

# A Solar Cell Powered Adaptive Charging Circuit for CMOS Integrated Micro Fuel Cells

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**Abstract.** This paper presents an autonomous interface circuit which uses solar cells to automatically recharge chip integrated micro fuel cell accumulator arrays. These accumulators comprise a fuel cell for powering systems and a hydrolysis cell for charging the integrated hydrogen storage. The charging current is continuously monitored and the interface circuit automatically maximizes and controls the charging current. The solar cells powering the charging process are projected to be part of the chip package. The presented system, in combination with a previously developed voltage regulator and integrated sensors or actuators enables the implementation of fully integrated energy autonomous systems.

## 1. Introduction

Various efforts in the last years aim for fully integrated autonomous microsystems [1, 2, 3]. While miniaturization of the system size is resulting in a reduction of power consumption, a reliable miniaturized fully integrated power supply is a common issue. Commonly, batteries are used as energy source. However the limited life time, maintenance requirements and the challenge of scaling down the size lead to new power supply strategies.

On one hand, energy harvesting is one of the promising approaches to overcome these drawbacks. Nevertheless, the variable available environmental energy requires a temporary energy storage to ensure a sustainable power supply.

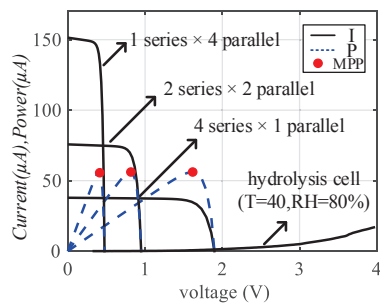
On the other hand, integrated micro fuel cells have been a novel approach [1, 4], providing a CMOS-integrated versatile power supply. However, the life time of this power supply is limited by the storage capacity of the fuel cells. In order to enable a virtually unlimited lifetime of autonomous systems, an electrical recharging of the fuel cells enabled by a hydrolysis cell was proposed [5].

Therefore, we present an adaptive interface circuit which enables the usage of solar cells as energy harvesting devices and fuel cell accumulators [5] as temporary energy storage. The presented interface circuit allows for a charge current control and maximization independent of the environmental conditions. This interface circuit in combination with the solar cells and the fuel cell accumulators, results in an autonomous power supply with virtually unlimited lifetime without any additional external power source.

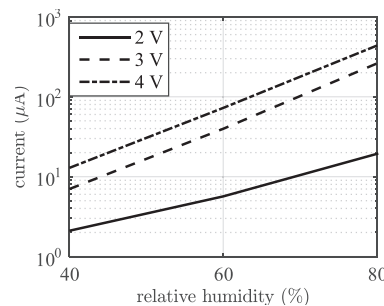
## 2. Fuel cell accumulator and solar cell as power supply

A cross section of the fuel cell accumulator (FCA) presented in [5] is shown in Fig. 3. It comprises a fuel cell to power a connected system and the hydrolysis cell to allow for an electrical recharge

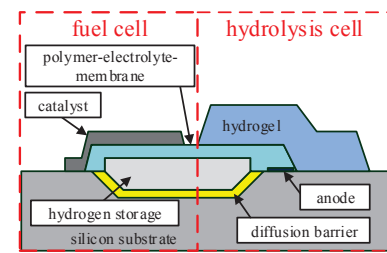




**Figure 1.** Typical voltage to current characteristics of the hydrolysis cell presented in [5] and a solar cell module with different configurations.



**Figure 2.** Dependency of the charging current on the charge voltage and ambient relative humidity



**Figure 3.** Cross section of the fuel cell accumulator proposed in [5]

of the hydrogen storage. The fuel cell converts the chemical energy stored as hydrogen in the palladium hydrogen storage and oxygen from the ambient air into electrical energy and releases water. In the hydrolysis cell, a hydrogel collects water from the ambient air which can then be electrically split into hydrogen and oxygen. The hydrogen then diffuses into the palladium storage while the oxygen is released into the ambient air.

A typical voltage to current characteristic of the hydrolysis cell at a temperature of 40 °C and a relative humidity of 80 % with an area of 3.15 mm<sup>2</sup> together with the different solar cell configurations with an area of 4 cm<sup>2</sup> is shown in Fig. 1. If a voltage higher than approximately 1.5 V is applied on the hydrolysis cell, the current is positive which means the FCA is being charged.

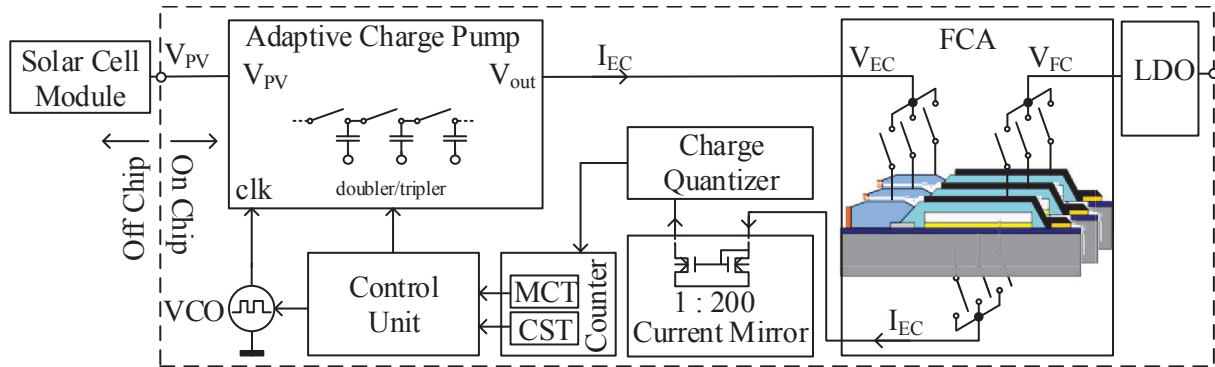
The voltage to current characteristic of the solar cell with an area of 4 cm<sup>2</sup> is modeled with a two diode model [6] and is shown in Fig. 1. It shows a typical open circuit voltage of approximately 0.6 V and a voltage of approximately 0.4 V at the maximum power point (MPP). In addition, this graph shows different configurations of solar cells while the area of all configurations is kept constant. If the area of each single solar cell is lowered but the number of series connected solar cells is increased, the open circuit voltage increases while the maximum output current decreases. Connecting more than 4 solar cells in series is not advisable due to resulting low area of each of the solar cells while the boundary losses increase, lowering the overall output power.

Connecting one of the solar cells directly to the hydrolysis cell is not advisable because of the low charge current and the operation of the solar cell far off its MPP. Moreover, due to the strong dependence of the electrical characteristic of the FCA [1] and the solar cell, a direct connection between these two would not provide an optimized charging time. The dependency of the FCA charging current can be seen in Fig. 2. It shows that the charging current can change by a factor of approximately 10 at equal hydrolysis voltage.

In addition, the charging current of the hydrolysis cell is not allowed to exceed a specific maximum current in order not to irreversibly damage the FCA. Therefore, we propose the application of a charge pump based interface circuit, monitoring and maximizing the charge current.

### 3. Charging System

The proposed power management circuit as shown in Fig. 4 fulfils three tasks: Maximize the charging current independent of input power (e.g., sunlight intensity) and ambient conditions (e.g., temperature, humidity), track the state of charge and set an over-current limit.



**Figure 4.** Proposed system with a solar cell module attached to the chip cover, the adaptive charging circuit, the rechargeable fuel cell array and a variable low drop-out voltage regulator (LDO).

The energy transfer stage is an adaptive 6 phase charge pump [7] with two modes of operation. In *doubler* mode, it acts as voltage doubler, in mode *tripler* it acts as a voltage tripler while the number of stacked capacitors is adjusted accordingly to two and three. Additionally, its operation frequency can be varied by a voltage controlled oscillator (VCO). In order to maximize the charge current, a maximum current tracking unit (MCT) monitors the charging current and modifies the operation mode and frequency of the adaptive charge pump. Therefore, with an active current mirror, a fraction of the charging current is mirrored into the charge quantizer. If a fixed amount of charge is delivered to the quantizer, the MCT counter is incremented. After a predefined charge period, the counter value is stored and compared to the previously stored counter value. An increase or decrease of the amount of the charge stored within one period is detected. This comparison is the input for a hill climbing algorithm, adjusting the VCO frequency and the charge pump operation mode accordingly. In addition, the output signal of the charge quantizer is also connected to the charge state tracking counter (CST) in order to track the charge transferred during a single recharge cycle. If this counter reaches a predefined value, representing a fully charged FCA, it is reset and the next empty fuel cell in the array is to be connected to the charging circuit.

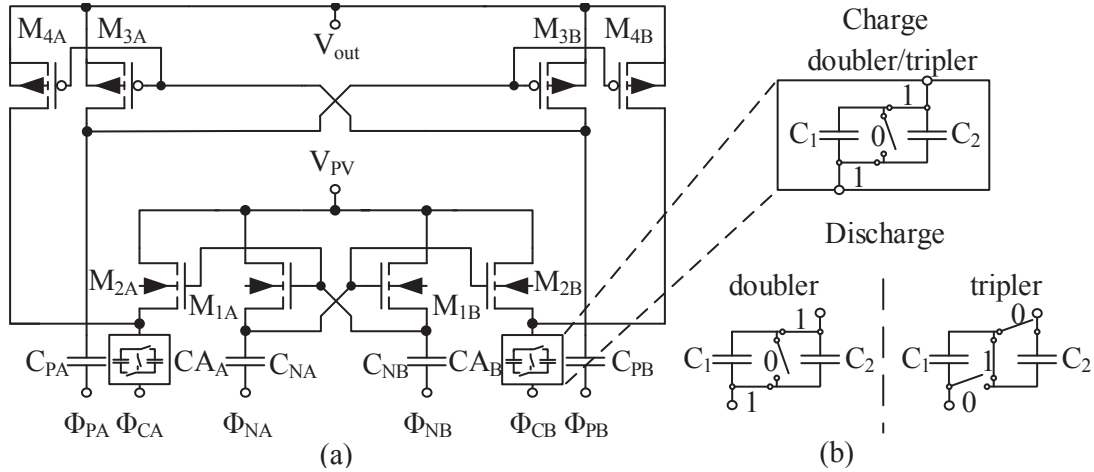
### 3.1. Adaptive Charge Pump

The circuit schematic of the 6 phase adaptive charge pump (CP) is illustrated in Fig. 5(a). The 6 phases driving the charge pump are generated by a dedicated non-overlapping phase generator [7]. To differentiate the left and the right side of the circuit, each component has subscript of A and B, respectively. In order to simplify the explanation, just one half of the CP is discussed next and the subscript is not mentioned in the explanation. The other half of the CP operates with a phase shift of  $180^\circ$ .

The circuit schematic consists of 3 closely coupled charge pumps. The main charge pump, consists of  $M_2$ ,  $M_4$  and CA. The gates of  $M_2$  and  $M_4$  are driven by boosted clock signals, generated with unloaded charge pumps much smaller than the main charge pump. Using a smaller unloaded extra charge pump has the advantage of a swingless driving signal, enhancing the on-resistance of  $M_2$  and  $M_4$  and lowering the charge pump losses.

The key component which makes this charge pump adaptive is the capacitance array CA with the corresponding switches as shown in 5(b). In the mode *doubler*, the two flying capacitors  $C_1$  and  $C_2$  are connected in parallel in both charging and discharging period. However, in the *tripler* mode, the discharge period,  $C_1$  and  $C_2$  are connect in series as shown in Fig. 5(b). In the charging period, both parallel capacitors  $C_1$  and  $C_2$  are charged up to  $V_{PV}$  via  $M_2$ . In the

discharging period, by applying  $V_{PV}$  to the bottom of CA, the top of CA would be connected via  $M_4$  to  $V_{out}$ . Depending on the mode of operation *doubler* or *tripler*, the boosted voltage on CA is  $2 \cdot V_{PV}$  and  $3 \cdot V_{PV}$ , respectively.



**Figure 5.** Circuit schematic of the adaptive charge pump (a) and illustration of the flying capacitor array (CA) switch matrix in charge and discharge state (b).the bulk of all NMOS is connected to ground.

#### 4. Results

Fig.6 shows the simulated autonomous operation with start-up and restart at 12ms of the system. Due to the clocked power transfer, there is a ripple on  $V_{PV}$ ,  $V_{out}$  and  $I_{out}$ . Since the logic of the control system is powered directly from the solar cell, the operating point of the solar cell module also has a voltage ripple with a frequency equal to the operation frequency of the logic unit.

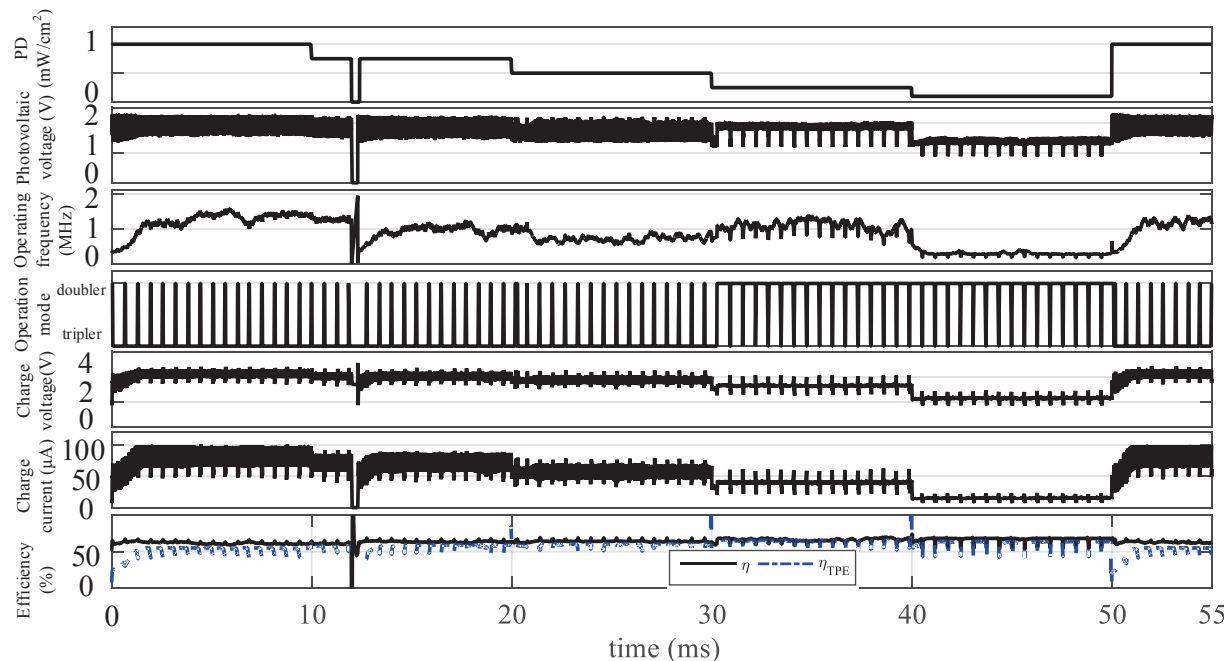
In order to show full system operation under varying ambient conditions, the input power density (light intensity) was changed each 10 ms. Within each change of the input light intensity, the system automatically maximizes the charging current, independent of the environmental conditions. The operation frequency and the operation mode are adopted accordingly.

The efficiency of the system, defined as  $\eta = P_{out}/P_{in}$  is shown in Fig.6.  $P_{out}$  is the power used to charge the FCA and  $P_{in}$  is the power extracted from the solar cell module. The power consumption of the control circuits, the charge quantizer, the corresponding counters and the clock boosters are all included in the input power. The efficiency of the charge pump and the resulting total system efficiency is limited by the stray capacitance. In this work, a poly over diffusion capacitor is deployed where the  $\alpha = \frac{C_s}{C_f} = 0.2$  and  $C_s$  is the stray capacitance of the top plate to ground. Therefore, the maximum power efficiency which can be assumed for the deployed charge pump in this work, is between 50 % to 64 % [8]. The presented system shows a peak efficiency of 60 % including the losses of all control circuits. Furthermore, a term named as total power extraction efficiency ( $\eta_{TPE}$ ) is defined as in equation 1 and is depicted as well with  $\eta$  in Fig.6.

$$\eta_{TPE} = \frac{P_{out}}{P_{in,MPP}} \quad (1)$$

Here  $P_{out}$  is the power used to charge the FCA and  $P_{in,MPP}$  is the maximum power which can be extracted theoretically from the solar cell module if this is operated at its maximum

power point. Therefore, where  $\eta_{TPE}$  is nearer to the efficiency of the system, it shows that the system is extracting more power from the solar cell module and nearer to the input maximum power point within the P-V curve.



**Figure 6.** Simulated autonomous system operation showing start-up and the self-adoption of the circuit according to the input power density (PD).

## 5. Conclusion

This paper presented an autonomous interface circuit which use small scaled solar cells to automatically recharge chip integrated micro fuel cell accumulator arrays. The interface circuit maximizes the charging rate of the fuel cell accumulator by maximizing the charging current. The presented system in combination with a previously developed voltage regulator and additional integrated sensors or actuators results in a autonomous fully integrated system for remote applications.

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