New Control for Stand Alone Solar Collector

J-L. Canaletti, C. Cristofari and G. Notton

***Abstract*—This study presents a new method for controlling the flow rate of a fluid by enslavement of the circulator in the stand alone production systems of heat using solar energy (PV/Th). The electronic control developed using this method allows to adjust in real time the speed of the circulator for converge to the needed set by the user and/or maximize the energy exchange (following the sun) between the solar collectors and the use. It will be presented here the results obtained with stand alone solar collectors using air as a heat fluid.**

***Index Terms*— control, heating, hybrid system, solar energy**

I. Introduction

A new method control has been developed to achieve two objectives: compensate the disadvantages of conventional control used in most heat production systems using solar energy and optimize the energy used to operate the circulator. For example, in systems of hot water production for dwellings, an on/off control is not suitable if the energy used to the pump comes from a photovoltaic module. The situation is similar for systems producing hot air for heating assistance [1].

This electronic control uses a new method to adjust in real time the speed of the circulator for converge to a desired temperature set by the user and/or optimize the energy exchange between the heat collector and the use.

Fig. 1. Wall with experimental solar shutters.

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J. L. Canaletti is with the University of Corsica, Georges Peri Laboratory, Vignola, UMR CNRS 6134- Sanguinaires road - F20000 Ajaccio, France (e-mail: canaletti@univ-corse.fr).

C. Cristofari, is with the University of Corsica, Georges Peri Laboratory, Vignola, UMR CNRS 6134- Sanguinaires road - F20000 Ajaccio, France (e-mail: cristofari@univ-corse.fr).

G. Notton, is with the University of Corsica, Georges Peri Laboratory, Vignola, UMR CNRS 6134- Sanguinaires road - F20000 Ajaccio, France (e-mail: notton@univ-corse.fr).

A study of this experimental command control unit was performed into an experimental wall (Fig. 1) equipped with a pair of stand alone solar shutters.

II. Description of a Stand Alone System

A conventional heat exchange between heat collector system and use usually consists of [2]:

1) heat collector(s)
2) photovoltaic module(s)
3) storage
4) circulator
5) control unit
6) heat exchange circuit

The control unit manages the starting and stopping of the circulator (on/off operating) through the external sensors (input management) and command transistor (output management).

In case of water system (Fig. 2) :

1) circulator is a pump
2) storage is a tank
3) heat exchange circuit is closed water circuit with exchanger
4) The control unit compares Tout, Tint and Tref.

   The pump is started when Tout > Tint + ΔT1.

   The pump is stopped when Tout < Tint + ΔT2

   With ΔT1 ≈ 5K-8K ; ΔT2 ≈ 1K-3K

   The pump is stopped when Tref > 362K

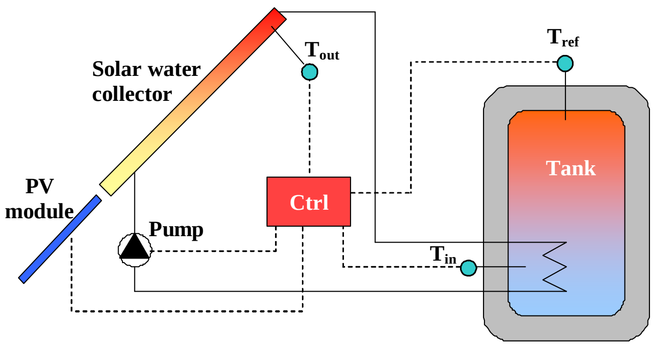

Fig. 2. Stand alone hot water system.

In case of air system (Fig. 3) :

1) circulator is a fan
2) storage is home
3) heat exchange circuit is closed or open circuit with air of home
4) The control is like water system but the fan is stopped when Tref > 292K

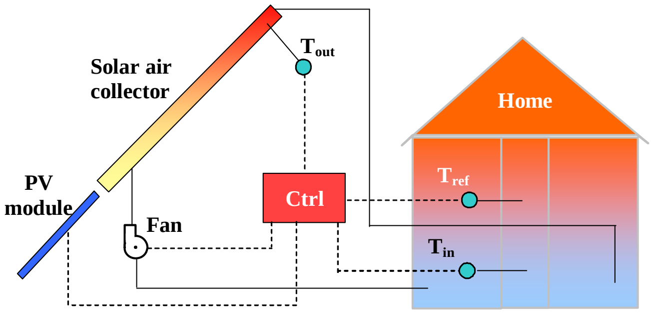

Fig. 3. Stand alone hot air system.

If the circulator works with direct current and agrees to operate in the voltage variation range of the photovoltaic module, it can be connected directly to the module (Fig. 4). With a proper sizing of all the elements, a natural adjustment occurs because the density of incident radiation is the same for the heat collectors and for the PV module [3]. The output temperature of thermal field is stable if the sun radiation does not vary abruptly. In this case the command control rarely operates.

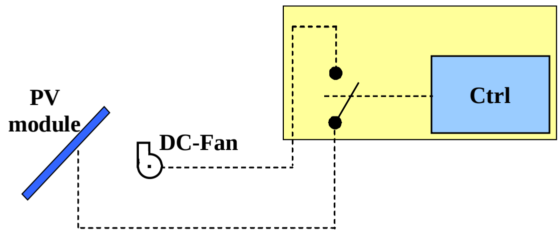

Fig. 4. DC-Fan control.

If the circulator operates with alternative current, the previous mode is not possible, because it does not accept too high change in voltage or variable frequency. In this case the command control is requested very often. In addition, an inverter is required (Fig. 5).

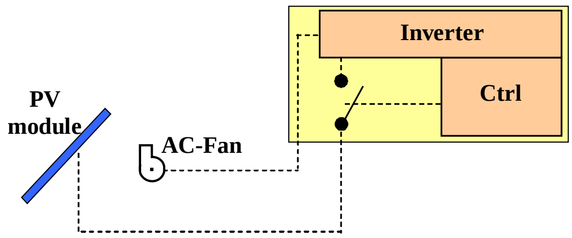

Fig. 5. AC-Fan control

This type of control causes some major drawbacks:

1) Frequently cycles on/off are hungry for energy and the circulator wears out prematurely.
2) The heat collector's temperature is swinging and induces many cycles of expansion, which accelerate the aging.
3) There is no management of inertia. The circulator responds instantly to a request from the PV module if it is subjected to an abrupt grow of solar radiation. The heat exchange is deferred under the heat capacity of the heat collectors. In a sharp fall of radiation, heat accumulated in the collector is dissipated to the outside
4) In the case of hot water system, high flow rate destroys the stratifications of the storage tank. The quality of water stored is altered in favor of quantity.

III. Conception of New Control Unit

This control unit has been tested on a fully instrumented solar shutters (Fig. 6) producing low temperature heat in open circuit directly into the home to be heated. It keeps the advantages of operating mode "following the sun" while controlling the air flow rate and its temperature in transient operating conditions (sunset, sunrise, cloudy, no conform temperatures, etc ...) to enslave the temperature to a reference required by the user [4].

Fig. 6. French shutters fully instrumented (inside view).

A) The measurement circuit

The measurement circuit reads in real time the parameters needed for the command control:

1) Outlet collector air temperature, Tout.
2) Air temperature inside the housing Tint.
3) Air Temperature chosen by the user Tref.

The temperature is measured with an integrated circuit LM35 [5] (temperature sensor) which, mounted with a resistor bridge divider R, give a voltage V proportional to absolute temperature T (Fig. 7). Thus, for a temperature ranging between 273 and 313K the voltage will be between 2.73 V and 3.13 V.

$$V(\text{Volt}) = \frac{T(\text{Kelvin})}{100} \qquad (1)$$

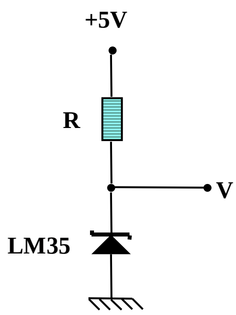

Fig. 7. Measure of temperature.

Outdoor temperature Text is not measured but it operates in the thermal power P produced by heat collector expressed by the simplified relationship:

$$P = k \cdot Qv \cdot (Tout - Text) \qquad (2)$$

P : power in W
Qv : air flow rate in $m^3.h^{-1}$
k : constant

It is important to note that the behavior of the temperature T is directly dependent of radiation and flow rate:

1) in constant radiation, Tout decreases when the flow increases, and vice versa.
2) in constant flow rate, Tout changes like the radiation.
3) In "following the sun" mode, the system connects radiation with flow rate but not any linearly for that Tout stays constant throughout the day and throughout the season.

B) Supply circuit

We chose to use a switching power supply that can deliver the +5V when the voltage from the photovoltaic module reaches 3V (Fig. 8). So, all Integrated circuit (measurement and management) are properly supplied with energy before the start up of the fan. This power supply is built around an integrated circuit switching µA78S40 [6]. The principle of the switching regulator is to store energy in an inductor, then return it to the output according to need [7]. It increases output voltage (step-up) when the input is less than 5V and decreases it (step-down) when the input voltage is higher than +5V.

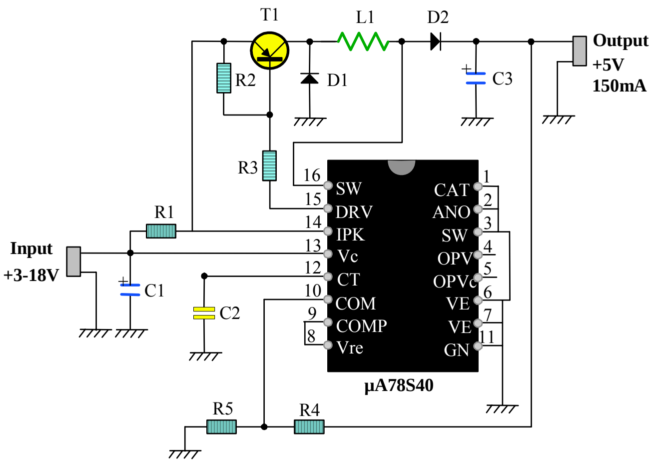

Fig. 8. Switching power supply

Output voltage is given by the formula:

$$V_s = 1.25 \cdot \frac{(R4 + R5)}{R5} \qquad (3)$$

C) Command circuit

The main objective is to control the temperature inside the house and keep it at a value set by the user. It is closely related to the thermal power injected and its temperature level. We must act on the air flow rate depending on the output temperature of the heat collector and the temperatures inside the room. For this, we must enslave the fan speed with the temperatures measured in order to converge, in all circumstances, the indoor temperature to a temperature set.

1) The potential

The temperature inside the housing being the key parameter of the system we wish to control, we define the solar thermal potential as the difference between this temperature and that of hot air collector.

We propose, initially, enslave the fan speed (and thus the flow rate of hot air) to the temperature difference between hot air collector and warm air inside the house (Fig. 9) for that if the difference is positive, the fan speed is an increasing function of the gap and if the difference is negative or null fan speed is null.

$$\Delta Tp = Tout - Tint \qquad (4)$$

This closed loop enslavement makes converge Tint to Tout. Indeed, for constant radiation, a decrease of flow rate causes a temperature increase in the collector and inversely.

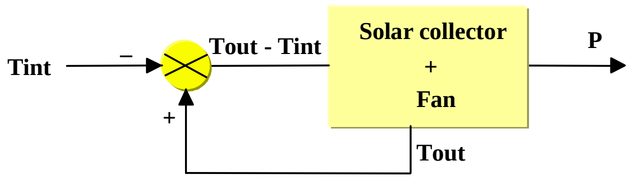

Fig. 9. Closed loop enslavement of Tint to Tout

Enslave like this, the fan speed allows to make converge Tint to Tout while remaining below Tout. Therefore, the amount of heat generated in the room is always optimal compared to the energy incident on the collector and the air pulsed temperature is never less than ambient temperature of the house.

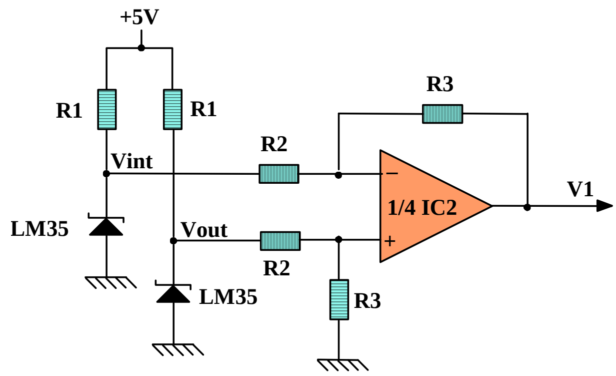

Fig. 10. Amplifier n°1; V1=K.(Vout-Vint).

An amplification by K=50 allows to obtain, for an input difference of 10 mV (either 1K), a gap of about 0.5 V on the output amplifier (Fig. 10). This gives a voltage V1 which is expressed as follows:

$$V1 = K \cdot (Vout - Vint) \qquad (5)$$

2) The request

In the previous state, the user has no control over the indoor temperature because Tout changes randomly above Tint. He must be able to fix a target temperature where Tint can converge without exceed it. Of course, if the radiation is not sufficient to achieve this target the solar collector must be able to continue to deliver its maximum power at a temperature above Tint.

For this, we define the user request as the difference between the indoor temperature Tint and a temperature of reference Tref fixed by the user. We propose, in a second time, to enslave the fan speed (and thus the hot air flow rate) to the temperature difference between inside the house and this reference (Fig. 11) for that if the difference is positive, the fan speed is an increasing function of the gap and if the difference is negative or null fan speed is null.

$$\Delta Tr = Tref - Tint \qquad (6)$$

But this opened loop enslavement (Fig. 11) can converge to different values:

if Tint<Tout<Tref, indoor temperature converges to Tout.
if Tout<Tint<Tref, indoor temperature converges to Text.
if Tint<Tref<Tout, indoor temperature converges to Tref.

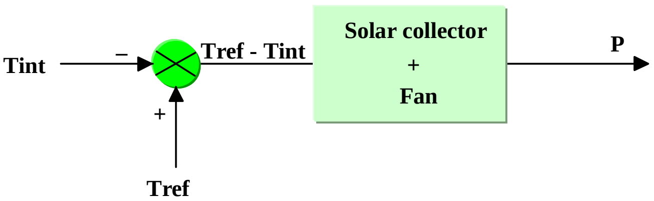

Fig. 11. Opened loop enslavement of Tint to Tref

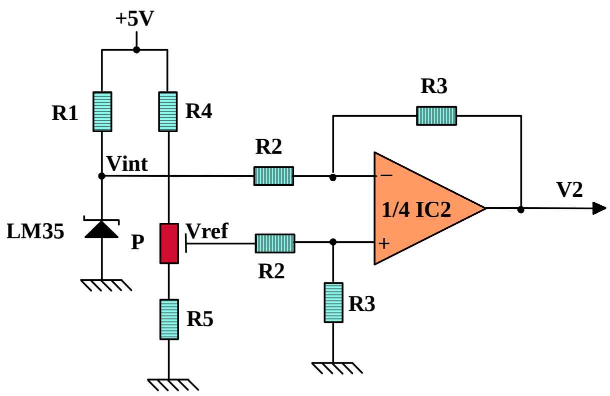

Fig. 12. Amplifier n°2; V2=K.(Vref-Vint).

Like in the previous case, an amplification by K=50 produces a voltage V2 (
Fig. 12) which is expressed as follows:

$$V2 = K \cdot (Vref - Vint) \qquad (7)$$

Indeed, in the first case where Tref is greater than Tout, increase of the difference ΔTr causes an increase of the flow rate Qv of ventilation, so a decrease of Tout. This one being greater than Tint, the thermal power supply leads in a convergence of Tint to Tout remains uncertain but still higher than Tint. In the second case where Tref is always greater than Tout, the increasing gap has the same effect on Qv and Tout as before, but the latter being lower than Tint, convergence occurs to Text, temperature to which Tout converges if the flow rate does not decrease.

It is in the third case that the desired convergence is achieved, because, Tout being larger than Tref, the internal temperature Tint can only converge to Tref.

3) The coupling

It therefore appears that the enslavement of the indoor temperature (Tint) cannot be achieved by considering only the potential or only the request. To eliminate divergent cases, we must coupling potential and request (Fig. 13) and satisfy two conditions:

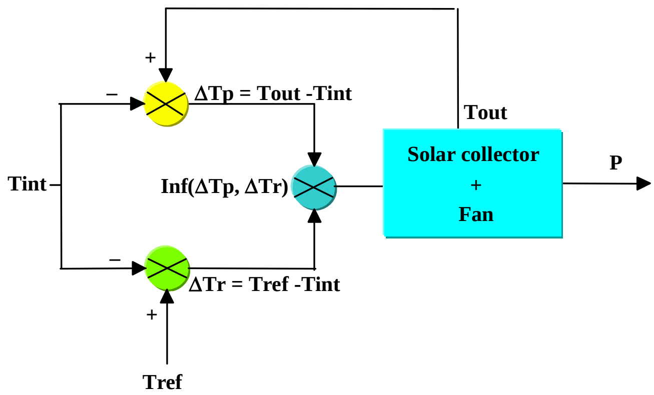

Fig. 13. Coupling of potential and request

- If the request ΔTr is greater than the potential Δtp, Tref is greater than Tout, it is the potential that will drive the power circuit. The solar collectors will provide all the heat that it will be possible to give by pulsing air at Tout temperature, temperature closest to the reference Tref.

- If the request ΔTr is below potential ΔTp, Tout is less than Tref, it is the request that will drive the power circuit. The solar collectors will provide only the amount of heat needed to meet demand and the indoor temperature Tint will converge to Tref.

In other words, it is the smaller of the two temperature differences that must drive the power circuit.

The voltage comparator with diodes shown on Fig. 14 allows delivering in output, with a gap of 0.6 V, the smaller of the two voltages mentioned above.

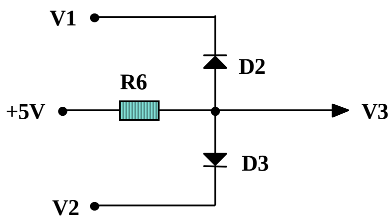

Fig. 14. Voltage comparator with diodes

We obtain a voltage V3 which is expressed as follows:

$$V3 = \inf(V1, V2) + 0{,}6 \qquad (8)$$

The circuit thus produced yields the following result:

if (Vc - Vint) > (Vref - Vint) :

$$V3 = K \cdot (Vref - Vint) + 0{,}6 \qquad (9)$$

if (Vc - Vint) < (Vref - Vint) :

$$V3 = K \cdot (Vout - Vint) + 0{,}6 \qquad (10)$$

We have built an enslavement which, whatever the system state, converges to V3 value between Vref and Vint.

4) Fan enslavement

To enslave the fan speed to the voltage V3, it makes a switching of the fan power supply. This switching is build around a signal of fixed frequency and variable duty cycle that will drive the power stage. The duty cycle must be a function of the voltage V3 (Fig. 15). It must be equal to 1 when V3 is zero and equal to 0 when V3 is max because the power stage, which will switch the power supply fan, is mounted in reverse. A relaxation oscillator (Fig. 16) is built around an amplifier, delivering on its inverting input a voltage saw tooth signal V4 and frequency fixed equal to 8 kHz. The choice of this frequency allows both to limit the level of noise generated by switching and to gain flexibility to enslave the fan speed. The V4 voltage between 0.6V and 3V attack the inverting input of a comparator voltage while the comparator gap diode V3 is applied to its non-inverting input.

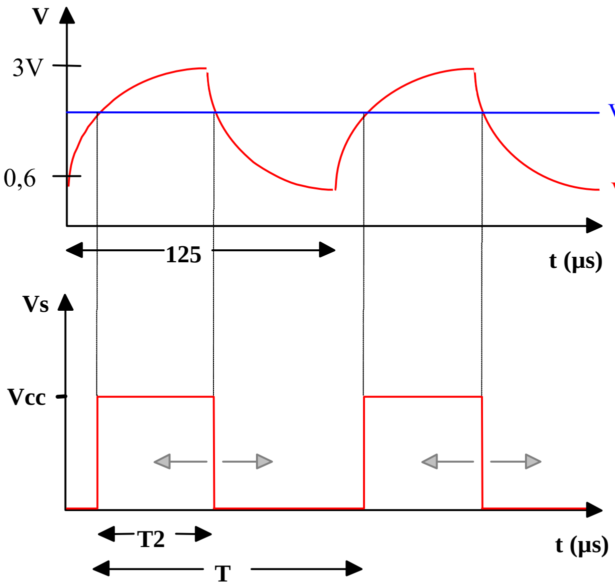

Fig. 15. Evolution diagram of Vs according to V3

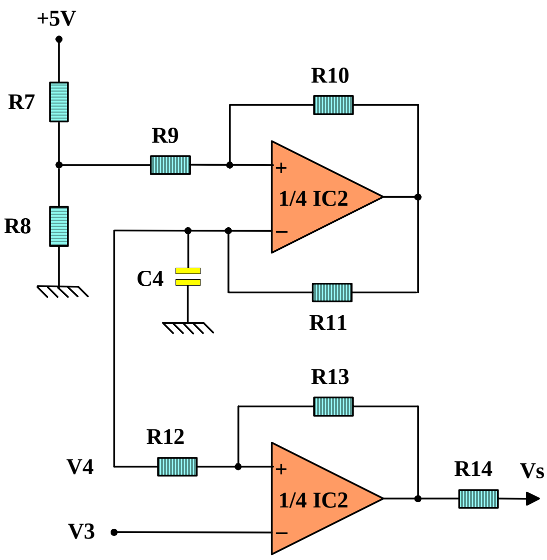

Fig. 16. Relaxation oscillator and hysteresis comparator

D) The power circuit

The modulated signal drives a Darlington power circuit (Fig. 17) composed of two transistors T1 and T2 (a NPN and a MOS N-channel power). It plays the role of switch controlled between photovoltaic module and fan. The diode D4 protects the transistor from over voltage due to possible inductance effects from fan.

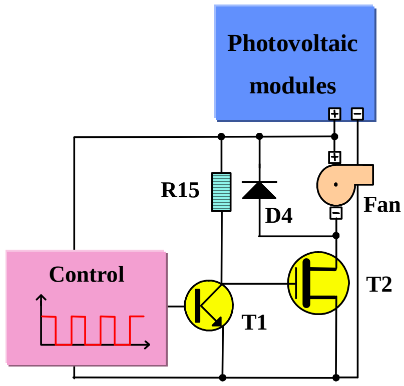

Fig. 17. Power stage

The Vm voltage applied across the fan is the average of the voltages supplied during the signal period (125 µs).

$$Vm = Vpv \cdot \left(\frac{T2}{T}\right) \tag{11}$$

E) Results

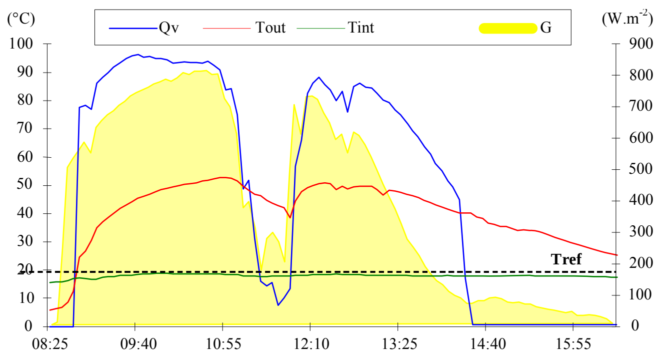

Fig. 18. Evolution of temperatures and flow rate

We can see on Fig. 18 that the "following the Sun" operating is satisfied: when Tout>>Tref>>Tint, the air flow rate is changing with the radiation. However, during several periods of the day, the control command affects air flow rate.

From 8:25am until 8:30am the fluid flow rate is null because the start threshold of fan is not reached.

From 8:30am until 8:45am the start threshold is far exceeded. But the fan does not work because the command control measures a negative gap between Tout and Tint.

From 8.45am ΔTr becomes positive and the fan starts.

Between 10am and 11am we see that radiation increases but the flow rate stabilizes and then slows. This reflects the difference between the set temperature Tref and the indoor temperature Tint becomes much lower than 5.28 K. ΔTr being smaller than ΔTp, the command control increases the duty ratio of switching signal and therefore decreases the fan speed. This has the effect of limiting Tint order not to exceed the set temperature Tref.

Between 11am and 12pm a cloudy passage leads a very large drop in flow rate. This shows that, in normal conditions, the command control will not affect the operating 'following the sun".

Around 2:15pm the radiation on the photovoltaic module is no longer sufficient to supply the fan. Then the flow rate falls sharply.

F) Adding an accumulator

It remains to solve the problem of the radiation fall down that stops the ventilation before that all heat can be extracted from the heat collector. The addition of an accumulator is required. However, its insertion in the circuit must not disturb the enslavement previously developed. If we want to keep the configuration "following the sun", we can not just add a battery in parallel with the photovoltaic module. It would impose the battery voltage on the fan (≈12V). Therefore, it must couple the battery only just to help the photovoltaic module when necessary and to ensure its maximum load.

As shown on Fig. 19, the battery is integrated into the system with the diode D which avoided the charge in the photovoltaic module. An additional measure is necessary, the voltage V1, which continuously informs the state of battery charge and the voltage delivered by the photovoltaic module.

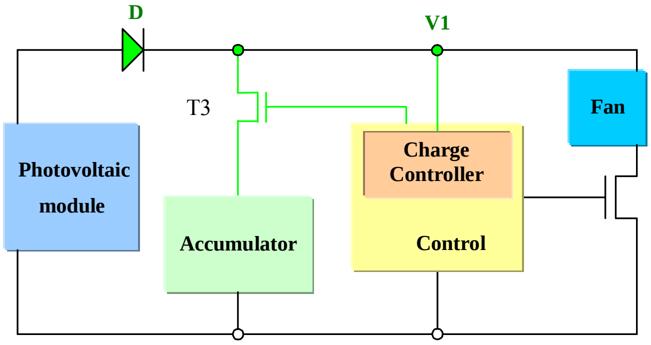

Fig. 19. Connection of an accumulator in the circuit

1) The charge controller

The function of the charge controller (Fig. 20), depending on the value of V1, is to close or open the power transistor T3 which connects the positive pole of the battery to the system (Fig. 21).

If V1 is between 11V and 13V the transistor must be closed. Otherwise it must be open. In fact, this interval is the range of voltage where the battery is usable or rechargeable by the photovoltaic module. Outside this interval, the battery is decoupled from the rest of the circuit to allow the direct operation (V1>13.5V) or to protect battery against deep discharge (V1<11.5V).

The fan used accepts to work from 6V until 15V.

If V1 is less than 11.5V, T3 is open. V1 represents the voltage across the photovoltaic module that controls the fan in the configuration "following the sun". The tension is too weak to seek or charge the battery

If V1 is between 11.5V and 13.5V, T3 is closed. V1 represents the voltage across the entire (PV module-fan). If radiation is sufficient, the photovoltaic module provides the energy needed to power the fan and recharge, if necessary, the accumulator.

If V1 is greater than 13.5V, T3 is open. V1 represents the voltage across the photovoltaic module. The battery is sufficiently charged. The opening of the transistor protects the battery against overload and allows the system to operate in the mode "following the sun".

When the voltage V1 is less than 11V, T2 is blocked. The transistor is off. The battery is decoupled from the photovoltaic module. If V1 exceeds 11.5V, the first comparator toggle and causes the toggle of the third. The transistor is on. The battery is connected to the system. The LED turns off. If V1 exceeds 13.5V, the second comparator toggle and causes the toggle of the third. The transistor is off again. The battery is disconnected from the system.

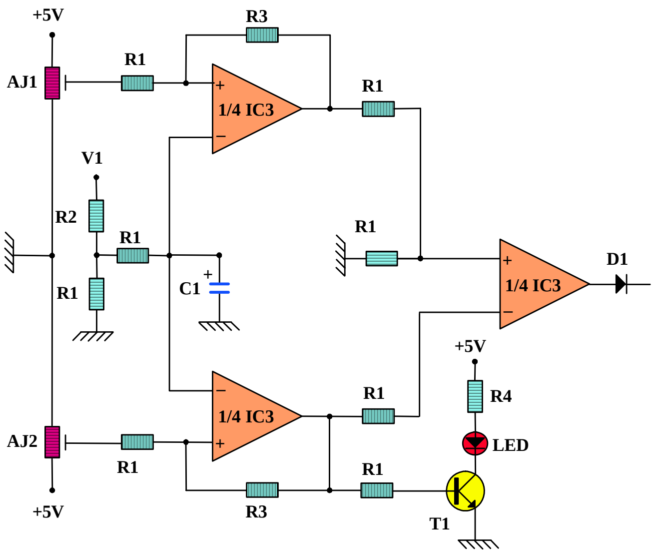

Fig. 20. Charge controller circuit

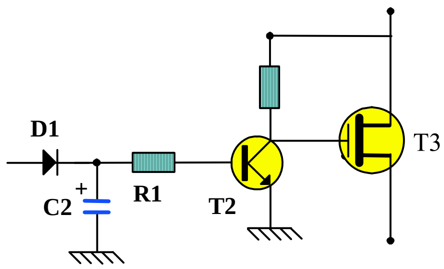

Fig. 21. Power stage

2) Capacity of the accumulator

The heat capacity and the relaxation time of solar shutters have been measured. We seek the time taken for the ventilation to remove heat from heat collector, from an operating temperature set to a temperature close to ambient temperature. It must 20 minutes maximum (in optimal condition) for that the outlet temperature reaches ambient temperature.

The characteristics of our elements are:

Fan: Papst 3412 NGMV (12V ; 2W)

PV Modules: Schott solar (ASI 3 Oo 07/122/115 FA × 8) (12V; 5.5W)

If we consider a maximum consumption of 2W during 4 hours (12 cycles per day), we need 8Wh, that is to say, at a rated voltage of 12V, a capacity of 0.7Ah. With an accumulator average yield of 0.72 [8], we achieve an effective capacity of 0.9Ah. For a best use and a longer lifespan of the battery an increase of 30% capacity is preferable [9] so a comfortable value of 1.17Ah. But the choice of the capacity of the battery also depends on the current load and discharge cycles.

The discharge occurs at constant current caused by the consumption of the fan. The consumption of the command control is a few milliamps and the fan is 0.17A (2W at 12V), thus a total consumption of 0.2 A max. The maximum load amounted to 0.33A (maximum current load of PV module). We selected a battery type specific to our use:

Lead Acid Accumulator: A1WP1.2-12
Nominal power: 12V
Nominal capacity: 1.2Ah
Maximum load current: 0.36A

G) Results

We have simulated a decreasing level of radiation simultaneously hiding the thermal module and the photovoltaic module. The ambient temperature was around 293K, so we set the reference temperature to 303K to see the work of the command control.

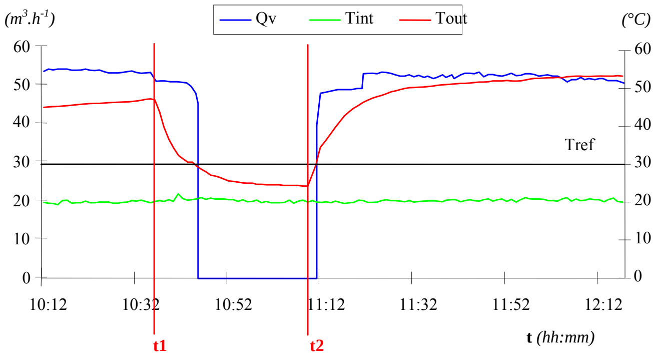

Fig. 22. Control of flow rate with accumulator

The Figure 22 shows that at t1 time, the temperature drops with a slight decrease in flow rate due to the taken over from the battery obtained at a voltage close to 12V. The flow rate remains constant until the outlet temperature of the fluid is greater than the temperature set. When the outlet temperature approaches the temperature set, the flow rate decreases sharply until be fully stopped. At t2 time, the masks are removed but the flow remains null until the outlet temperature does not exceed the set point. Then, the flow is established at nominal flow imposed by the accumulator. When the voltage exceeds 13.5V at its poles, the command control decouples the battery and the flow rate is established again in the configuration "following the sun" without the influence of the full charged battery.

IV. Perspectives

To help implementation and installation, we can improve this regulation with the establishment of an HF radio link (Fig. 23). Indeed, for various reasons, control can be placed far from the sensors installation place. The wired connection between sensor and control can become problematic and lead to additional costs of installation. A connection is wireless avoid this extra cost and promote the aesthetic. This improvement is even more interesting as it develops much in all domestic applications such as alarms, remote controls for lighting, etc ... This allows for standard modules transceivers easily exploitable in very low costs. A prototype is being tested on the solar shutters from modules transmitters-receiver type Zegbee^{TM} [10].

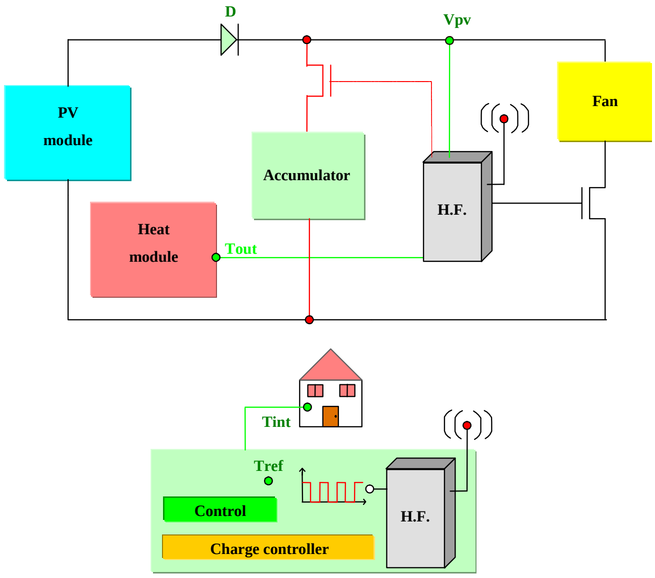

Fig. 23. Command control with Wifi connection

V. Conclusion

This specifically command control manages the quality and quantity of hot air blown into the house in all types of operation (established or transient) and as required by the user. The prototypes were tested in the laboratory and their performance has been highlighted by It showed, since its installation on different prototypes of solar collector a good effective management of the thermal power and the quality of the inside temperature in the heated space. In addition to its low power consumption (a few milliamperes) required for this type of applications (photovoltaic energy source), it showed high reliability.

It has an excellent value for money because it uses known and currents components (30$ max with the accumulator) and has an accuracy quite sufficient for this use. Low footprint, it also offers an easy implementation by the simplicity of his connections.

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Dr Jean-Louis Canaletti was born in Palaiseau, France on February 1st, 1964. He studied at the University of Corsica and received Dr. degree in 1998. His field of interest concerns integration of renewable energies in Building, solar energy study. He is today Assistant Professor in the Corsican Institute of Technology. He works in the Research Centre of Vignola, University of Corsica, UMR CNRS 6134, route des Sanguinaires, F20000 Ajaccio, France (e-mail: canaletti@univ-corse.fr)

Publications: 4 international publications and 20 Conferences.

Pr Christian Cristofari was born in Ajaccio on July 19th, 1966. He studied at the Institute of Chemical Engineering in Toulouse and received Dr. degree in 2000 and Research Agreement in 2006 from the same university His field of interest includes renewable energy systems, thermal conversion and renewable sources. He is today Professor and Director of the Corsican Institute of Technology. He works in the Research Centre of Vignola, University of Corsica, UMR CNRS 6134, route des Sanguinaires, F20000 Ajaccio, France (e-mail: cristofari@univ-corse.fr)

Publications: more than 35 international publications and 100 conferences

Dr Gilles Notton was born in Saint Avold, France, on January 23rd, 1964. He studied at the University of Corsica and received Dr. degree in 1992 and Research Agreement in 2002 from the same university His field of interest includes renewable energy systems and renewable sources. He is today assistant professor and responsible of the French Research ADEME network between France and Oriental and Central European Countries. He works in the Research Centre of Vignola, University of Corsica, UMR CNRS 6134, route des Sanguinaires, F20000 Ajaccio, France (e-mail: gilles.notton@univ-corse.fr)

Publications: more than 35 international publications and 120 conferences