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MODELING OF SYSTEMS WITH THE PHOTOVOLTAIC POWER SOURCE AND WATER PUMPS

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The article is devoted to the calculation of systems consisting of a solar photovoltaic power source and water pumps. It is noted that such systems can be used both in households or industry, and in agriculture, in particular for irrigation. Several variants of water pumps are shown. An analysis of the operational modes where the photovoltaic power source is connected to the pump has been carried out. The selection of equipment was carried out and the expediency of using a system with an electric energy booster was indicated. A booster for providing current during start-up modes can be a capacitor, a battery of capacitors or an ionistor. Emphasis is placed on the fact that for doing of such systems it is necessary to apply modeling with the use of electrical models. It is shown that for developing of electric models of solenoid-based pumps and pumps based on rotating direct current motors, it is necessary to use the methods of electromechanical analogies. Electrical models of a photovoltaic power source and, based on analogies, a solenoid-based pump and a direct current motor-based pump with permanent magnet excitation and parallel excitation were developed. When developing electrical models, controlled sources of voltage and current were used with mutual influence of the electrical and mechanical parts of the pumps. The need to use direct current motors with parallel excitation is indicated, as they are more stable to emergency modes. It is also stated that in general, the mechanical load of the rotating part of motors is non-linear and depends on the number of revolutions of the shaft. A nonlinear resistance that models a nonlinear mechanical load is shown, and it is noted that the higher-order nonlinearity is insignificant. Conclusions are drawn and further development in the direction of the use of digital technologies is outlined.

Keywords: *photovoltaic power source, water pump, photovoltaic pump, electrical model, electromechanical analogy, solenoid, direct current motor.*

МОДЕЛЮВАННЯ СИСТЕМ З ФОТОЕЛЕКТРИЧНИМ ДЖЕРЕЛОМ ЕНЕРГІЇ ТА ВОДЯНИМИ НАСОСАМИ

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Стаття присвячена розрахунку систем, які складаються з сонячного фотоелектричного джерела живлення та водяних насосів. Зазначено, що такі системи можуть використовуватись, як в побуті чи промисловості, так і сільському господарстві, зокрема для здійснення зрошення. Показано декілька варіантів водяних насосів. Проведено аналіз режимів роботи під час підключення фотоелектричного джерела живлення до насоса. Здійснено підбір обладнання та вказано на доцільність використання системи з бустером електричної енергії. Бустером для забезпечення струмом під час пускових режимів може бути конденсатор, батарея конденсаторів чи іоністор. Акцентовано на тому, що для побудови таких систем необхідно застосувати моделювання з використанням електричних моделей. Показано, що для побудови електричних моделей насосів на основі соленоїда та насосів на основі обертових двигунів постійного струму потрібно використовувати методи електромеханічних аналогій. Було побудовано електричні моделі фотоелектричного джерела живлення і, з використанням аналогій, насоса на основі соленоїда й насоса на основі двигуна постійного струму зі збудженням на постійних магнітах та з паралельним збудженням. При побудові електричних моделей використовувались керовані джерела напруги та струму з взаємним впливом електричної та *механічної частин насосів. Наголошено на необхідності використання саме двигунів постійного струму з паралельним збудженням, оскільки вони стійкіші до аварійних режимів. Також зазначено, що в загальному випадку механічне навантаження обертової частини двигунів є нелінійним і залежить від кількості обертів валу. Показано нелінійний опір, який моделює нелінійне механічне навантаження та зауважено, що нелінійність високих порядків є несуттєвою. Зроблено висновки та окреслено подальший розвиток в напрямі застосування цифрових технологій.*

Ключові слова: *фотоелектричне джерело енергії, водяний насос, фотоелектричний насос, електрична модель, електромеханічна аналогія, соленоїд, двигун постійного струму.*

Introduction

The development of renewable energy sources, especially solar energy, prompts us to search for technical solutions where such sources would be most appropriate [1]. It would be convenient to use solar energy when it is available because solar generation is highly variable and depends on the meteorological conditions of the environment, geographical location and time of day. One of such applications is powering a water pump from solar energy generators. This is especially appropriate in the sector of agriculture and landscaping, where irrigation and pumping of water for agricultural purposes is required, as well as in autonomous water supply systems, especially with the use of thermal collectors [2].

There are quite a few implementations for such use [3,4], but from the point of view of efficiency, convenience and versatility, the most appropriate is the use of pumps with electric motors, which are connected to solar photovoltaic energy sources directly [5]. Also note that to simplify the system, it is advisable to use direct current (DC) motors with a rated operating voltage that corresponds to the rated operating voltage of the vast majority of solar photovoltaic sources. This approach will avoid the use of additional converting equipment, which will lead to the complication and increase in the cost of the system.

In order to choose the proper equipment, we face a number of challenges, such as technological, economic, social, etc. [6]. Therefore, it is very important to choose the correct equipment and carry out its modeling and simulation. To conduct research on energy and mechanical processes involving energy sources and electric motors, it is advisable to use a way that performs modeling of energy processes of various nature and combines them. One of these devices can be a research method based on the creation of electrical models and equivalent electrical circuits [7]. This approach is convenient to use both for modeling electrical processes and electronic circuits, as well as mechanical systems and processes. That is, the main task is to build a system from a photovoltaic energy source and a water pump and create an electrical model.

Materials and methods

Two main types of water pumps are used to pumping water: centrifugal and positive displacement. In centrifugal pumps, rotation of an impeller sucks water in through the middle of the pump and gives out water at the edge [8]. In positive displacement pumps, parts of water are transferred by a primary mover, like a piston or a screw-type device [9]. In centrifugal pumps, rotary engines are primarily used, and in positive displacement pumps, both rotary engines and solenoid-based mechanisms can be used.

Source of electrical energy is a PV-panel or PV-array. Photovoltaic power sources could be connected to motors of pumps by different ways [10].

Direct connection of a photovoltaic (PV) panel or PV-array to the pump is possible only if the pump has a DC-motor [11]. The operating point results from the intersection of the pump volt-ampere (VI) curve with the PV-source VI-curve. If the curve of pump is too high (array current is undersized), the pumping threshold will be high, that is penalizing during low irradiances (low season, cloudy days and morning/evening). If it is too low, the full potential power of the array is not used during bright hours. The optimal sizing therefore depends either on the irradiance distribution (i. e. location, orientation, meteorological data), and on the periods when the water needs are more important.

Another way of the direct connection is through configuration of PV-array [12]. Getting necessary parameters of voltage and current may be improved by performing a PV-array reconfiguration by reconnecting of PV-panels [13]. If we use two identical groups of PV-panels, at low irradiance all groups are connected in parallel, providing the high currents necessary to start the pump. From a given irradiance level, the groups are connected in series, increasing the voltage and decreasing the current of the PV array. This configuration requires electric or electronic switches [14].

However, the better method is a direct connection of the PV-panel to a booster and to motor of the pump. Thus, the direct coupling configuration is improved, especially, that of DC displacement pumps. Most displacement pumps require significant current when DC-motor starts. The current of PV-panel or array may not be able to provide the peak, increasing the irradiance threshold. Help is usually provided by a booster device, which stores the PV energy in a big capacitor and gives it back as a peak current. Also, one could use a supercapacitor (ionistor) or electric battery with significant peak of the output current [15].

The high-tech method supposes using of converters and controllers, for example maximum power point tracker. This electronic device connects PV-panels to a load with fixed voltage and current for maximum output power, and behaves as a current generator for supplying the DC motor of the pump. At the input side, the voltage may be chosen close to the maximum power point. At the output side, the power is supposed to be transmitted to the motor at the optimal current/voltage point corresponding to the available power and the motor needs.

The opposite option is to use alternate current (AC) pumps. It includes a DC/AC inverter with harmonic output of supplying power and some requirements to voltage and frequency that must be met for proper operation of the pump.

Having analyzed connection options as per the list above, we can come to the conclusion that the optimal way, at the initial level, to structure a system with a PV-source and a pump - from an economic and operational point of view - is to use a direct connection with a booster (Fig. 1).

The method of using electromechanical analogies [16, 17] (Table 1) was applied to build the electric model of the engine [18, 19]. The main and basic concepts when building analogies are basic definitions, such as effort and flow.

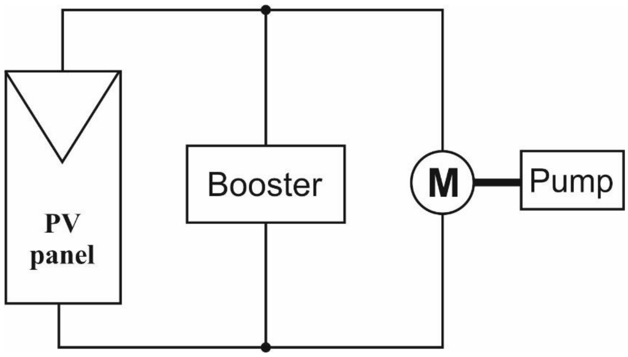

Fig. 1. PV-panel with a booster connected to a pump (where M is DC-motor)

Table.1. Mechanical–electrical analogies

	Effort *e*	Flow *f*
Mechanical translation variable	Force *F*, N	Velocity *V*, m/s
Mechanical rotates variable	Torque *M*, Nm	Angular velocity w, rad/s
Electrical variable	Voltage *U*, V	Current *I*, A

It can be seen from Table 1 that the following dependence is formed for motors with translational motion:

$$F \to U \,, \tag{1}$$

$$V \to I \,. \tag{2}$$

It can be seen from Table 1 that the following dependence is formed for motors with rotating motion:

$$M \to U, \tag{3}$$

$$\omega \to I. \tag{4}$$

Results

A modeling mechanism using electrical models was used for the calculation.

Considering the electrical model of an energy source with a booster, we have a circuit that comprises an ideal I_{SUN} current source, a diode *D* (which can be represented by a nonlinear resistor), a shunt resistor R_P and a series resistor R_S, as well as a capacitor *C*, which is a booster (Fig. 2).

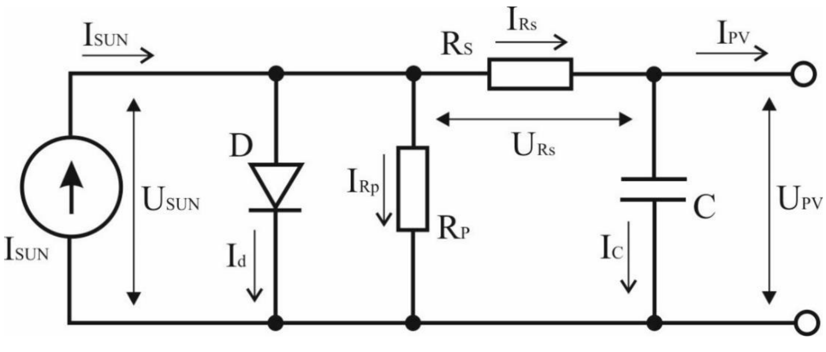

Fig. 2. PV power source with a booster

Electrical equations of a photovoltaic source with a connected booster:

$$I_{SUN} = I_d + I_{Rp} + I_{Rs} \,, \tag{5}$$

$$I_{PV} = I_{Rs} + I_C \,, \tag{6}$$

$$U_{SUN} = U_{Rs} + U_{PV} \,, \tag{7}$$

where I_{SUN} – current of a photon-charge conversion; I_d – current of a reverse diode; I_{Rp} – current of a shunt resistor; I_{Rs} – current of a series resistor; I_{PV} – current of a PV-source; I_C – current of a booster; U_{SUN} – voltage of a pn-junction; U_{Rs} – voltage of a series resistor; U_{PV} – voltage of a PV-source

$$I_C = C\frac{dU_{PV}}{dt} \,, \tag{8}$$

$$I_{Rs} = \frac{U_{Rs}}{R_S} \,, \tag{9}$$

where C – capacity of booster.

$$I_{SUN} = \alpha G A_{cells}, \tag{10}$$

where G – solar global irradiance at the level of solar cells; *α* – the effective transmittance–absorptance product of the cell; A_{celsl} – the surface area of cells.

The reverse current is given by the standard diode theory [20]:

$$I_d = I_0\left(e^{\frac{eU}{kT}} - 1\right)$$

where I_0 – saturation current [21]; U – voltage of a diode; e – charge of electron; k – Boltzmann's constant; T – cell temperature.

Series resistance R_s and shunt current R_p of PV cells can be determined by different ways from materials and analysis of V-I-curves [22].

Electrical equations of pumps with solenoid [23]:

$$U_{IN} = I_{Sl}R_{sl} + L_{sl}\frac{dI_{Sl}}{dt} + U_{SLN}\ , \tag{11}$$

$$U_{SLN} = I_{Sl}\frac{dL_{sln}(x)}{dx}\frac{dx}{dt}, \tag{12}$$

where U_{IN} – input voltage of a pump; I_{Sl} – current of a solenoid; U_{SLN} – voltage of a nonlinear part of solenoid; R_{sl} – resistance of solenoid; L_{sl} – linear inductance of a solenoid; $L_{sln}(x)$ – nonlinear inductance of a solenoid.

Equation of motion of pumps with solenoid [24]:

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx + F = 0\ . \tag{13}$$

where x – displacement of piston of a solenoid; m – mass of piston of a solenoid; b – dissipation coefficient; k – elasticity coefficient; F – input force.

$$L_{PDP}\frac{dI_{PDP}}{dt} + I_{PDP}R_{PDP} + \frac{1}{C_{PDP}}\int I_{PDP}dt + U_{PDP}(U_{SLN}) = 0. \tag{14}$$

where I_{PDP} – modeling current of a positive displacement pump; U_{PDP} – modeling voltage of a positive displacement pump; L_{PDP} – modeling inductance of a positive displacement pump; R_{DPD} – modeling resistance of a positive displacement pump, C_{PDP} – modeling capacity of a positive displacement pump.

Proceeding from the equivalent circuit of solenoid and equations (11), (12), (14) an electric model of a solenoid-based pump is presented (Fig. 3).

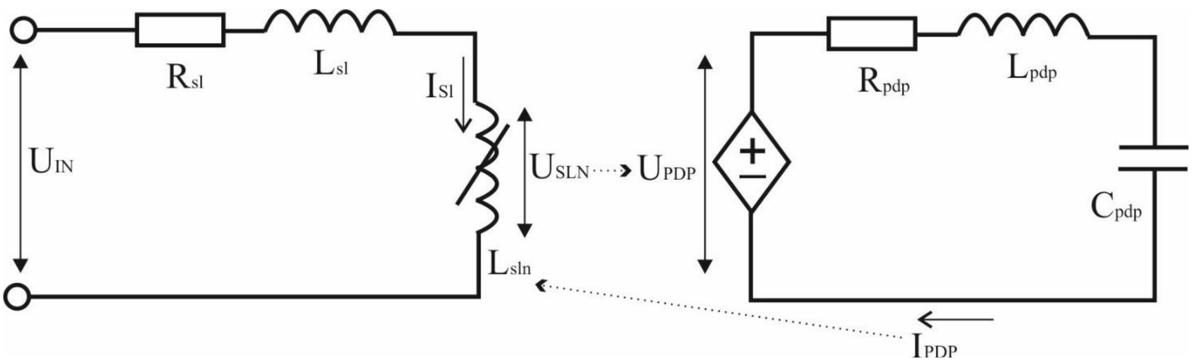

Fig. 3. Electric model of a solenoid-based pump

From equation (12) and the electrical model (Fig. 3), we can see that there is a dependence of the nonlinear inductance on the I_{PDP} current, which models the speed of movement of the core in the solenoid:

$$L_{sln} = \alpha(x)I_{PDP}\ , \tag{15}$$

where $a(x)$ – nonlinear factor.

The electrical model from Fig. 3 contains a controlled power source U_{PDP} [25], in which the voltage depends on the U_{SLN} voltage:

$$U_{PDP} = \beta U_{SLN}\ , \tag{16}$$

where b – factor of transformation.

DC motor equation [26]:

$$U_{in} = \mu\varphi\omega + I_{rot}R_{rot} + L_{rot}\frac{dI_{rot}}{dt}\ , \tag{17}$$

$$J\frac{d\omega}{dt} = \mu\varphi I_{rot} - M\ , \tag{18}$$

where U_{in} – input voltage of a pump; m – proportionality coefficient; φ – magnetic flux in the gap; ω – angular velocity; I_{rot} – current of rotor; R_{rot} – resistance of rotor; L_{rot} – inductance of rotor; J – moment of inertia; M – torque.

According to expressions (3)-(4), (17)-(18) we have the following equations for the electrical model of pumps and a rotating DC motor:

$$U_{PV} = U_1 + I_{rot}R_{rot} + L_{rot}\frac{dI_{rot}}{dt}, \tag{19}$$

$$L_M\frac{dI_M}{dt} = U_2 - U_M. \tag{20}$$

where U_1 and U_2 – mutually controlled voltage sources that simulate the joining of armature (rotor) current and angular velocity; U_M м voltage that simulates the torque; I_M – current that simulates the angular velocity; L_M – inductor that simulates the moment of inertia.

Fig. 4 presents an electrical model based on equations (19), (20). R_M is modeling resistance of mechanical loads and equals voltage that simulates the torque divided by current that simulates the angular velocity.

This electrical model (Fig. 4) contains controlled power sources U_1 and U_2, in which the voltage depends on the currents I_M and I_{rot}:

$$U_1 = \gamma_1 I_M\ , \tag{21}$$

$$U_2 = \gamma_2 I_{rot}\ , \tag{22}$$

where γ_1, γ_2 – conversion factors.

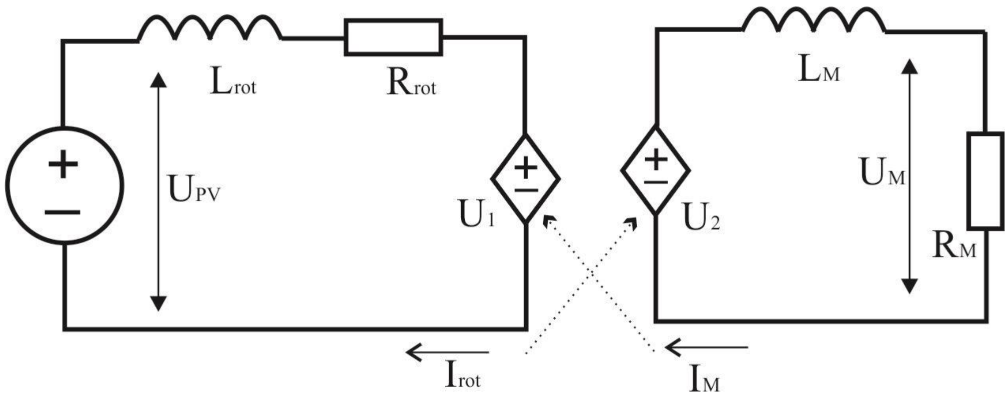

Fig. 4. Electric model of a pump with DC motor

The electrical model of the DC motor in Fig. 4 does not take into account the presence of excitation windings, which can be dependent and independent. In motors, where the magnetic field of the stator is created by inductors, they must be taken into account in the circuit and in the calculation. Having considered the various configurations of such motors, it should be noted that when the excitation winding is connected in parallel to the armature winding, the direct current motor provides the maximum stable number of revolutions [27], which we need for stable and controlled pumping of water. In this case, the electrical model looks as shown in Fig. 5.

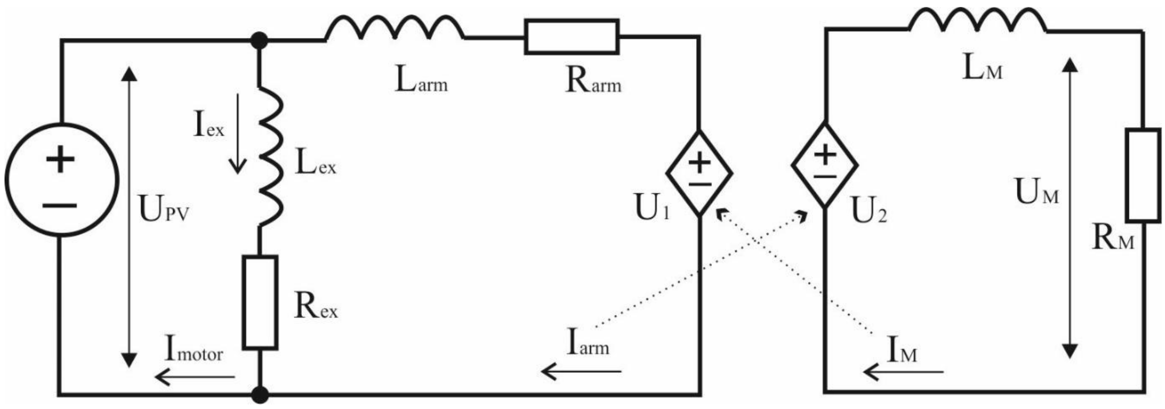

Fig. 5. Electric model of DC-motor pump with parallel excitation

The electrical model from Fig. 4 contains controlled power sources U_1 and U_2, in which the voltage depends on the currents I_M and I_{arm}:

$$U_1 = \gamma_3 I_M \,, \tag{23}$$

$$U_2 = \gamma_4 I_{arm} \,, \tag{24}$$

where γ_3, γ_4 – conversion factors.

It should be noted that when the excitation winding and the armature winding are connected in series, in the absence of a load or a small load, an emergency mode may occur in which the revolutions will begin to increase uncontrollably. This mode is not permissible in our case. Motors with mixed (parallel and series) excitation [28], which is an intermediate option between parallel and series excitation, do not have the mentioned disadvantages.

Another aspect of water pump operation is that, in general, the mechanical load is non-linear [29]. Accordingly, the value of the mechanical torque M and the value of the resistance that models the mechanical torque, R_M, are also non-linear.

In this case, we present the mechanical torque in the form of a polynomial:

$$M = a + b\omega + c\omega^n, \tag{25}$$

where a is the static torque of the rotating parts; b reflects the proportional component of the load torque; c and n depend on the nonlinear properties of the mechanical load. The properties of mechanical loads are such that the main part of the mechanical torque consists of the first two terms, that is, the coefficient c can be considered a small parameter.

According to (25), the resistance simulating the mechanical load looks as follows:

$$R_M = A + B(I_M) + C(I_M^n), \tag{26}$$

where A is a linear resistance that simulates the mechanical load of rotating parts; B is a non-linear resistance that depends on the current I_M and simulates a mechanical load that is proportional to the revolutions; C is a resistance that depends on higher harmonics and is, as noted above, insignificant.

It should be noted that the inclusion in the calculation and modeling of the nonlinear component of the mechanical moment is the process that doesn't depend on the motor type (with dependent or independent excitation winding) process. Thus, we can simulate the entire range of DC motors for different load modes.

Conclusion

As a result, we have produced electric models of various types of pumps that are connected to solar photovoltaic power sources. The obtained models make it possible to conduct simulations both with the help of specialized software for simulation of electrical circuits [30] and with the help of software for general modeling [31, 32].

Modeling is a productive means of calculating renewable energy systems, especially using electrical models. Analysis and calculation of circuits containing electromechanical converters should be carried out using analogies that represent mechanical values via electrical values.

Conducting modeling and simulation before building real water supply systems in agriculture and in everyday life based on solar power sources is an expedient and rational step. Further development in this research area would be via the application of digital technologies, namely the use of brushless DC motors controlled by a microcontroller.

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