Scientific Review Engineering and Environmental Sciences (2023), 32 (3), 270–283

Sci. Rev. Eng. Env. Sci. (2023), 32 (3) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.4994

Received: 20.06.2023
Accepted: 15.07.2023

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Designing optimal solar water pumping stations for irrigation of agricultural lands

Keywords: solar panel, optimization system, buck converter, FLC, engineering model, fill factor

Introduction

The irrigated lands allocated for agricultural purposes on the planet, according to the forecasts of the UN experts, in 2050 will have an acute shortage of water resources. In accordance with the forecasts of these experts, water resources will become very valuable and scarce in the near future. One of the main causes of uncultivated agricultural lands is the poor condition of the irrigation water system and in some cases its absence.

In a number of developing countries, the irrigation of agricultural lands, especially the lands near the houses, is often carried out with potable water, as a result of which large losses of potable water occur, which in turn leads to the shortage of potable water.

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In order to minimize the drinking water losses, the irrigation of lands should be carried out with water resources from rivers, natural lakes, reservoirs and other water sources, which is both economically efficient and useful from the point of view of irrigation.

It should be noted that in agricultural lands, as a rule, medium and small rivers flow near owned irrigation lands, but the irrigation of these agricultural lands mostly continues to remain unirrigated. One of the main reasons for the impossibility of organizing irrigation is the lack of access of the agricultural enterprises to the power grid.

If new technologies and financial investments in the water transportation and management system are not implemented in the irrigation system of lands, then the water deficiency will deepen in these countries.

Thus, irrigation water systems must be modernized, old ones restored, existing ones used sparingly and managed efficiently.

There are many scientific and practical justifications that prove that it is effective to use solar water pumping stations for irrigation of agricultural lands, in which it is necessary to use new irrigation management technologies, such as drip irrigation and the development and implementation of an automated remote control system. This will contribute to solving a number of environmental problems, such as reducing CO_2 emissions and increasing irrigated agricultural lands, which in turn will lead to improved yields.

According to the European Energy Commission (EEC):

– the level of environmental pollution is proportional to the level of energy consumption;
– given the observed rate of growth in energy consumption, a global energy catastrophe is possible by 2050.

One of the ways to solve this problem is using renewable power sources: solar, wind, bioenergy, etc. It has been established that the energy received by the Earth from the Sun per hour is equal to the total amount of power consumed by people in a year. More attention is paid to the development of energy based on the use of solar radiation, which is associated with a number of factors: environmental safety and the unlimited supply of solar energy. Photovoltaics is one of the main directions in the field of solar energy. The photovoltaic effect is the direct conversion of solar energy into electrical energy. Recently, solar panels have found much needed applications in irrigation systems. Solar panel pumps, which pump water from rivers and from deep aquifers.

To optimize the conventional solar water pumping station, its optimal point (at a given condition) is tracked, using online or offline algorithms, and the system operating point is forced toward this optimal point. There are various kinds of optimization methods reported (Deokar, Bindu & Deokar, 2021; Gevorkov,

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Domínguez-García & Romero, 2023) and one of the optimization methods which have demonstrated a solar pumping system's fine performances and high accuracy under different environmental operating conditions is the fuzzy-based optimization method. Solar water pumping stations are recognized as a sustainable and environmentally friendly solution to provide water for irrigation of lands.

The goal of this article is the calculation, computer simulation, and optimization of the important engineering parameters, which are the water discharge rates of the local networks of solar water pumping stations driven by the DC motors.

Engineering model of the solar water pumping stations

The station mainly comprises a solar panel, a centrifugal pump load driven by a DC motor, and a reservoir as shown in Figure 1.

The engineering model of a solar water pumping station differs from q_e the model of a solar water pumping system in that the station includes a water reservoir with a network of water lines. Water from the river is pumped into the reservoir by a pump and each land user can turn on the water on his land plot for irrigation. The main purpose of the reservoir is to automatically maintain a predetermined water level. The change in the level (Δh) depends on the difference in flows ($Q - q$), where Q is

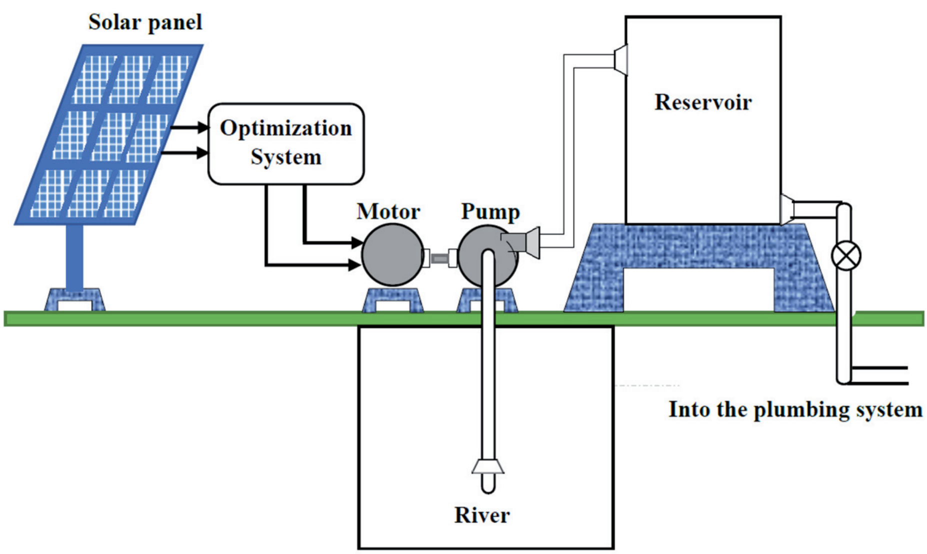

FIGURE 1. The scheme of the solar pumping station

Source: own work.

the incoming water flow, q is the outgoing water flow and S is the cross-sectional area of the reservoir. We will assume that one of the land users always has water turned on and the pump is constantly working to pump water into the reservoir during the daytime. The reservoir can operate in series or parallel modes of irrigation of land located near the river and extending along the river. The parallel irrigation mode is achieved due to the increased activity of the pump, which twitches all the time. In this case, the mechanical parts of the pump wear out, and its service life is significantly reduced. It is found that the solar panel energy utilized by the centrifugal pump is much higher than the energy consumed by the volumetric pump. In fact, in the case of centrifugal pumps, the operation takes place for longer periods even for low solar radiation levels, and the load characteristic is in closer proximity to the solar panel optimal point.

The topology of the global network of solar pumping stations is illustrated in Figure 2.

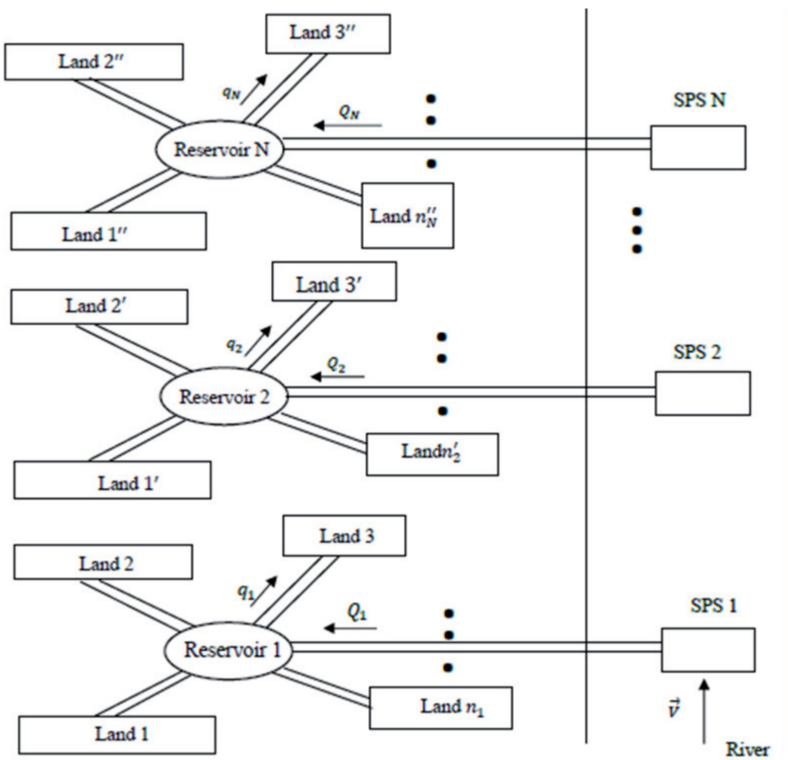

FIGURE 2. The topology of the network of solar pumping stations

Source: own work.

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The reservoir is connected to the lands using a network of water pipes. The local network of the solar pumping station is a solar pumping system including a network of water pipes. The local networks of solar pumping stations are installed along the river equidistant in a consistent manner.

The right side of Figure shows 2 solar pumping systems (SPS), and the left one the reservoirs with inflow (Q_i) and outflow (q_i) pipes of a water network. During a small interval Δt, the volume of water added to the i-th reservoir by the pump is $Q_i\Delta t$, and the volume of water flowing out of the i-th reservoir is equal to $q_i\Delta t$. Given that the cross-sectional area of the reservoir is equal to S_i, we obtain a change in the water level in the i-th reservoir

$$\Delta h_i = \frac{Q_i - q_i}{S_i}\Delta t. \tag{1}$$

Since the topology of the global network of solar pumping stations is a superposition of the topologies of the local networks of solar pumping stations, the amount of pumped water per day is an additive quantity. The water discharge rate (Q) for the global network of solar pumping stations is given by

$$Q = \sum_{i=1}^{N} Q_i, \tag{2}$$

where Q_i is the incoming water flow to the i-th reservoir of solar water pumping stations. This means that in order to optimize a solar pumping station, it is necessary and sufficient to maximize the water discharge rate for one local solar pumping system. Therefore, in the future, we will consider the model of one local network of the solar pumping system.

The simulation model of the solar pumping system

Figure 3 shows the scheme of the solar water pumping system. The solar panel directly converts solar radiation into DC electrical power. The magnitude of the solar panel current depends upon the intensity of solar radiation. The solar panel is connected to the DC/DC buck converter with an optimization technique, which allows matching the load characteristics with the solar panel characteristics.

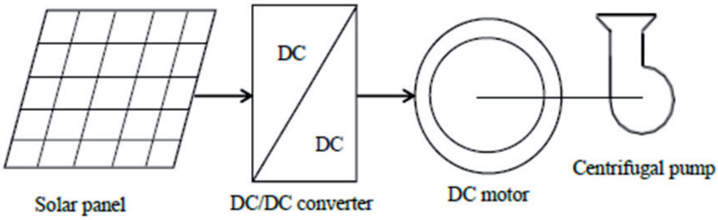

FIGURE 3. The solar pumping system scheme
Source: own work.

The DC/DC buck converter modeling

The DC/DC buck converter is the main part of the optimization system. As the name implies, the average output voltage is less than the DC input voltage. Here, switching control is done by a power insulated gate bipolar transistor. When the transistor is switched on, the diode D_1 becomes reverse-biased and the input provides energy to the load as well as to the inductor. When the transistor is switched off, an inductor current flows through the flywheel diode D_1, transferring some of its stored energy to the load. This inductor current falls until the transistor is switched on again in the next cycle. The filter capacitor at the output is assumed to be very large, so that a nearly constant instantaneous output voltage is obtained.

Thus, by varying the fill factor of the insulated gate bipolar transistor, we can vary the average output voltage and output power. The regulation is generally achieved with a pulse-width modulation technique at a fixed frequency and the fill factor γ can be defined by the following equations:

$$\frac{V_o}{V_s} = \gamma, \tag{3}$$

$$\frac{I_o}{I_s} = \frac{1}{\gamma}. \tag{4}$$

Since we are dealing with non-linear energy sources here, a fuzzy logic controller (FLC) will be used to find the optimal point on the solar panel's current-voltage characteristic. Usually,a DC/DC buck converter is utilized between the solar panel and the pump load for optimization system. A functional block diagram of FLC is shown in Figure 4.

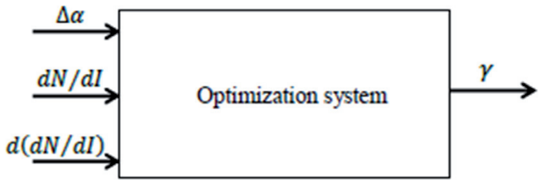

FIGURE 4. The general diagram of the proposed fuzzy logic controller (FLC)
Source: own work.

The FLC is a multiple input multiple output system where the input parameters are dN/dI, $d(dN/dI)$ and $\Delta\alpha$. Fill factor γ is the output parameter of the MIMO system. As a term-set of the input variable dN/dI we will use the set

$$\frac{dN}{dI} = \{negative\ big, negative\ small, zero, positive\ small, positive\ big\}$$

or in symbolic form $\frac{dN}{dI} = \{NB, NS, Z, PS, PB\}$ with triangular membership functions. A similarterm-set is also considered for the input variable $d(dN/dI)$ and the output variable γ. As a term-set of the input variable $\Delta\alpha$ we will use the set $\Delta\alpha = \{negative, zero, positive\}$ or in the symbolic form $\Delta\alpha = \{N, Z, P\}$ with triangular membership functions.

The input and output parameters of the multiple input multiple output system are related by the following relationships:

$$\frac{dN}{dI} = \frac{NA(j) - NA(j-1)}{IA(j) - IA(j-1)}, \tag{5}$$

$$d\left(\frac{dN}{dI}\right) = \frac{dN}{dI}(j) - \frac{dN}{dI}(j-1), \tag{6}$$

$$\Delta\alpha = d\gamma(j-1), \gamma(j) = \gamma(j-1) + d\gamma(j), \tag{7}$$

where $NA(j)$ is the output power of the solar panel and $\gamma(j)$ is the fill factor of the DC/DC buck converter at j-th iteration number. The iteration is stopped when $\gamma(j)$ is approximately equal to $\gamma(j-1)$.

The algorithm for calculating the output parameter γ for FLC (Fig. 4) according to the fuzzy logic is carried out by Eqs (5)–(7), and the steps of this algorithm are described in the work by Kirakosyan, Avetisyan, Kondjoryan and Kirakosyan (2014).

The DC motor model

The simulation model of a DC motor is a single input single output system that has one input $V_{app}(t)$ – voltage, and one output $\omega(t)$ – angular speed of the rotor.

In this model, the dynamics of the motor itself are idealized; for instance, the magnetic field is assumed to be constant. The resistance of the circuit is denoted by R and the self-inductance of the armature by L.

The electromagnetic torque τ acting on the motor shaft is proportional to the induced current $i(t)$ and has the form:

$$\tau(t) = K_m i(t), \tag{8}$$

where K_m is the coupling coefficient between armature current and electromagnetic torque. The induced electromotive force V_{emf} is proportional to the angular velocity of the rotor ω and is expressed by the formula:

$$V_{emf}(t) = K_b \omega(t), \tag{9}$$

where K_b is the coupling coefficient between angular velocity and back electromotive force.

The mechanical part of the motor equations is derived, using Newton's law, which states that the inertial load J times the derivative of the rotor angular speed equals the sum of all the torques about the motor shaft. The resulting equation can be written in the form:

$$J\frac{d\omega}{dt} = \sum \tau_i = -K_f \omega(t) + K_m i(t), \tag{10}$$

where $K_{f\omega}$ is a linear approximation for viscous friction.

Finally, the electrical part of the motor equation is given by

$$V_{app}(t) = L\frac{di}{dt} + Ri(t) + K_b \omega(t). \tag{11}$$

This sequence of equations leads to a set of two differential equations that describe the behavior of the motor, the first for the induced current:

$$\frac{di}{dt} = \frac{-R}{L}i(t) - \frac{K_b}{L}\omega(t) + \frac{1}{L}V_{app}(t), \tag{12}$$

and the second for resulting rotor angular speed:

$$\frac{d\omega}{dt} = \frac{-1}{J}K_f\omega(t) + \frac{1}{J}K_m i(t). \tag{13}$$

Rewrite the system of equations in a matrix form:

$$\frac{d}{dt}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \frac{-K_m}{L} \\ \frac{K_m}{J} & \frac{-K_f}{J} \end{bmatrix}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}V_{app}(t), \tag{14}$$

$$y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} i(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix}V_{app}(t). \tag{15}$$

We can construct single input single output models using simple commands in the Control System Toolbox. The state of the system in this case is often written as a column vector $x = [i(t), \omega(t)]^T$. The applied voltage V_{app} is the input of the system $u = V_{app}$, and the angular velocity ω is the output $y = \omega$.

The centrifugal pump model

The mechanical part modeling of an electric motor is given by:

$$J\frac{d\omega}{dt} = k_m i(t) - k_f\omega(t) - \tau_L, \tag{16}$$

where k_f is the viscous-friction coefficient, J is the total inertia of the motor shaft, and τ_L is the load torque.

In this case, τ_L is the hydrodynamic load torque of the centrifugal pump, which is given by the following equation:

$$\tau_L = \tau_N = A_N\omega^2, \tag{17}$$

where:

$$A_N = \frac{N_n}{\omega^3}. \tag{18}$$

The centrifugal pump is also described by an $H(Q)$ characteristic given by:

$$H(Q) = C_1\omega^2 - C_2\omega Q_i - C_3 Q_i^2, \tag{19}$$

where C_1 is the constant parameter corresponding to the «shut off» point, C_2 is the constant parameter corresponding to the «peak head» point and C_3 is the constant parameter corresponding to the «best-efficiency» point.

The pump performance is predicted by specifying a load curve:

$$H = H_g + \Delta H, \tag{20}$$

where H_g is the geometrical height which is the difference between the free level of the water to pump and the highest point of the piping circuit, and ΔH is the friction losses in the piping circuit, which depend on the flow rate. The pump functioning point can be obtained by the intersection point of the pump characteristic and load curve (Kenge, Hasija, Tare & Raghuwanshi, 2020).

Results and discussion

For the engineering parameter optimization, the linguistic description is expressed in termsof IF-THEN statements and the following fuzzy logic inferences:

- RULE_1: IF dN/dI is PB and $\Delta(dN/dI)$ is PB and $\Delta\alpha$ is P then γ is NB.
- RULE_2: IF dN/dI is PB and $\Delta(dN/dI)$ is NS and $\Delta\alpha$ is P then γ is PS.

Fuzzy inference systems are designed to transform the values of input variables of the control process into output variables based on the use of fuzzy production rules. To do this, systems must contain a base of rules for fuzzy productions and implement fuzzy conclusions based on premises or conditions presented in the form of fuzzy linguistic statements. Inference fuzzy rules for the local network of solar pumping stations include 85 fuzzy control rules. In this section, the simulation results of the fuzzy water discharge rate optimization of a solar pumping station driven by a DC motor coupled to a centrifugal pump are presented. Based on the proposed fuzzy optimization method, we investigated the water discharge rate for the solar water pumping station (Nawel, Mourad & Mongi, 2019; Ghosal, Badra & Sahoo, 2021; Singh, Yadav, Kumar & Kumar, 2022). The optimization of the water discharge rate is carried out by maximizing the power of the centrifugal pump for a given intensity of solar radiation (E), which varies slowly with time. This will consequently tend to maximize the DC motor speed (Nasir, 2019; Ganesh, Siva & Rao, 2020; Jafarkazemi & Dabaghi, 2021).

The motor dynamic model associated with the mechanical differential Eq. (16) is solved using the fourth-order Runge–Kutta numerical method. Then, the water discharge rate is calculated using Eqs (19) and (20).

We can write a computer program using MATLAB to evaluate the water discharge rate using Eqs (19) and (20). Such a program is the M-file named pump.m and can be called as follows:

```
>> x = 0: 0.1: 20;
>> plot(x, pump(x)); gridon;
>> x1 = fzero('pump',[0   20])
x1 = 1.99.
```

Listing of the M-file pump.m is as follows:

```
function f=pump( x )
%water discharge rate
lambda=0.0396;
l=7.4;
d=0.1;
xi=4.3;
omega=188.336;
g=9.8;
H=7.4;
C1=4.9234*exp(-2);
C2=8.5825*exp(-5);
C3=-0.041;
f=C1*(omega^2)-C2*omega*x-C3*(x.^2)-H(lambda*(l/d)+xi)*((8*(x.^2))/((pi^2)*(d^4)*g));

end
```

The optimization of the solar water pumping station driven by the DC motor was carried out using fuzzy logic, and the simulation results are shown in Table 1.

TABLE 1. Simulation results of the solar water pumping station with fuzzy optimization

E [W·m^{-2}]	Non-optimized ω [rad·s^{-1}]	Optimized ω [rad·s^{-1}]	Q_i [m^3·h^{-1}]
1 000	188.237	188.336	1.99
900	182.228	182.634	1.93
800	173.956	175.725	1.85
700	164.101	168.152	1.77
600	152.706	159.748	1.68
500	136.746	150.269	1.58
400	121.999	139.333	1.47
300	106.254	126.271	1.33
200	85.644	109.724	1.00

Table 1 also summarizes the simulation results of the non-optimized and optimized solar water pumping system driven by the DC motor, for some solar radiation intensity levels. This explicitly shows the significance of the proposed fuzzy optimization algorithm in terms of the increase in water discharge rates.

Conclusions

This article presents the mathematical modeling of the global network of solar pumping stations for irrigation using MATLAB environment. We have demonstrated that the best method to perform the functioning of the local networks of Solar pumping stations is to introduce the optimization system for the DC/DC buck converter, in particular for the local networks of stations functioning without batteries.

The advantages of the global network of solar pumping stations with the fuzzy-based optimal point tracker over the conventional global network of solar pumping stations include:

1. The online adaptive search of the local network optimal points;
2. Robustness to environmental conditions and parameter variations;
3. High accuracy under different operating conditions;
4. No need for external sensors to detect solar intensity and temperature.

It is clear from the results that DC motor speed, power, and water discharge rate increase when solar insolation increases.

In MATLAB, we have developed a simulating program based on the obtained adequate mathematical models of different components of the solar water pumping station.

Acknowledgements

This work was supported by the Austrian Partnership Program in Higher Education and Research for Development, in the frames of the research project N Prep252 Armenia.

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Summary

Designing optimal solar water pumping stations for irrigation of agricultural lands. An investigation into the design of a stand-alone solar water pumping station for supplying rural areas is presented. It includes a study of system components and their modeling. The solar water pumping station comprises a solar panel, DC/DC buck converter, DC motor driving a centrifugal pump, and a reservoir. The fuzzy-based maximum power point tracker is developed to optimize the drive speed and the water discharge rate of the coupled centrifugal pump. These use dN/dI, $d(dN/dI)$ use parameters, and a variation of the fill factor $\Delta\alpha$ input variables. The proposed solution is based on a judicious fuzzy adjustment of a converter fill factor, which adapts the load impedance to the solar panel online. The simulation results show the effectiveness of the drive system for both transient and steady-state operations. Hence, it is suitable to use this fuzzy logic procedure as a standard optimization algorithm for such solar water pumping stations. The modeling is carried out in MATLAB/Simulink.