

## Development of a voltage regulator for solar photovoltaic cathodic protection system

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**Abstract** - The voltage regulator is one of the main elements from which depends the reliability and the efficiency of the photovoltaic system. Among the large number photovoltaic applications, we are interested by the cathodic protection, it's recognized as one of the most efficacious means of the active prevention against the corrosion. Photovoltaic cathodic protection is one of the possible solutions for the structures subjected to corrosion, mainly in oil and gas industries [Tanasescu et al., 1988]. In this paper, the study about the design of a voltage regulator with variable output for solar photovoltaic cathodic protection has been carried out. Our system is based on two microcontroller controlled DC/DC converters: the first one is a buck used to match the maximum power point voltage of the solar panel to the battery charging voltage; and the second one is a buck-boost used between the batteries and the load in order to adapt the regulator at any cases of the cathodic protection stations. Usually, cathodic protection systems are working with constant current output which is the necessary condition to procure immunity voltage of the structures that strictly required preventing corrosion from occurring. The major difficulty to achieve this goal is the variations of the surrounding medium resistivity to overcome this difficulty, we propose an automatically adjustment of the output voltage of the buck-boost converter to feed the load (sacrificial anode-protected structure) thanks to the microcontroller by generating the required duty cycle by way of its PWM output. The developed system allows the solar panel to operate at its maximum power point output (MPP), when the MPP changes, the microcontroller changes the conversion ratio (duty cycle) of the buck circuit to keep the solar panel at its MPP. The buck steps higher voltage panel down to the battery charging voltage. In this paper, the study about the design of this voltage regulator with variable output for solar photovoltaic cathodic protection has been described.

**Résumé** - La protection cathodique par voie photovoltaïque est l'une des solutions utilisées pour les structures métalliques enterrées et exposées à la corrosion, principalement dans les industries du pétrole et du gaz. Dans ce papier, nous décrivons un dispositif de régulation et de contrôle qui permet l'ajustement automatique de la tension de sortie vers la charge (déversoir - canalisation à protéger) afin de maintenir le courant de protection constant. Ce régulateur permet aussi au champ de modules photovoltaïques 'GPV' de fonctionner à sa plus haute performance par le biais de la poursuite du point de puissance maximum et utilise comme circuit d'adaptation entre le champ photovoltaïque et le stockage électrochimique, un convertisseur CC/CC qui abaisse la tension du 'GPV' pour charger la batterie. Ce dispositif de régulation et de contrôle développé est conçu autour d'un buck et d'un buck-boost contrôlés par un  $\mu P$ . Nous présentons l'étude et la simulation du circuit buck-boost, ainsi que de sa commande représentant l'interface d'adaptation du système photovoltaïque aux différents cas de figures imposées par la protection cathodique.

**Keywords:** Corrosion - Photovoltaic system - Cathodic protection - Regulation - Buck-boost converter.

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## 1. INTRODUCTION

To stop the corrosion entirely, the protected structure is to be fed by a constant current determined by the structure's metal, the area and the surrounding medium [Wagdy, 1995]. The main difficulty to reach this goal is the variations of the surrounding medium resistivity due to climatic conditions changes. To overcome this difficulty, an automatically regulated cathodic protection system is proposed. This system senses the variations of the surrounding medium resistivity and adjust the direct current (DC) voltage automatically so that the current is kept nearly constant at the required level regardless of the soil resistivity variations [Wagdy, 1995] [Kharzi, 2005].

This system is developed around the microcontroller 16F877 which manage the operating of the whole parts, as known the output voltage of the buck-boost, the charging voltage of the battery and the maximum power point tracker of the photovoltaic generator [Nolan, 2005]. The acquisition of the different parameters as well as the measure of the pipe voltage against the buried reference electrode Cu/CuSO<sub>4</sub> is allowed by the 16F877's ADC ports.

## 2. THE REGULATED SYSTEM IN CATHODIC PROTECTION

Concerning the specificity of this regulated system, the adjustment of the dc voltage is done continually and automatically. The basic circuit is a buck-boost converter. The driving signal of its main switch is obtained thanks to the 16F877 microcontroller by way of its PWM port. The PWM generate the required duty cycle in order to adjust the output voltage applied to the protected structure to reach the cathode potential (preventing the protection).

The figure 1 shows the block diagram of the proposed regulated cathodic protection system [Kharzi, 2005].

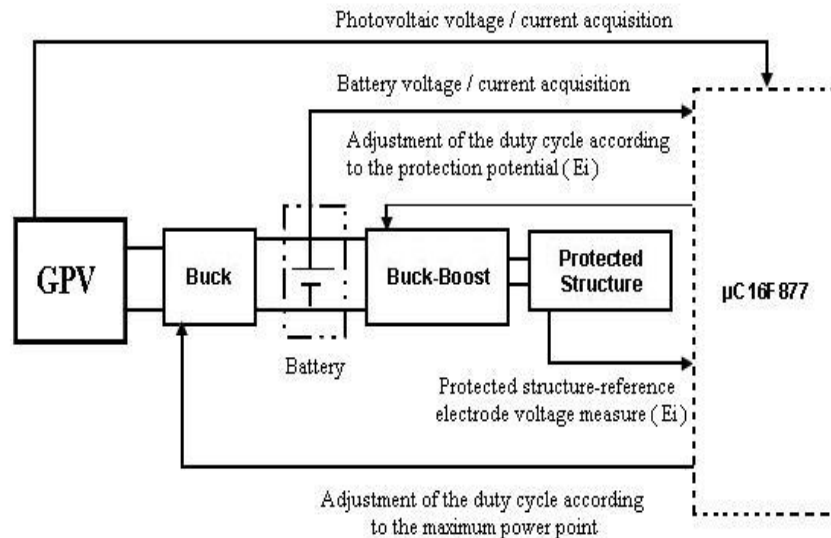
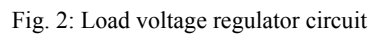


Fig. 1: Block diagram of the regulated cathodic protection system

## 3. LOAD VOLTAGE REGULATOR CIRCUIT

This circuit supplies a controlled DC voltage to the load according to control signal voltage. In the case of the figure 2, the switch is driven by a pulse generator simulating the microcontroller role. The switching frequency was fixed at 50 kHz.


$$V_{\text{out}} = \frac{\alpha \times V_{\text{in}}}{(1 - \alpha)} \quad (1)$$

$$\alpha = \frac{V_{out}}{(V_{out} + V_{in})} \quad (2)$$

$$L = \left(\frac{1}{f}\right) \times \left(\frac{1}{\Delta I_L}\right) \times (V_{out} + V_f) \times \left(\frac{V_{in\_min}}{V_{out} + V_F + V_{in\_min}}\right) \quad (3)$$

$$\Delta I_L = (0.4 \times I_L) = 0.4 \times \left( \frac{V_{in\_min} + V_{out} + V_F}{V_{in\_min}} \right) \quad (4)$$

$$I_{\text{out}} = (1 - \alpha) \times I_L \quad (5)$$

$$\Delta V_{\text{out}} = \frac{\alpha \times I_{\text{out}}}{f \times C} \quad (6)$$

$$C_{out} = \frac{\alpha \times I_{out}}{0.1 \times f} \quad (7)$$

The inductance and the capacitance values are determined thanks to the Eq. (3) and Eq. (7). The duty cycle  $\alpha$  of the chopper is generated by the microcontroller's PWM output signal

according to the developed program as so as to reach the criteria of the cathodic protection which is included between 1.5 V and 0.850 V range in absolute value. This range represents the difference of the potential between the protected structure (the pipe in our case) and the reference electrode Cu/CuSO<sub>4</sub>.

#### 4. THE BUCK-BOOST COMMAND

In our case, the buck-boost output voltage  $V_{out}$  must be able to assure the immunity voltage for the protected structure. To obtain this value, one measures  $E_i$  the impressed voltage (the cathode potential) against a buried reference electrode Cu/CuSO<sub>4</sub> and we act on the duty cycle to have the buck-boost adequate command. Consequently, the structure voltage ( $E_i$ ) is kept at the effective protection value.

The figure 3 shows the control circuit.

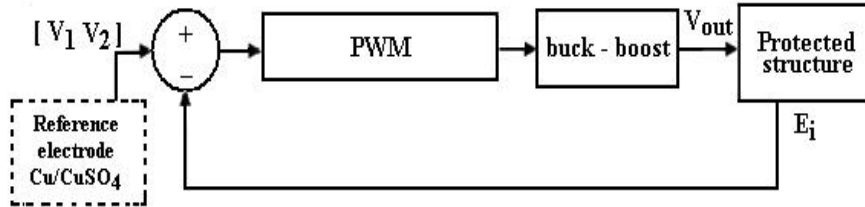


Fig. 3: The buck-boost control schema

One acknowledges that the structure protection is assured if its voltage  $E_i$  against the reference electrode belong to the range of:  $V_1 = 1.2\text{ V}$  and  $V_2 = 0.850\text{ V}$  (in absolute value). The control is set according to [Kharzi, 2005]:

If:

$$(E_i - V_1) > 0 \quad (8)$$

The output voltage should be equal to:

$$V_{out}(k) = V_{out}(k-1) + (E_i - V_1) \quad (9)$$

$V_{out}(k-1)$  is the previously measured output voltage.

According to Eq. (2), the duty cycle becomes:

$$\alpha = \frac{V_{out}(k)}{V_{out}(k) + V_{in}} \quad (10)$$

Therefore the output voltage (the load voltage) increases if  $E_s$  exceeds  $V_1 = 1.5\text{ V}$ .

If:

$$(E_i - V_2) < 0 \quad (11)$$

Then:

$$V_{out}(k) = V_{out}(k-1) + (E_i - V_2) \quad (12)$$

As in the above, the duty cycle is calculated by Eq. (2). It results that the output voltage decreases if  $E_i$  drops below  $V_2 = 0.850\text{ V}$ .

This kind of control is based on the input voltage (battery voltage) and the output voltage of the buck-boost circuit (the load voltage). This last one must be adjusted to reach the limits values imposed by the cathodic protection.

## 5. RESULTS AND DISCUSSION

In the following example, we consider the output voltage  $V_{out} = 24V$  so  $\alpha = 0.5$ .

1<sup>st</sup> case:  $(E_i - V_1) > 0$  with  $V_1 = 1.5V$ ,  $E_i = 2.5V$ , the figure 4 shows the simulations results of the output voltage and the duty cycle in this case. It is seen that the buck-boost output voltage increases when  $E_i$  (the impressed voltage) is larger than  $1.5V$ .

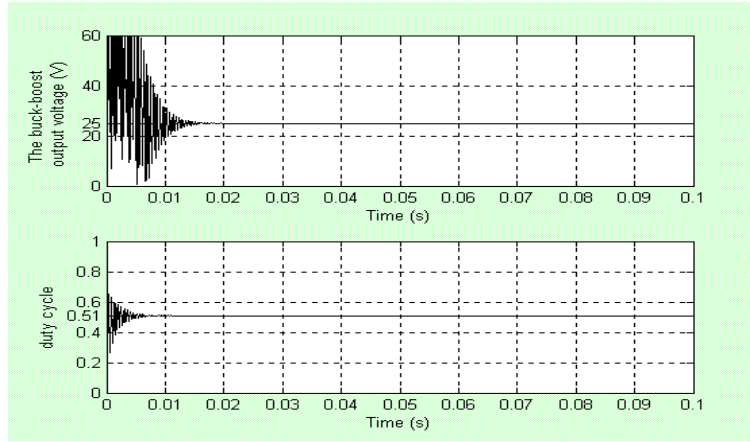


Fig. 4: The buck-boost output voltage and duty cycle in the 1<sup>st</sup> case

2<sup>nd</sup> case:  $(E_i - V_2) < 0$  with  $V_2 = 0.850V$ ,  $E_i = 0.3V$ , the figure 5 shows the simulations results of the output voltage and the duty cycle in this case. The buck-boost output voltage decreases as  $E_i$  is smaller than  $0.850V$ .

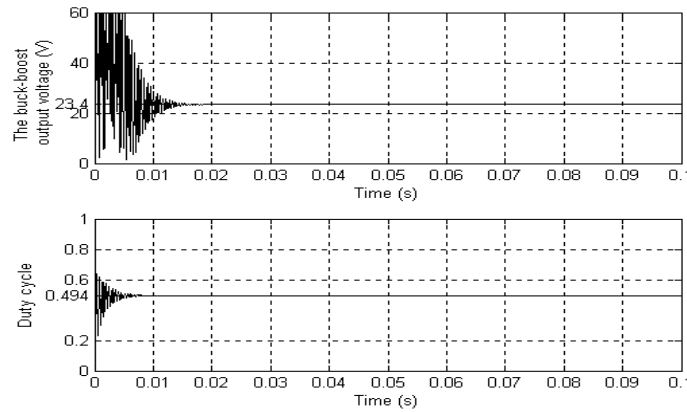


Fig. 5: The generated output voltage and duty cycle in the 2<sup>nd</sup> case

3<sup>rd</sup> case:  $(E_i - V_1) < 0$  and  $(E_i - V_2) > 0$  with  $V_1 = 1.5V$  and  $V_2 = 0.850V$ ,  $E_i = 1V$ , the figure 6 shows the simulations results of the output voltage and the duty cycle in this case. When  $E_i$  is included in the allowed limits the buck-boost output voltage is kept unchanged.

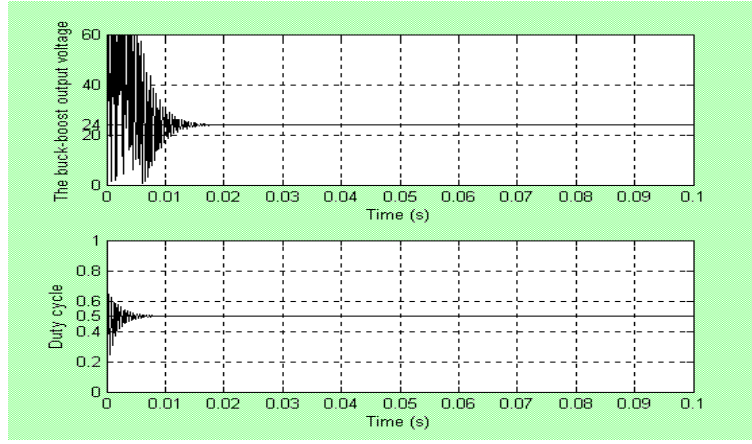


Fig. 6: The generated output voltage and duty cycle in the 3<sup>rd</sup> case

From there, one notices well that the simulated control circuit according to the introduced cases delivered the required buck-boost output voltage accordingly to the generated duty cycle. It varies in a concordance with the impressed voltage variation  $E_i$ . The duty cycle is stable. It increases in the 1<sup>st</sup> case, decreases in the 2<sup>nd</sup> case and remains invariable in the last case. Proportionally, the buck-boost output voltage varies in the same way while tending to reach the protected structure immunity criteria.

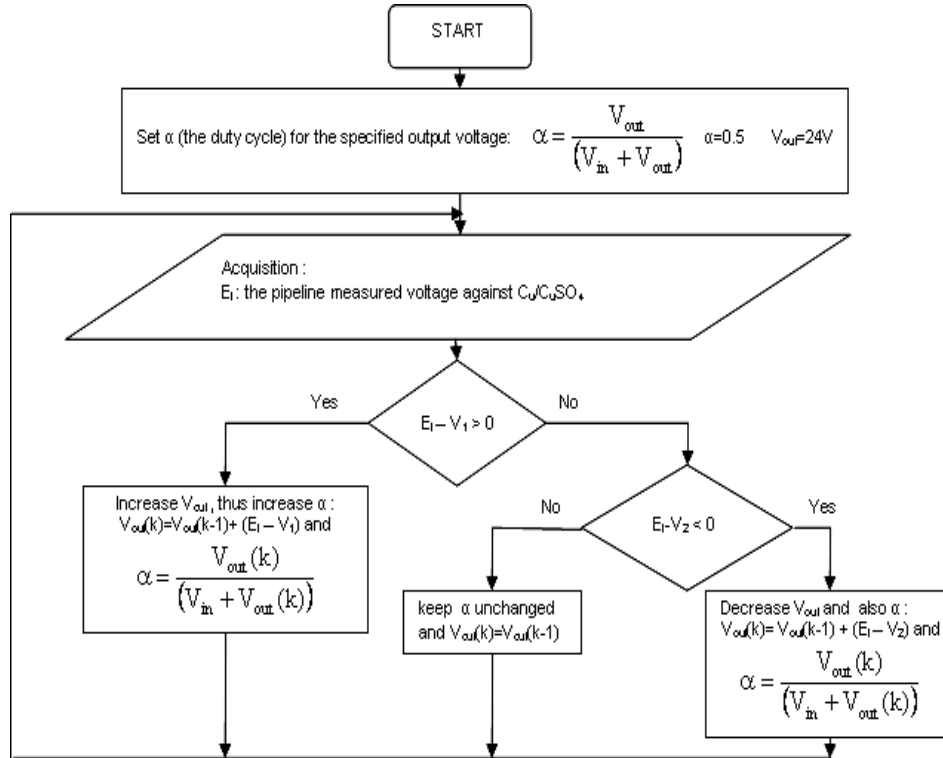


Fig. 7: The cathodic protection control and monitoring algorithm

## 6. APPLICATION OF A MICROCONTROLLER 16F877 TO OUR MODEL

The microcontroller is used to develop our real time multitask application. We must assign a priority orders to tasks mentioned above to must be achieved by our microcontroller. We also must synchronize between the tasks. We have to carry out an interrupt management program by including the specific concepts allowing the communication between the various tasks.

The classification of the tasks is as follows:

- The GPV current and voltage acquisition. These read values are used to calculate the GPV power so that the microcontroller may accomplish the tracking of the maximum power point.
- The batteries current and voltage acquisition. The voltage is used for the charge control of the batteries.
- The control and the regulation of the cathodic protection which must operate permanently. This last one must have the highest order of priority (the 1<sup>st</sup> order of priority).

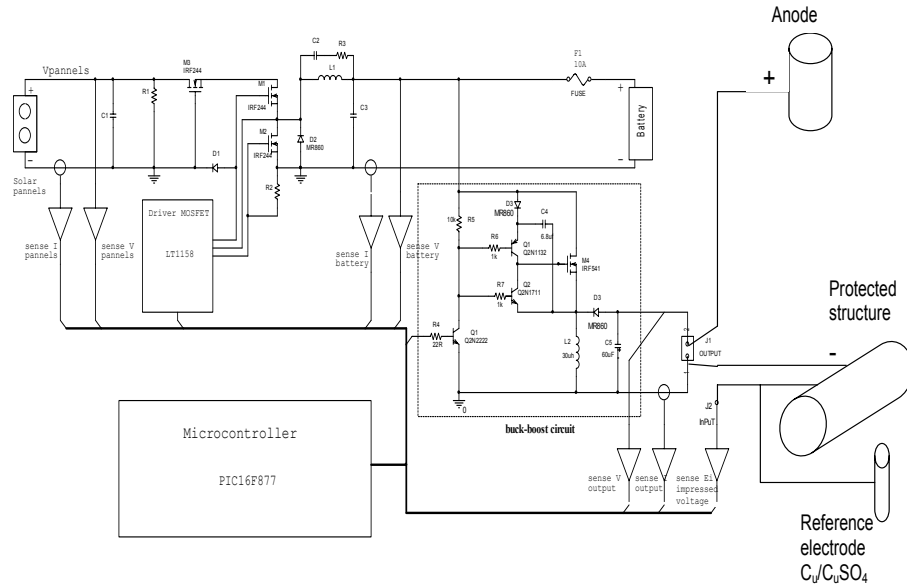


Fig. 8: Schematic design of the cathodic protection regulator system

## 7. CONCLUSION

In this work, a regulated cathodic protection system powered by solar photovoltaic energy is proposed. It avoids the difficulties associated with conventional cathodic protection system. This regulator is specific to cathodic protection system. It adjusts automatically the applied voltage so that to supply the structure by a constant protection current. The basics circuits to achieve this task are the buck-boost converter driven by a microcontroller 16F877. The driving signal is obtained by the variation of the duty cycle thanks to the microcontroller by way of its PWM output port. The variation of the duty cycle must be in accordance with the optimal values of the cathodic protection ranges from -0.850 to -1.5 V.

This developed regulator for cathodic protection system powered by solar photovoltaic energy carries out the following tasks:

- The maximum power point tracking of the photovoltaic generator (solar panel) so as to allow the generator to operate with its highest performance.
- The control of the battery charge.

- The monitoring of the cathodic protection operating.

Among the advantages of the novel system:

- It saves the energy because the voltage is automatically adjusted so that the output voltage never exceeds the required voltage and thus minimum dissipation is attained.
- Corrosion is stopped and also the coating destruction since the overprotection and under protection are both eliminated.

The use of the microcontroller of Microchip provides economic advantages. It allows reaching the highest performance with an extremely reduced cost.

## NOMENCLATURE

$C_{out}$	Buck-boost output Capacitance, F
$E_i$	Structure protected voltage measured against a reference electrode Cu/CuSO <sub>4</sub> , V
$f$	Switching frequency, kHz
GPV	Photovoltaic generator (solar panel)
$I_{out}$	Output current, A
$I_L$	Inductor current, A
$\Delta I_L$	Current ripple of the inductor current
$L$	Inductor, H
PPM	Maximum power point of the photovoltaic generator
PWM	Pulse width modulation
$V_1$ and $V_2$	Allowed voltage range [- 1.5 V _ - 0.850 V]
$V_{in}$	Input voltage of the buck-boost circuit, V
$V_{in\_min}$ and $V_{in\_max}$	Input range of the input voltage, V
$V_F$	Diode forward voltage, 0.7 V
$V_{out}$	Buck-boost output voltage, V
$V_{out}(k)$	Recent measured buck-boost output voltage value
$V_{out}(k-1)$	Previously measured buck-boost output voltage value
$\Delta V_{out}$	Voltage ripple of the buck-boost output voltage
Cu / Cu SO <sub>4</sub>	Reference electrode
$\alpha$	Duty cycle

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