

Simulation Study for a UV Water Disinfection Unit Powered by a Photovoltaic System

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Abstract

This work presents a simulation model for a specific UV disinfection system (UVDS) powered by a Photovoltaic System. The global UVDS also includes the electronic converters, Electronic Ballast, UV Lamp and Motor Pump. The equations that model the physical components' behaviour are connected to obtain a dynamic global model. The latter is converted in a Simulink/Matlab model, which allows to carry out simulation series concerning the entire UVDS.

The physical parameters: the irradiation G and the temperature T , are considered as inputs. series of measurements carried out in order to show how these parameters affect the current, the voltage of the PVs and especially the value of the current of the UV lamp, on the other hand a study on the behavior and the evolution of the parameters of the motor pump such as the armature current, motor torque, speed of rotation and the water flow. The purpose of all this is to realize how important are the two parameters concerning the lamp current and the water flow because they are two very important factors to keep an adequate water quality.

Key words:

dynamic model, converters, photovoltaic system, simulation, UV disinfection system.

1. Introduction

The UV water disinfection is a complex technology whose effectiveness depends on some important parameters corresponding to the water flow rate, the UV intensity, the water quality, the temperature, the exposure time, the microorganism concentration etc[1-3]. In this work, we present mainly a complex system that integrates the UV disinfection system (UVDS) and a power source, which is a Photovoltaic System (PVS). Other electronic subsystems make the necessary processing of the electric signals between the PVS and UVDS. The structure of this complex system, including the UVDS, is presented in Fig.1 It also includes a

The most used UV water disinfection systems employ tubular germicidal lamps surrounded by a quartz tube submerged in a chamber through which the fluid flows. Usually, a low-pressure mercury arc lamp is the UV source of radiation. It generates shortwave UV in the range of 253.7

nm [5-7-18].

The disinfection system also includes the motor pump for aspirating contaminated water from the inlet tank, a flow control valve to generate different flow rates, and a filter to improve the quality of the contaminated water [2-3].

Our work aimed to construct a simulation model for all the components of the complex disinfection system. A simulation model will be constructed using Simulink/Matlab system for each subsystem[8-9], starting from the electronic circuit and the equations governing the physical component at hand. Finally, the global simulation model is achieved by connecting these partial models.

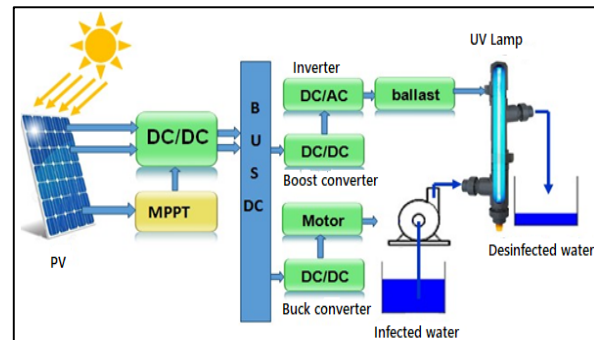


Fig. 1 Structure of the UVDS powered by the PVS

2. Photovoltaic System

The photovoltaic system yields the total needed power for the UVDS.

The use of photovoltaic panels as a source of energy is an adequate solution to avoid the problems of energy shortages and ensure a good performance of the system.

From the mathematical equations involved, we have developed a photovoltaic panel model using the Matlab / Simulink environment.

In this work, we have used a specific photovoltaic system compound of N_s cells, each one consisting of a photovoltaic module KC200GT [8-9] having $1000\text{W}/\text{m}^2$ and the

characteristics given by TABLE 1 at 25°C.

Table 1 : Specifications Of The Photovoltaic Modules

Designation	KC200GT
Maximum power (P_{max})	200.143W
Voltage at maximum power (V_{mp})	26.3V
Current at maximum power (I_{mp})	7.61A
Open circuit voltage (V_{OC})	32.9V
Short circuit current (I_{SC})	8.21A
Temperature coefficient of V_{OC} (K_V)	-123mV/°C
Temperature coefficient of I_{sc} (K_I)	3.18mA/°C
Number of cells (N_s)	54

the electrical model of the photovoltaic generator corresponding to a cell is presented in figure 2 :

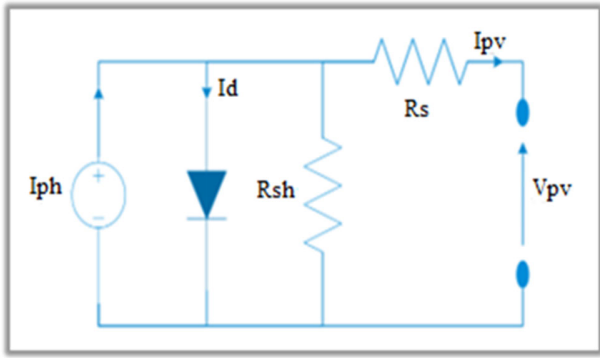


Fig. 2 Model of a single diode photovoltaic generator

With the identical circuit of figure 2 and using Kirchoff's law, we obtain the following condition for the load current :

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

The significance of the variables is given below:

I_{pv} : the output current ;

I_{ph} : the generated photocurrent;

I_d : the diode current ;

I_{sh} : the shunt resistance current ;

Using the Shockley condition, it holds:

$$I_d = I_0 \left[\exp\left(\frac{V_j}{n \times V_t}\right) - 1 \right] \quad (2)$$

where n is the ideal diode factor ($1 < n < 2$ for a unique junction), I_0 the diode inverse saturation current, and V_t the thermic voltage at 25°C. In our case, we have

$V_t = 0.0259$ V calculated according to (3) :

$$V_t = K \times T \times N_s / q \quad (3)$$

where K is the Boltzmann constant, q is the electronic charge, and T is the functioning temperature. The current through the series resistor, R_s , is given by (4)

$$V_j = V_{pv} + I_{pv} \times R_s \quad (4)$$

where the appearing variables are:

V_{pv} : the output voltage;

V_j : the junction voltage (the voltage across the diode and resistor R_{sh});

I_{pv} : the output current;

R_s : the series resistor.

The diode inverse saturation current I_0 can be computed using (5)

$$I_0 = I_{rs} \left(\frac{T}{T_n}\right)^3 \cdot \exp\left[q \cdot E_{g0} \cdot \left(\frac{1}{T_n} - \frac{1}{T}\right) / (n \cdot K)\right] \quad (5)$$

where I_{rs} is the nominal saturation current given in (6).

$$I_{rs} = I_{sc} / \left[\exp\left(\frac{q \times V_{OC}}{n \times N_s \times K \times T}\right) - 1 \right] \quad (6)$$

Equations (3), (4), (5), and (6) allow calculating the value I_d from (2).

The photocurrent generated by the cell, which depends on the ambient temperature and solar Irradiation (G), can be calculated using equation (7)

$$I_{ph} = I_{sc} + K_I \cdot (T - 298) \cdot G / 1000 \quad (7)$$

The value K_I is given in Table 1.

The current through the shunt resistor R_{sh} is given by (8)

$$I_{sh} = (V_{pv} + I_{pv} \times R_s) / R_{sh} \quad (8)$$

Finally, we have all the elements to evaluate the output current by (9).

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{q \times (V + I \times R_s)}{n \times K \times N_s \times T}\right) - 1 \right] - I_{sh} \quad (9)$$

The Fig. 3 depicts the simulation model for the global photovoltaic subsystem (PVS) using MATLAB /Simulink environment. The parameters of this model are given in Table 2.

According to equation 9 of the output current, we made the necessary connections between the Simulink blocks, to finally obtain a global model of a photovoltaic panel as follows in figure 3.

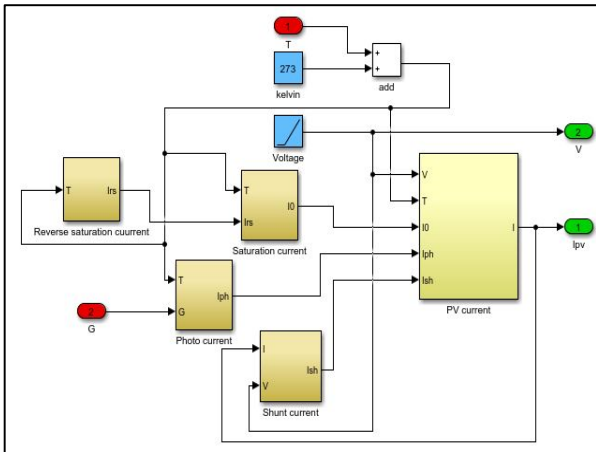


Fig. 3 The photovoltaic system.

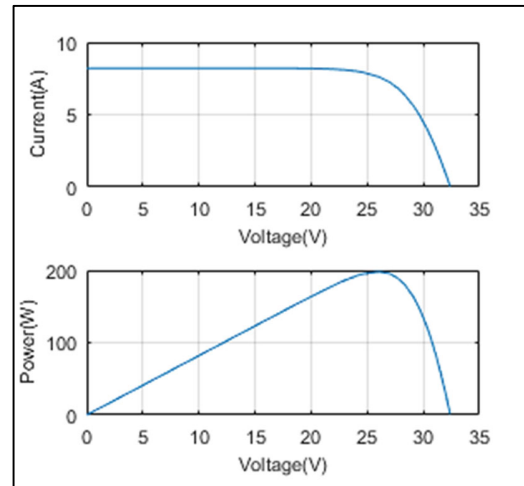


Fig. 4 The characteristic curves of the PVS.

Table 2 : Parameters Of The Global Photovoltaic System

Parameter	Value	Param.	Value
R_s	0.221 (Ω)	G	1000 (W/m^2)
R_{sh}	415.4 (Ω)	E_g	1.1
K	$1.38 \cdot 10^{-23}$	q	$1.6 \cdot 10^{-19}$ (C)
N_p	1	T	$25^\circ C$
n	1.3		

3. Global Simulation Model

In this work, the simulation study of the UV water disinfection system is made using the Simulink model presented in Fig. 5. Besides the PVS, the UV lamp and the DC motor pump, the model presents all the converters that assure the interface among the former subsystems.

The simulations have yielded the characteristics plotted in Fig. 4, namely the power-voltage and current-voltage, respectively. This figure shows that the maximal power produced by the photovoltaic system is $P_{max}=200$ W.

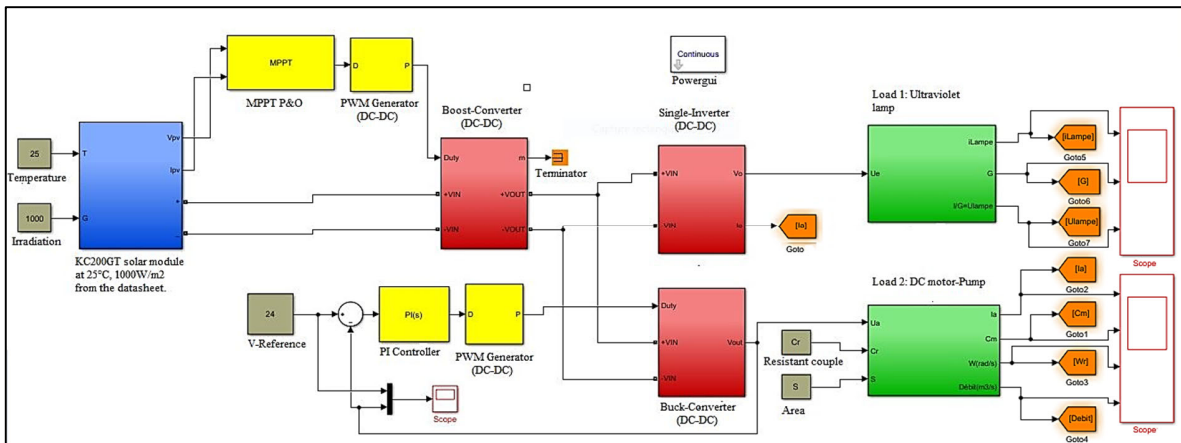


Fig. 5. Simulink model of the UV water disinfection unit.

3.1 Convertors

The *boost converter* is a static DC/DC converter that increases the output voltage compared to the input voltage

produced by the PVS.

The photovoltaic conversion chain aims to optimize the power supplied by the photovoltaic system. Fig. 6 presents

the generic structure of a boost converter endowed with the MPPT algorithm [17]. The latter one establishes the duty cycle α that involves the maximum power transfer toward the DC Charge. This desideratum is achieved whatever the meteorological conditions are and the system's charge is. The command can be calculated using the well-known Perturbation and Observation (P&O) algorithm. The boost converter's electronic scheme used in this work has a usual structure[9-10].

The *static inverter* is a power electronic device that converts direct current to alternating current. In Fig. 5, the single inverter interfaces the boost converter and the UV lamp. This device has a usual structure.

The *buck* or *step-down converter* is a DC-to-DC power converter that steps down the input voltage to produce the output voltage. The considered electronic circuit, together with a PI controller and a PWM generator, make up a control loop that supplies the voltage for the motor pump.

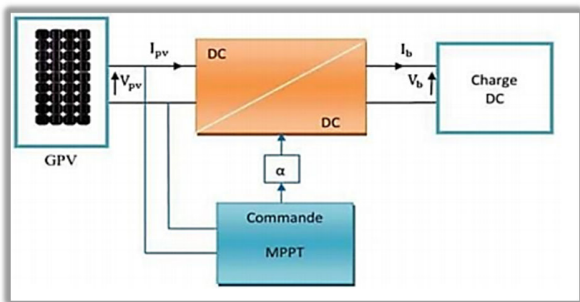


Fig. 6. The boost converter chain with MPPT command

3.2 Electronic ballast and UV lamp

The disinfection system is equipped with a single low-pressure mercury discharge lamp supplied via electronic ballast [4-13-16]. The latter consists of a single-phase rectifier, a transistor inverter producing 25–100 kHz at its output, and a resonant circuit that achieves the lamp ignition. The ballast circuit must ensure three general functions: the starting of the discharge lamp, lamp relighting each half cycle and control of the electric current through the discharge lamp. Fig. 7 gives the general structure of this subsystem.

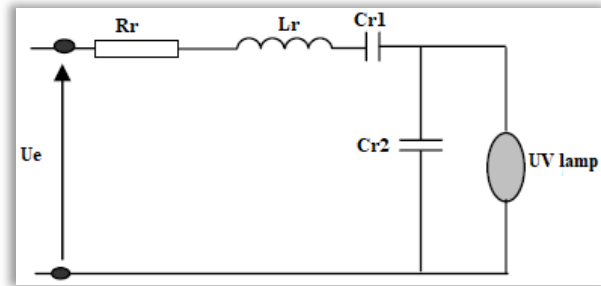


Fig. 7 Electrical diagram of the power supply UV lamp

The discharge UV lamp needs a voltage assuring its triggering. That is why it uses an electronic ballast that supplies the UV lamp with a high-frequency voltage and increases the voltage value for a short while to produce the discharge [14]. This increase is produced by a resonant series circuit made of the resistor R_r , inductor L_r and two capacitors Cr_1 and Cr_2 [12], as in Fig. 7. The ballast – UV lamp dynamic model is described using equations (10)–(12).

$$U_e(t) = R_r i(t) + L_r \frac{di(t)}{dt} + U_{Lamp}(t) \quad (10)$$

$$U_{Lamp}(t) = \frac{I_{Lamp}(t)}{G(t)} \quad (11)$$

$$\frac{dG}{dt} = a_2 i^2 - b_2 G^2(t) - b_1 G(t) \quad (12)$$

$G(t)$ is the UV lamp's conductance.

Equation (12) allows calculating the discharge lamp conductance by a differential equation named *G*-model (Herrick's nonlinear model, see [6-7-15]).

Discharge lamps need certain electrical circuits for their proper functioning. This is achieved by ballasts, which can be constructed from semiconductors and passive components (electronic ballast).

It is very difficult to obtain models for discharge lamps because of the negative impedance of discharge lamps and the complexity of the analysis and physical phenomena that occur inside the discharge tube.

In addition, discharge lamps can be operated at different with electromagnetic or electronic ballasts. These different operating conditions can affect the behavior of the lamp such as the I-V characteristic which changes with frequency.

The figure 8 shows a simulink model concerning the UV ballast-lamp part is realized to obtain the different parameters of the lamp such as the lamp current and voltage and the conductivity G .

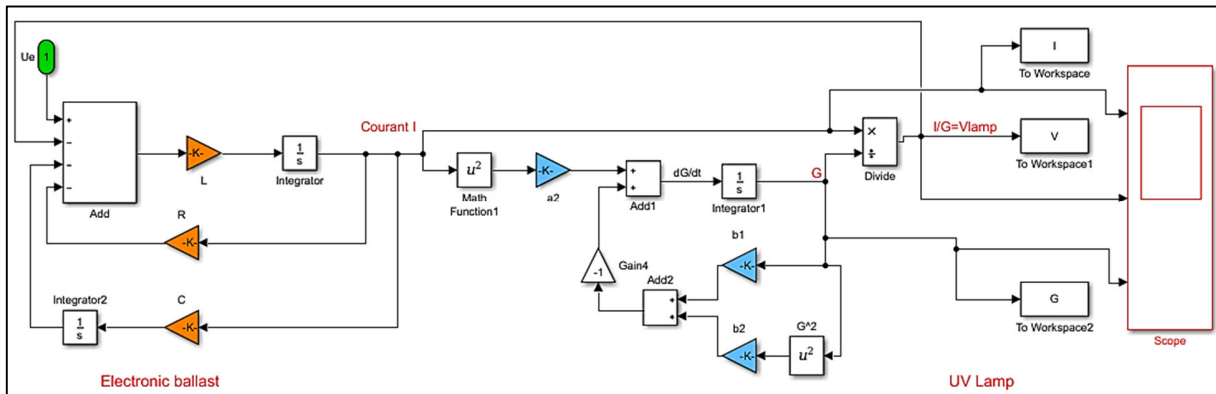


Fig. 8. Simulation model for the Electronic Ballast - UV lamp subsystem.

The determination of parameters a_2 , b_1 , and b_2 is done using an identification approach (see [7]), leading to an optimization problem: the identification errors must be minimized. A possible optimization method consists in using a metaheuristic algorithm as Particle Swarm Optimization. We have used the same metaheuristic algorithm (see [11]) to determine the three parameters.

The simulation model for this subsystem, electronic ballast - UV lamp, is depicted in Fig. 8.

3.3 Motor Pump

The UVDS also has a motor pump for aspirating contaminated water from the inlet tank. The motor pump subsystem must have the possibility to control the infected water flow rate, which will set the exposure time to UV irradiation. The following equation can express the latter:

$$t_{\text{exposure}} = V / Q \quad (13)$$

The values V and Q are the reactor's volume and water flow rate, respectively. The variation of Q determines the possibility to control the exposure time and consequently the UV dose received by the infected water.

The hydraulic system constitutes a very significant part in the pilot unit of water disinfection.

The motor dynamics can be described by the following equations:

$$U_a = R_a I_a + L_a \frac{dI_a}{dt} + K_b w \quad (14)$$

$$C_m = J_m \frac{dw}{dt} + Fw + C_r \quad (15)$$

We have considered a DC motor with a permanent magnet stator and a centrifugal pump whose simulation model is depicted in Fig. 9. The parameters of the Motor Pump considered in the proposed model are the following: U_a - Motor voltage; R_a - Rotor resistance; L_a - Inductance of the armature; I_a - Induced current; C_m - Motor torque; C_r -

Load torque; F - the viscous friction coefficient; J - the moment of inertia of the load; S - the area of the passage section;

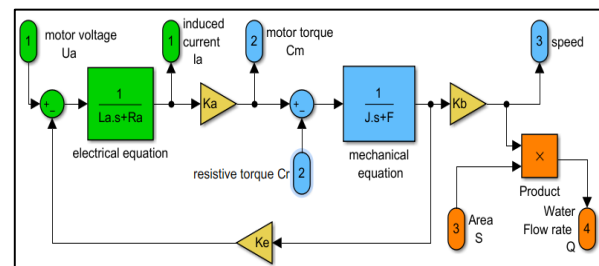


Fig. 9. Motor Pump simulation model.

4. Simulation results

The global simulation model presented in Fig. 5 allowed us to perform series of simulations for the entire UVDS. Table 3 shows the results obtained when two physical input parameters were considered: solar irradiance G [W/m^2] and operating temperature T [$^{\circ}C$]. These values refer to the PVS current and voltage and the maximum value of the UV lamp current (I_{lamp}).

A small program realized on matlab in order to obtain the curves of evolution of the parameters under the effect of G and T . Figure 10 shows the evolution of the lamp current as a function of solar irradiation for each temperature.

The low pressure discharge lamp used in this work has the following characteristics: power -70 W, nominal current - 0.65 A, length -400 mm, diameter -15 mm. For this UV lamp, the current-voltage characteristic curve is shown in Fig. 11 produced by the simulation model described in Fig.8.

the current and the conductivity of the UV lamp represented respectively in fig. 13 and 14.

Table 3 : Results Of The Uvds Simulation Considering Two Input Variables: G And T

G	800			900			1000			1100			1200		
	I_{pv}	V_{pv}	I_{lamp}	I_{pv}	V_{pv}	I_{lamp}	I_{pv}	V_{pv}	I_{lamp}	I_{pv}	V_{pv}	I_{lamp}	I_{pv}	V_{pv}	I_{lamp}
$T=25$	0.379	129.1	0.644	0.382	130	0.649	0.384	130.8	0.653	0.386	131.6	0.657	0.388	132.2	0.66
$T=20$	0.392	133.5	0.666	0.395	134.4	0.671	0.397	135.1	0.675	0.399	135.9	0.678	0.401	136.5	0.681
$T=15$	0.405	137.8	0.688	0.407	138.7	0.692	0.41	139.5	0.696	0.412	140.2	0.7	0.414	140.8	0.703
$T=5$	0.43	146.4	0.731	0.433	147.3	0.735	0.435	148.1	0.739	0.437	148.7	0.742	0.439	149.4	0.745
$T=0$	0.443	150.8	0.752	0.445	151.6	0.757	0.448	152.4	0.760	0.45	153	0.764	0.451	153.6	0.767

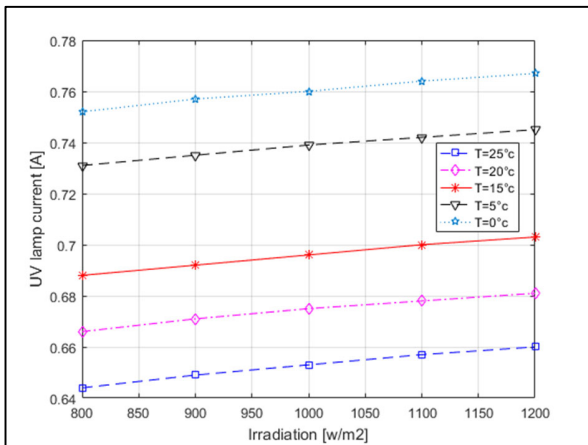


Fig. 10 Evolution of the UV lamp current versus Irradiation

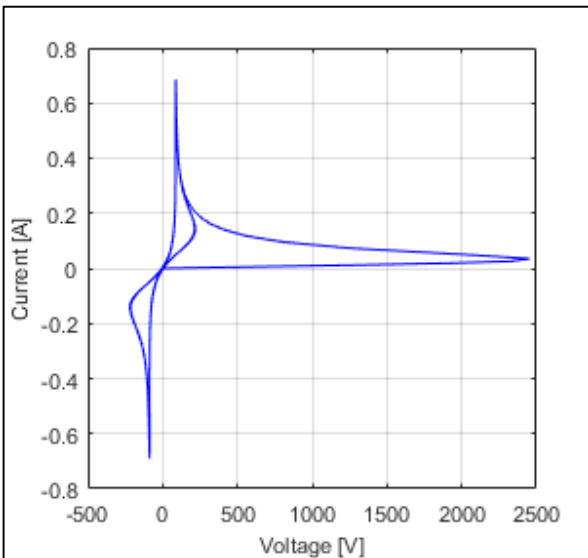


Fig. 11 The Current-Voltage characteristic curve of UV lamp

The simulated evolution of the UV lamp voltage and the lamp current are shown successively in figures 12 and 13.

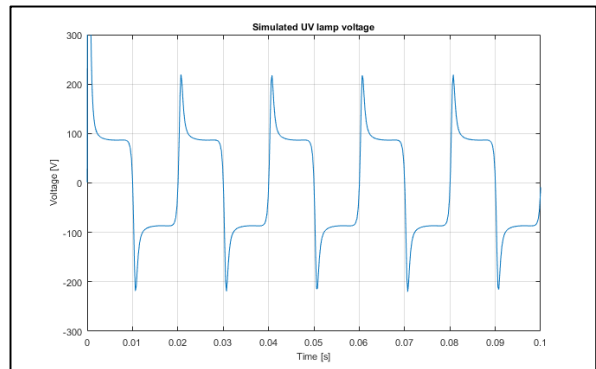


Fig. 12. The evolution of the UV lamp voltage

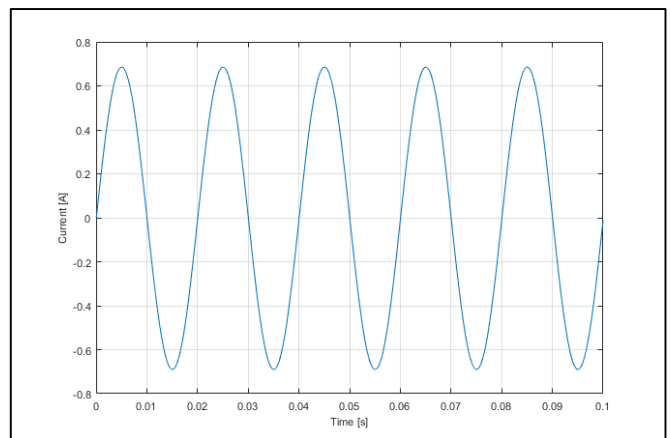


Fig. 13 The evolution of the UV lamp current

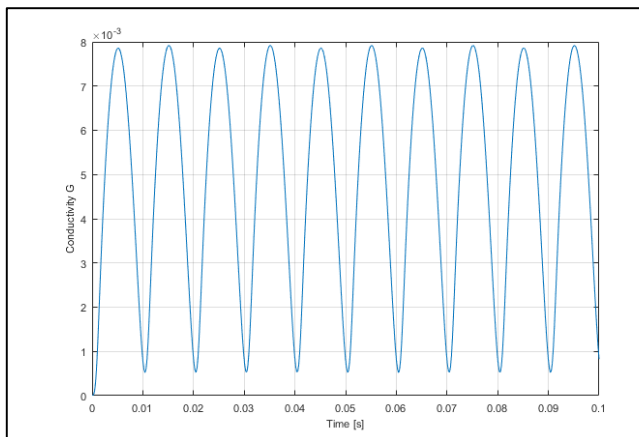


Fig. 14 The conductivity of the UV lamp.

The curves presented in Fig. 11 and 12 are typical of the low-pressure discharge lamp. This fact proves that the Ballast-UV lamp simulation models are realistic and fulfil the requirements.

The Motor Pump subsystem simulation was also carried out using the control loop, including the PI controller and the Buck-Converter. The setpoint of the control loop, represented by the "V-Reference" value, was set to multiple values to study the Motor Pump behaviour. Fig. 15 presents the evolution of the Induced current, Motor torque, Rotation speed and Water flow rate for three setpoint values. These values have produced three different values of the motor voltage U_a : 24, 20 and 16 V. The obtained curves are depicted in Fig. 15 in blue, brown and yellow, respectively. One can see a normal evolution of the four parameters of the Motor Pump.

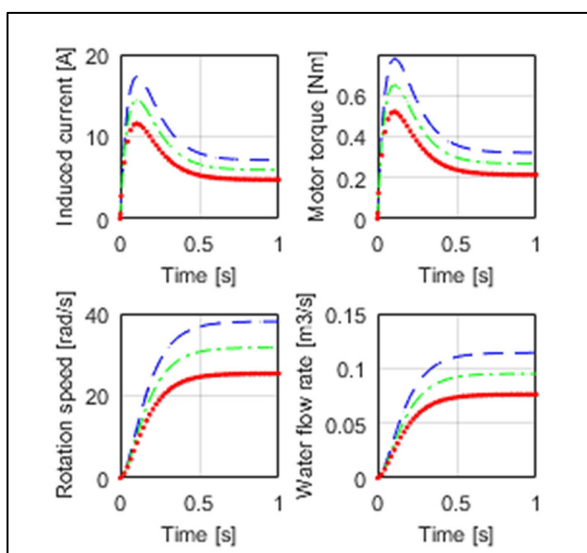


Fig. 15 Evolution of the Motor Pump's parameters

5. Conclusion

This paper has proposed analytical models for each subsystem of the specific UVDS considered in this work. These models were connected to produce a dynamic global model of the UVDS at hand, which has been the basis for the simulation model's construction. Using the Simulink/Matlab system, a general simulation model has been proposed. The simulation series carried out proved that the models were realistic and produced useful data.

Otherwise this work is a validation of the simulations of the global system of the UV water treatment unit, further highlighting the importance of the values of lamp current and water flow to keep an adequate water quality, this work is considered as a continuation of what we have done in detail in [3] as a process control of water treatment to ensure water quality and using the PSO algorithm.

Future work could use this UVDS global model to determine the optimal parameters for all subsystems in given circumstances (G , T). The performance index could be the maximal quality of water disinfection.

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