SEPIC - MPPT controller with photovoltaic energy for groundwater extraction

C L Corzo¹, R A Núñez¹, J I Flórez², P A Rodríguez¹ and K J Plata¹

¹Electronic Engineering Program, Unidades Tecnológicas de Santander -UTS-, Calle de los estudiantes # 9-82 Ciudadela Real de Minas, Bucaramanga, Colombia
²Master in Industrial Controls, Universidad de Pamplona, Calle 5 # 3-93, Pamplona, Colombia

ccorzo@correo.uts.edu.co

Abstract. The model-based design methodology is presented for the development of an experimental SEPIC-MPPT controller powered by a photovoltaic module, designed to extract water from a deep well using a DC submersible motor pump. To specify the proposed methodology, a photovoltaic panel was characterized under various conditions of solar radiation and the modeling of its Voltage-Current relationship was carried out. The best tilt angle for the installation was determined to be nine degrees (9º). Similarly, a SEPIC controller was developed from model-based design. The results obtained showed an average adjustment error of less than 4%, on the performance parameters contrasted in the modeled / experimental system. The efficiency achieved by the SEPIC-MPPT controller was 85.26%. It is concluded that the methodology implemented for the design is coherent and valid for the development of SEPIC-MPPT controllers with application in underground water extraction systems, in areas with photovoltaic potential.

Keywords: Maximum power monitoring algorithm, Digital control, SEPIC controller, Submersible motor pump, Photovoltaic system.

1. Introduction

The incorporation of renewable and clean energy sources is a priority generated by the depletion of conventional sources due to the overexploitation of natural resources [1], which is emerging as a viable alternative to solve the problem of electricity supply in non-interconnected areas existing in the Colombian rural sector; in which the data show that the average solar irradiation is around 4.3 KW / m² [2] [3]. To take advantage of the energy potential, the scientific community has improved the efficiency of photovoltaic systems with technologies such as controllers with algorithms for monitoring the maximum power point [4] [5]. Therefore, this research proposed the development of an experimental prototype using the technique of model-based design, the integration of a solar panel as an energy source, an electronic power controller to improve the efficiency of the system and an algorithm control for monitoring the maximum power point. The methodology aims to develop a controller that applies in the efficient operation of a submersible motor pump to extract available underground water in a deep well, with solar energy.
2. Methodology
As a methodological strategy for the development of the research, the model-based design with the SIMULINK® tool was used, as well as the design of experiments for the development of a functional prototype of the SEPIC-MPPT controller, powered by photovoltaic energy, which used the Perturb & Observe technique for tracking the maximum power point. The experimental modeling and validation of the panel was carried out, with emphasis on the evaluation of the angle of inclination in the installation. In addition, the modeling and implementation of the SEPIC-MPPT controller was carried out with management of the Perturb & Observe algorithm, which was validated in the functional hardware prototype, developed on a programmable platform with ARM-CORTEX-M3 architecture. Static load modeling was also implemented (DC powered submersible motor pump) in which the characteristic curve that relates power in operation with flow and head was identified. The results obtained established the adjustment error between the modeled controller and the experimental controller and the efficiency of the system.

3. Materials and methods
For the modeling and development of the experimental prototype of the proposed controller, the characterization of a solar panel, the design of a DC-DC converter, an algorithm for monitoring the maximum power point and the characterization of water extraction systems were carried out. These developments are described below.

3.1. Solar panel modeling
It started from the analysis to establish the parallel resistance and series [6], which is based on equations (1), (2) and (3) presented below.

\[ I = I_{pv} - I_o \left[ \exp \left( \frac{V + R_s I}{aV_t N_s} \right) - 1 \right] - \frac{V + R_s I}{R_p} \]  \hspace{1cm} (1)

\[ I_o = \frac{i_{sc} + K_I \Delta_T}{\exp \left( \frac{V_{oc} + K_V \Delta_T}{aV_t} \right) - 1} \]  \hspace{1cm} (2)

\[ I_{pv} = (I_{pm} + K_I \Delta_T) \frac{G}{K_n} \]  \hspace{1cm} (3)

Where \( I_{pv} \) is the photovoltaic current, \( I_o \) the nominal saturation current of the diode, \( V \) the voltage across the cell, \( a \) the ideality factor of the diode, \( V_t \) thermal voltage of the diode, \( N_s \) the number of cells in series, \( I \) output current through the cell, \( R_s \) series resistance, \( R_p \) parallel resistance, \( I_{sc} \) short circuit current, \( V_{oc} \) open circuit voltage, \( \Delta_T \) difference between current and nominal temperature, \( G \) current solar irradiation, \( K_n \) nominal solar irradiation, \( K_I \) current coefficient and \( K_V \) voltage coefficient. The coefficients were assumed according to photovoltaic panels with similar characteristics. The expression corresponding to the parallel resistance was derived, which is presented in equation (4).

\[ R_{p/min} = \frac{V_{mp}}{I_{scn-I_{mp}}} - \frac{V_{acn-V_{mp}}}{I_{mp}} \]  \hspace{1cm} (4)

Through the iteration of the expressions with the Newton-Raphson methodology, the values of the missing parameters were obtained, \( R_p = 89.786278 \), \( R_s = 0.350000 \), \( a = 1.200000 \), \( R_{pv} = 6.024692 \) y \( R_{l_0} = 4.763799e^{-13} \). With the data found, the panel was modeled (figure 1).
Figure 1. Complete model of the available monocrystalline solar panel.

To integrate a variable resistive load that would allow deriving the power characteristic of the solar panel, a SIMULINK® model was implemented, which connected eight 27 ohm and 20W resistors sequentially and in parallel, with the purpose of establishing the behavior of the panel model with variable load. The model made is presented in (figure 2).

Figure 2. Model of eight resistors in parallel connected to the panel for load simulation

The procedure began with a resistive load connected in parallel with the output of the solar panel subjected to a radiation of 712 W / m², an inclination of nine degrees, an ambient temperature of 27 ºC and a panel temperature of 36 ºC. The process presented in [7] [8] was adapted to carry out the load change experimentally, through the sequential addition of resistors in parallel until reaching the minimum resistance value when connecting eight resistors. In each of the steps, the current and voltage values were taken, to contrast them with those generated in the experimental characterization of the same system.

3.2. Characterization of the photovoltaic panel available
This process started from the on-board specifications available in the panel used for the investigation, listed in (table 1). Similarly, a calibrated Middleton SK01-D pyranometer with a resolution of 1mV per W / m² and a Datalogger connected to the CoolTerm serial acquisition program was used for radiation measurement.
Table 1. On-board specifications for monocrystalline solar panel available.

| Specification          | Value         |
|------------------------|---------------|
| Nominal Power (Pmax)   | 100 W         |
| Output Tolerance (Pmax)| 3 %           |
| Max Voltage (Vmp)      | 18.0 V        |
| Max Current (Imp)      | 5.56 A        |
| Open circuit voltage   | 22.32 V       |
| Short circuit current  | 6.0 A         |

The proper tilt of the panel with respect to the horizontal global solar radiation was verified by the response of the panel at three different tilt angles (0º, 9º and 15º) based on the latitude of the panel location, which was 7º 06 '19, 05 ''. Experimentally, the power curves obtained in the three test angles were compared with simulated loads using eight resistors of 27 ohms and 20W and a variation step of 3.375 ohms.

3.3. SEPIC controller modeling

The SEPIC controller modeling considered contributions from the comparison carried out in [9] and the analyzes presented in [10] [11] as a starting point. The design requirements considered the parameters Minimum input voltage = 15 V, Maximum input voltage = 22 V, Diode conduction voltage = 0.7 V, Output voltage = 12.6 V and Output current = 1.1 A. With these considerations performed the calculations described below.

3.3.1. Duty cycle selection. The operation of the controller in continuous conduction was chosen, the maximum and minimum critical duty cycles were considered and calculated, through equations (5) and (6).

\[
D_{\text{max}} = \left( \frac{v_{\text{out}} + (\text{vD})}{(v_{\text{in}} \text{Min}) + (v_{\text{out}} + \text{vD})} \right) = \left( \frac{12.6 + (0.70)}{15 + (12.6) + (0.70)} \right) = 0.47
\]

\[
D_{\text{min}} = \left( \frac{v_{\text{out}} + (\text{vD})}{(v_{\text{in}} \text{Max}) + (v_{\text{out}} + \text{vD})} \right) = \left( \frac{12.6 + (0.70)}{22 + (12.6) + (0.70)} \right) = 0.3768
\]

3.3.2. Inductance selection. For the calculation of inductances, a peak-to-peak current oscillation of 40% was considered in relation to the maximum input current at minimum voltage. Equations (7), (8), (9) and (10) were used for the calculation.

\[
\text{Delta}L = \left( l_{\text{out}} \right) \times \left( \frac{v_{\text{out}}}{v_{\text{in}} \text{Min}} \right) \ast (0.4) = \left( (1.1) \ast \frac{(12.6)}{15} \ast (0.4) \right) = 0.3696A
\]

\[
L1 = L2 = L = \left( \frac{v_{\text{in}} \text{Min} \ast (D_{\text{max}})}{(\text{Delta}L) \ast (f_{\text{sw}})} \right) = \left( \frac{15 + (0.47)}{(0.3696) + (90000)} \right) = 211.92 \ast 10^{-6}H
\]

\[
\text{il1pico} = \left( l_{\text{out}} \ast (v_{\text{out}} + \text{vD}) \ast (12) \right) = \left( 1.1 \ast (12.6 + 0.70) \ast (12) \right) = 1.1704A
\]

\[
\text{il2pico} = \left( l_{\text{out}} \ast (1 + \frac{0.4}{12}) \right) = \left( 1.1 \ast \left( 1 + \frac{0.4}{12} \right) \right) = 1.3200A
\]
3.3.3. Mosfet transistor selection. Minimum threshold voltage Vth (min), ignition resistance RDS (ON), gate drain load QGD and maximum drain voltage to source, VDS (max) were used as base parameters in the selection. The RFZ44N transistor was chosen, which has Rds(on) = 0.032 ohms, Qgd = 25 * 10⁻⁹, Vds = 5V, Ig = 1.47A. Based on these values, the current and power requirements of the switch were calculated using equations (11), (12) and (13).

\[
IQ_{pico} = iL_{pico} + iL_{2pico} = 1.1704 + 1.32 = 2.4904A
\]  
(11)

\[
IQ_{rms} = \left\{(\text{Iout}) \times \sqrt{\frac{(vout+vinMin+vD)+(vout+vD)}{(vinMin)^2}}\right\} = 1.4227A
\]  
(12)

\[
pQ1 = \left\{(IQ_{rms})^2 \times (Rds_{on}) \times (D_{max}) + \right\}(vinMin + vout) \times (IQ_{pico}) \times \frac{(Qgd) \times (f_{sw})}{Ig} = 0.1356W
\]  
(13)

3.3.4. Output diode selection. In the SEPIC, the current that flows through the diode is the same that passes through the MOSFET, which is the maximum current of the switch. The minimum peak voltage across the diode was calculated using equation (14).

\[
vRD1 = vinMax + vout = 22 + 12.6 = 34.6V
\]  
(14)

The Schottky diode reference SR350 was chosen, which exceeds the calculated parameter.

3.3.5. Coupling capacitor selection. The selection of the capacitor (Cs) depends on the RMS current, and the ripple voltage (DeltaCs). Equations (15), (16) and (17) were used to calculate this component.

\[
I_{csrms} = I_{out} \times \sqrt{\frac{(vout+vD)}{vinMin}} = 1.1 \times \sqrt{\frac{12.6+0.70}{15}} = 1.0358A
\]  
(15)

\[
DeltaCS = \frac{(I_{out}) \times (D_{max})}{(CS) \times (f_{sw})}
\]  
(16)

\[
CS = \frac{(I_{out}) \times (D_{max})}{(DeltaCS) \times (f_{sw})} = \frac{(1.1) \times (0.47)}{(1.16 \times 10^{-3}) \times (90000)} = 5000\mu F
\]  
(17)

3.3.6. Output capacitor selection. The output capacitor must be able to handle the RMS current calculated by equation (17) and flowing through the MOSFET switch. The calculation of the capacitor was carried out using equations (18) and (19).

\[
ESR = \frac{(vripple \times 12.6)+(0.5)}{iL_{pico}+iL_{2pico}} = \frac{(0.02+12.6)+(0.5)}{1.1704+1.32} = 0.0506
\]  
(18)

\[
Cc = \frac{I_{out} \times (D_{max})}{(vripple)+(12.6)+(0.5)+(f_{sw})} = \frac{(1.1) \times (0.47)}{(0.02)+(12.6)+(0.5)+(90000)} = 45.58\mu F
\]  
(19)

3.3.7. Input capacitor selection. The waveform of the input current is triangular so the inductor ensures that the ripple seen by the capacitor is low. The RMS current in the input capacitor is defined by equation (20) and a minimum value of 10\mu F is established for this component as it is not a critical component.

\[
I_{cinrms} = \frac{\text{Delta}U}{\sqrt{12}} = \frac{0.3606}{\sqrt{12}} = 0.1067A
\]  
(20)

With the calculations carried out, the SEPIC controller model was generated in which an input for the useful cycle signal generated by a Perturb & Observe algorithm, and an output multiplexed with voltage and current signals for the respective measurements, was provided. The SIMULINK® model implemented for the controller is presented in (figure 3).
3.4. SEPIC-MPPT controller implementation

The controller was implemented on the SAM3X8E processor with ARM Cortex-M3 architecture, available on an Arduino-DUE development board, which has 512 KBytes of program memory, 96 KBytes of data memory and multiple input / output modules. This processor has a 32-bit data bus, and operates at a frequency of 84 MHz, the circuit components calculated for modeling the controller were also integrated on a PCB, as well as the voltage and current sensor modules for the corresponding validations. The experimental prototype is shown in (figure 4).

3.5. Static modeling of the motor pump for groundwater extraction

The hydraulic behavior of a motor pump relates the flow with parameters such as required operating power, total manometric head, operating voltage and current, among others [12] [13]. In the absence of these values, an experimental characterization was necessary to determine the dynamics of the device, in which the power was established as an independent variable and as dependent variables the flow, the height at which the water extraction is carried out, the performance, operating voltage and current. Based on the stated method and based on the technical specifications available in the data sheet of a DC powered submersible motor pump (Table 2), an experiment was designed to derive the required characteristics.
Table 2. Technical specifications of DC powered submersible motor pump, available.

| Specification         | Value                        |
|-----------------------|------------------------------|
| Material              | ABS-Steel                    |
| Size                  | (80x48x63) mm                |
| Input diameter        | 12 mm                        |
| Output diameter       | 6.9 mm                       |
| Voltage               | 6-12 V                       |
| Nominal Current       | 1.2 A                        |
| Power                 | 18.8 W                       |
| Max Flow              | 700 L/h                      |
| Water Head Max.       | 5 m                          |
| Water temperature     | 60 ºC                        |

In the implemented experiment, two six-liter tanks were located for water storage. One fixed and the other with the possibility of changing the height. The motor pump was energized with 12.68 Volts to fill the tank with variable height and ten repetitions were performed for each height. The fill time, flow rate, current and power absorbed by the motor pump were measured and averaged. The measured values are presented in (table 3).

Table 3. Experimental characterization of the submersible motor pump

| Power (W) | Current (A) | Flow (L/S) | Height (m) | Time (S) |
|-----------|-------------|------------|------------|----------|
| 10.66     | 0.841       | 0.012265508| 4.00       | 489.2    |
| 10.79     | 0.851       | 0.018525310| 3.67       | 323.9    |
| 11.72     | 0.924       | 0.041097441| 3.09       | 146.0    |
| 13.33     | 1.051       | 0.078027236| 2.46       | 76.90    |
| 13.95     | 1.100       | 0.098699101| 1.82       | 60.80    |
| 14.07     | 1.110       | 0.106203008| 1.22       | 56.50    |
| 14.38     | 1.134       | 0.123076923| 0.60       | 48.75    |

With the data of the experimental characterization and with the use of the MATLAB® CFTOOL tool, the characteristic curves of the submersible motor pump were generated, which are presented in the results section.

3.6. Implementation of the Perturb & Observe algorithm

The P&O algorithm is initialized with the product of the current voltage of the photovoltaic panel, and the duty cycle that changes in constant increments [14-16]. The algorithm establishes that, if the difference between the current power and the previous power is positive and the difference of the current voltage with the previous voltage is also positive, the duty cycle is decreased to increase the output voltage so that the MPPT. If the difference in powers was positive and the difference in voltages was negative, the duty cycle is increased until the MPPT is reached. If both differences are negative, the control action to take is to decrease the duty cycle to increase the output voltage of the solar panel until it reaches the MPPT. Finally, if the power difference is negative and the voltage difference was positive, the duty cycle is increased until the maximum power point is reached [17]. The flow diagram of the Perturb & Observe algorithm integrated into the controller model is presented in (figure 5).
4. Results

After validating the proposed implementations for both the modeling and the experimental prototype of the different components that make up the SEPIC-MPPT controller, the results achieved are presented. The modeling of the solar panel and simulated resistive loads were compared with the actual connected resistive loads. Similarly, the modeled controller was contrasted with the experimental prototype and its operation was validated without the P&O - MPPT algorithm and with the integration of the algorithm. The results obtained for each component are presented below.

4.1. Solar panel modeling

The solar panel model developed in SIMULINK® based on the Standard Test Conditions -STC-, generated the power curves presented in (figure 6). The solar radiation curve corresponding to 1000 W / m² (upper curve) was taken as a reference to contrast with the results of the characterization of the solar panel.

Figure 5. Perturb and Observe algorithm flow chart built into controller

Figure 6. Solar panel power curves modeled by SIMULINK®
4.2. Experimental characterization of the solar panel
The curves obtained for the inclination angles used in the validation with solar radiation of 1000 W / m\(^2\) were derived from measurements made with the sun at the zenith. In (figure 7) the response for the three values of inclination tested are presented.

![Figure 7. Result of the experimental characterization of the solar panel.](image)

When comparing the results obtained in the modeling with the power values measured in the solar panel installed with an inclination of nine degrees and with the sun at the zenith (1000 W / m\(^2\)), a small difference is appreciated between the power generated and the characteristic delivered by the simulation. This difference is tolerable and valid to consider the model developed in the implementation of the SEPIC controller.

4.3. Characteristic Voltage - Current with resistive loads
The curves obtained with the simulated and real resistances connected in parallel with a radiation of 712 W / m\(^2\) were compared to establish the corresponding adjustment error. The results obtained for the Voltage - Current characteristic with the resistive load connected in parallel to the panel are presented in (figure 8).

![Figure 8. Characteristic Voltage - Current with resistive loads](image)

The average adjustment error found in the comparison between the simulated model and the experimental model with the resistors connected was 2.59% for voltage and 2.70% for current.
4.4. Static modeling of the submersible motor pump

From the experimental characterization of the motor pump, the flow/head (figure 9) and flow/power/head (figure 10) curves for groundwater extraction were generated using the Cftool and Fitting Tool of MATLAB®.

![Figure 9. Characteristic Flow/Height of the submersible motor pump](image)

Based on the recorded data, the function \( h(c) = -129.4c^2 - 11.21c + 3.995 \) with determination coefficient \( R^2 = 0.984 \) was generated, which describes the dynamics of the submersible motor pump to integrate it into the system model. It is inferred from (figure 9) the decrease in flow rate as the extraction head increases.

![Figure 10. Characteristic Power/Flow/Height of the submersible motor pump](image)

The function \( c(p) = -0.001p^3 + 0.0108p^2 + 0.0138p + 0.0141 \) was established with coefficient of determination \( R^2 = 0.9862 \) that describes the behavior of the flow as a function of the power, which is modulated by the height extraction.
4.5. SEPIC-MPPT controller modeling
The SEPIC-MPPT controller (figure 11) was implemented with the calculated components and the P&O algorithm with a frequency of 82 KHz.

![Figure 11. Complete SEPIC-MPPT experimental model in SIMULINK.](image)

The voltage, current and power values at the input and output of the controller, as well as the radiation and temperature were recorded using a Datalogger and averaged for analysis. The calculated averages are presented in (table 4).

| Parameter | Modeling | Experimental | Error % | Prototype |
|-----------|----------|--------------|---------|-----------|
| Vin (V)   | 20.17    | 20.25        | -0.38   | 20.06     | -0.95     | -3.30     |
| Iin (A)   | 0.58     | 0.71         | 0.13    | 0.60      | 0.72      | 1.39      | -1.40     |
| Pin (W)   | 11.63    | 14.35        | 2.72    | 11.70     | 14.62     | 0.60      | 1.85      | 0.68      |
| Vout (V)  | 11.24    | 12.53        | -1.29   | 11.21     | 12.55     | -0.27     | 0.16      | 2.68      |
| Iout (A)  | 0.93     | 1.04         | 0.11    | 0.96      | 1.02      | 3.12      | -1.96     | 2.59      |
| Pout (W)  | 10.49    | 13.09        | 2.59    | 10.75     | 12.84     | 2.42      | -1.95     | 2.24      |
| Rad. W/m² | 980.86   | 998.23       | 1.77    | 980.86    | 998.23    | 0.00      | 0.00      | 0.00      |
| Temp. ºC  | 24.53    | 24.56        | 0.00    | 24.53     | 24.56     | 0.00      | 0.00      | 0.00      |

The evaluation of the performance parameters of the modeled / experimental controller was carried out in reference to the Standard Test Conditions -STC-. The results obtained indicate an oscillation in the adjustment error of less than ± 5% for the system without MPPT algorithm. For the system with the MPPT algorithm, the oscillation in the adjustment error was less than ± 2%. In order to obtain absolute indicators, the results of the test with MPPT and without MPPT were averaged for the experimental prototype and a variation of less than 4% was determined.

To validate the efficiency of the experimental controller, three measurements were made with different solar radiation and operating temperature, in which both the input power and the output power were measured. The measurements were made with the application of the MPPT algorithm and without the application of the MPPT algorithm. In (table 5) the results obtained are presented, which show an efficiency of 65.61% for the controller without MPPT and 85.26% for the controller with MPPT.
Table 5. Efficiency of the SEPIC-MPPT experimental system.

| Parameter | No-MPPT | MPPT |
|-----------|---------|------|
| Rad. W/m² | 320,00  | 735,00 |
| Temp. ºC  | 27,75   | 30,50 |
| Pin (W)   | 7,72    | 10,45 |
| Pout (W)  | 4,90    | 6,94  |
| η %       | 63,47   | 66,36 |

5.5. Conclusions
Based on the results obtained in reference to the methodology implemented to develop an experimental SEPIC-MPPT controller powered by photovoltaic energy with application in the extraction of groundwater, the following conclusions were derived.

5.1. Solar panel tilt angle
It is inferred from the inspection on the curves presented in (Figures 6 and 7), that the highest power level was reached with the installation of the panel at nine degrees (9º) based on the latitude of the geographical location, which was 7 06'19.05 ".

5.2. Load resistor bank
It is concluded based on the results with respect to the simulated / experimental resistance bank, that the adjustment error of the Voltage - Current characteristic generated (figure 8) is less than 3%, which indicates coherence between the simulation and the characterization, that validates the design specifications integrated into the model in reference to the behavior of the solar panel.

5.3. Static model of the motor pump
The model derived from the experimental evaluation of the submersible motorized pump presented a coefficient of determination R² of 98.4% (figure 9), in the adjustment to the dynamics of the motorized pump, which validates the result for its integration into the experimental controller model. There was also evidence of a restriction in the extraction height (figure 10), which imposes a minimum height for the depth of groundwater extraction from 0.5 meters, which is equivalent to 12.5% of the total depth evaluated.

5.4. SEPIC-MPPT controller
From the results obtained, the complete model of the SEPIC-MPPT controller (figure 11) and the experimental prototype (figure 4) were developed on which the performance parameters were evaluated (table-4). It was evidenced from the results that the MPPT algorithm decreased the percentage of error in the performance parameters (± 2%) in contrast to the performance of the controller without MPPT (± 5%). By averaging the results, it is concluded that the average adjustment error was less than ± 4%, so that the developed solution is coherent and valid for extrapolation to higher operating conditions.

5.5. SEPIC-MPPT Controller Efficiency
In relation to the efficiency of the experimental controller and based on the results obtained by subjecting the system to various radiation and temperature conditions (table 5), the efficiency achieved by the controller without MPPT was 65.61%, while for the controller with MPPT, the efficiency achieved was 85.26%. It is concluded from these results that the SEPIC-MPPT controller is feasible to be implemented in underground water extraction systems since its loss is less than 15%, which represents a high level of use of the photovoltaic potential available in the study region.
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