The average annual insolation on the horizontal surface is 6.69 kWh/m^2/day, and the average maximum and minimum annual temperatures are 21ºC and 16ºC, respectively. The monthly average is 12 hours of daylight per day; however, the radiation power is over 400 W/m^2 in just 8 hours per day.

The water on a site is usually about 15 m below the surface, so the effective height for the calculation was taken as equal to 18 m. The water consumption of 12.5 m^3 per day is sufficient to meet the needs of a small rural community of about 250 people. The force required to pump the water, F_H, is 500 N, and the counterweight amounted to 46 kg.

A locally manufactured piston water pump was used in this system as it met all the requirements (Fig. 5). The piston and riser diameter was 2½ inches. The piston moved by 125 mm between upward and downward.

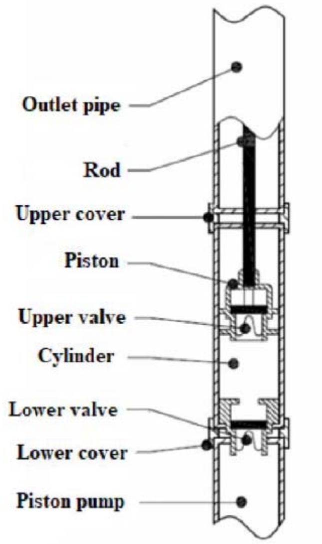

Fig.5. Scheme of piston pump

In accordance with the system parameters, a linear stepper motor with variable resistance was designed. The photovoltaic matrix consisted of two rows of solar panels connected in parallel. This array is oriented to the south and its inclination angle is 12º. The panels used had a power of 125–135 W. The electronic control unit is fed through an adjustable power stage from the output of the photovoltaic matrix.

The paper [12] presents a cost analysis of using a conventional diesel generator and SFPVW systems for water pumping. The costs of using and maintaining this system and a system with a diesel generator in developed and developing countries were compared. Data for developed countries are based on US data and data for developing countries – on Bangladesh. Any process involves manual work, which is much cheaper in developing countries. The cost of fuel and original equipment in the U.S. and Bangladesh is the same. However, costs for materials are lower in Bangladesh. The cost of transportation in Bangladesh is very low because people in remote areas use hand-held vehicles. The diesel generator needs to be checked every day to turn it on and off, as well as for refueling, while the SFPVW system needs a check once per week. The engine/pump and controller must be replaced every 10 years, while the generator requires replacement every 5 years. These costs are considered to be constant through the entire life cycle of the engine/pump. Prices for gas (diesel, oil) have increased by 10% every year. For 25 years (depending on the lifetime of the photovoltaic module), the engine/pump and controller were replaced twice and the generator four times. The results provided by the authors show that the total costs of the SFPVW system and the system with a diesel generator are comparable. However, the cost of fuel and maintenance of systems with diesel generator is very high in comparison with the SFPVW system. Economic analysis has shown that this system is preferable in the long term for developing countries.

Conclusions

A solar photovoltaic water pumping system with a two-phase linear stepper motor with variable resistance, suitable for use in developing countries, was proposed. The system consists of a piston water pump and a linear motor mounted on a piston rod that drives the pump with a rope, pulley, and counterweight. The drive pump ensemble is controlled by a simple electronic unit that controls the electrical energy generated by the photovoltaic panel. The water tank completes the installation. This system has been tested in a rural community near Asella city in Ethiopia. The SFPVW system has proven its technical, economic, and environmental importance for developing countries. Some improvements can be made to reduce the maintenance and operation costs of these systems. In developing countries, repair and maintenance costs remain a major obstacle to their widespread use. In this work, the SFPVW systems were shown as economically viable for use in developing countries. Also, these systems can compete with traditional diesel generator water pumping systems.

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REFERENCES

[1] Antonello, R., Carraro, M., Costabeber, A., Tinazzi, F., Zigliotto, M., Energy-efficient Autonomous Solar Water-pumping System for Permanent-magnet Synchronous Motors, *IEEE Trans. Ind. Electron.*, 64 (2016), No. 1, 43p51
[2] Sandwell, P., Chan, N.L.A., Foster, S., Nagpal, D., Emmott, C.J., Candelise, C., et al. Off-grid Solar Photovoltaic Systems for Rural Electrification and Emissions Mitigation in India, *Solar Energy Materials and Solar Cells*, 156 (2016), 147-156
[3] Prakash, V.V., Raturi, A.K., Proceedings from the Asia Pacific Solar Research Conference 2018, APSRC, 2018: *Solar Energy for Clean Water Access in Fiji*, Australian PV Institute, 2018
[4] Gieras, J.F., Piech, Z.J., Tomczuk, B., *Linear Synchronous Motors: Transportation and Automation Systems*, CRC press, 2016
[5] Silva, R.G. *Dimensionamento e levantamento de custos de fontes energéticas, considerando os recursos hídricos para uso em sistemas de bombeamento* [Dimensioning and Costing of Energy Sources, Considering Water Resources for Use in Pumping Systems], Universidade Federal de Uberlândia, Uberlândia, 2014
[6] Muhsen, D.H., Khatib, T., Nagi, F., A Review of Photovoltaic Water Pumping System Designing Methods, Control Strategies and Field Performance. *Renewable and Sustainable Energy Reviews*, 68 (2017) 70-86
[7] Cota-Espericueta, A.D., Foster, R.E., Gomez-Rocha, L.M., Ross, M.P., Hanley, C.J., Gupta, V.P., et al. (2012). *Ten Year Reliability Assessment of Photovoltaic Water Puming Systems in Mexico,* 2012
[8] Purohit, I., Purohit, P., Shekhar, S., Evaluating the Potential of Concentrating Solar Power Generation in Northwestern India, *Energy Policy*, 62 (2013), 157-175
[9] Gao, X., Liu, J., Zhang, J., Yan, J., Bao, S., Xu, H., Qin, T. Feasibility Evaluation of Solar Photovoltaic Pumping Irrigation System Based on Analysis of Dynamic Variation of Groundwater Table, *Appl. Energy*, 105 (2013), 182-193
[10] Walker, G., Devine-Wright, P., Hunter, S., High, H., Evans, B., Trust and Community: Exploring the Meanings, Contexts and Dynamics of Community Renewable Energy, *Energy Policy*, 38 (2010), No. 6, 2655-2663
[11] Chandel, S.S., Naik, M.N., Chandel, R., Review of Solar Photovoltaic Water Pumping System Technology for Irrigation and Community Drinking Water Supplies, *Renew. Sust. Energ. Rev.*, 49 (2015), 1084-1099
[12] Meah, K., Ula, S., Barrett, S., Solar Photovoltaic Water Pumping—Opportunities and Challenges, *Renew. Sust. Energ. Rev.*, 12 (2008), No. 4, 1162-1175
[13] Andrada Gascón, P., Castro, J., Solar Photovoltaic Water Pumping System Using a New Linear Actuator, *Renewable Energy and Power Quality Journal*, 5 (2007), 321-326