**AUTOMATION PROCESS FOR POWER MANAGEMENT IN STAND-ALONE PHOTOVOLTAIC SYSTEM**

Carlos Armenta-Déu1 (\*)(cardeu@fis.ucm.es), Alexandre Beaufour2 (alexandre.beaufour@etu.uca.fr)

1. Dpt. of Matter Structure, Thermal Physics and Electronics, Faculty of Physical Sciences, Complutense University of Madrid, 28040 Madrid, Spain
2. Polytechnical Institute. Université Clermont Auvergne, Campus Universitaire des Cézeaux, 2, avenue Blaise-Pascal, TSA 60206 - CS 60026, 63178, Aubière Cedex

 (\*) Author to whom correspondence should be addressed

**ABSTRACT**

This paper is focused to the development of an automation process for managing the energy generated by stand-alone photovoltaic installations. The work not only includes the study and analysis of the proposed method, but also the design and manufacturing of a prototype that controls the process of energy transfer from the PV array to the load circuit. The design has been specifically developed for a dual inverter configuration that uses a high and a low power inverter, making the system to operate at optimum conditions under automatic turning process from one to another and vice versa depending on the operating conditions. A prototype has been built and tested to verify the validity of the process and the suitability of the design for stand-alone installations. The system takes into account all relevant parameters involved in the energy transfer from the PV panel, as well as the energy losses associated to the switching between inverters. The goal of the automation process is to optimize not only the operating efficiency of the panel, but also the global performance of the entire unit, so we can reduce the size of the PV array to supply energy to any specific load circuit. The performance of the new design has been evaluated and compared to that of the conventional configuration of single inverter unit. A theoretical approach has been used and applied to determine the efficiency of the single and dual inverter configuration. Experimental validation has been run for variable operating conditions simulating the real behavior of a stand-alone PV system; the results of the experimental tests have shown a very good correlation factor between theoretical approach and experimental results, proving that the system is well designed and that the applied protocol operates at high performance within maximum efficiency for the specific rated conditions. The use of the dual inverter system increases the global efficiency by 5%, from an initial value of 88.5% to 93.5%, on average. Maximum and standard deviation of experimental results from theoretical approach have been halved by the use of the new design, what indicates not only the validity of the proposed system and methodology, but also the quality of the results, The proposed methodology and prototype represents a very useful tool for PV array designers, manufacturers and users, and can save money and management time.

**KEYWORDS:** Stand-alone photovoltaic system. Dual inverter operation unit. Automation process. Control unit. Experimental validation.

**INTRODUCTION**

Stand-alone photovoltaic systems have become a realistic and useful alternative for non-connected to grid installations that require electric current for operation [1-6]. The design and sizing of the stand-alone PV arrays has been the focus of many studies in the past decades and it can be considered an already mature topic [7-14]. Furthermore, the control of the stand-alone PV systems has been also the subject of research and development, aimed at improving the performance of these kind of devices [15-21]. Power and load management have deserved the attention of some researching groups [22-29]. In dual current, AC and DC, load circuits the use of inverters is mandatory; since the inverter efficiency may change from high to low values depending on the load ratio, the management control of the inverter may become one of the key point to optimize the stand-alone PV systems [30-33]. The automation of power management, for both the inverter and the DC converter, is critical to avoid energy losses due to time delay or uncertainties when taking the decision to switch from AC to DC or vice versa [34-40]. To this goal, this paper intends to go further in the development of an automation process to control the switching process from AC to DC current in stand-alone PV systems.

**THEORETICAL BACKGROUND**

The global efficiency of a stand-alone PV system can be defined as:

 (1)

Where *η* is the efficiency and sub-indexes *PV*, *inv* and *DC* account for the PV panel, the AC/DC inverter, and the DC/DC converter.

In current systems the regulator includes the switching unit from AC to DC and vice versa.

If a MPPT unit is implemented in the PV system, the PV panel operates at the maximum power point, therefore at the maximum efficiency which is given by:

 (2)

*V* and *I* are the supplied voltage and current by the PV panel, with the sub-index *M* accounting for the maximum value, *G* is the global solar radiation onto the PV surface, and *S* the front surface.

The DC converter efficiency depends on the voltage ratio, but for low voltage operation like in the case of stand-alone systems, the efficiency is around 91% to 92%, remaining rather constant even for variable operating conditions. A good design helps the converter to work at high efficiency and optimum conditions [41-51].

Efficiency of an AC/DC inverter depends on the load factor (LF) [52-56], what represents a serious problem if the system operates in a wide range of power requirements. Typical evolution of AC/DC inverter efficiency with load factor can be seen in figure 1.

Load factor

*Figure 1. Efficiency of AC/DC inverter with load factor [57]*

It can be noticed that for very low values of the load factor the efficiency of the AC/DC inverter drops drastically; this means that below a load factor of 0.1, it is said, 10% of the maximum allowed capacity of the inverter, the device operates at rather poor conditions, and the global efficiency, *ηg*, is severely penalized.

Stand-alone PV systems currently operates at a wide range of power demand, from very low to very high values, depending on the user’s needs. Depending on how long the low loads are preeminent, the AC/DC inverter efficiency is higher or lower; if most of the times the low load appliances are working, the efficiency will be moderate or even low; however, if the high load appliances are preeminent, the daily average efficiency of the inverter will be high.

The aforementioned situation leads to the searching for a solution to the inconstancy of the efficiency of the power inverter. A good way is to split the load factor in two sections separated by a threshold value which is defined by the point where the inverter efficiency starts dropping; this point, according to what shows figure 1, is the load factor of 0.1, and every section is assigned to a different type of inverter, the upper section, from 0.1 on to a high power inverter, and the lower section, from 0.1 down, to a low power inverter. This configuration warranties the system operates at high efficiency values for any external load.

Considering that the two inverters has the same performance related to the load factor, the threshold value must be at 0.01 Lo, being Lo the upper limit of the high power inverter. Using figure 1 and averaging the inverter efficiency within the range 0.1-1.0 for the load factor, it results in a value of 93.7%; therefore, we can establish this value as the average efficiency for the dual inverter system.

The energy demand of the external appliances can be defined as:

 (3)

Where *Pi* is the power demand of the appliance *i*, *ti* is the time during which the appliance is operating, and *n* is the number of external appliances.

Applying the dual inverter configuration to the energy demand, we have for loads over LF=0.1:

 (4)

Where super-index HP corresponds to the high power inverter, and sub-index *j* accounts only for the external appliances with power demand over LF=0.1

Analogously,

 (5)

With sub-index *k* accounting for external appliances with power demand below LF=0.1

***Inverter efficiency***

In general terms, the conversion of current from DC to AC is produced at very high efficiency, currently over 90%; however, some energy losses arise during the process, mainly due to open circuit, voltage drop and resistance. In such a case, the inverter efficiency for a specific load factor can be defined as:

 (6)

Where *PDC* is the conversion power in DC current, and *PL* represents the power losses that depend on the conversion power through a second degree polynomial function:

 (7)

Where constants *ao, a1* and *a2* are empirically determined.

Applying equations 6 and 7 to figure 1, it results:

 (8)

Where subscripts of the efficiency in equation 8 indicate the LF value at which the efficiency is calculated, and *f* is the weighing factor of the external load power demand.

It can be noticed that the highest coefficients correspond to high LF values, with the peak for LF=0.5

The analysis of equation 8 shows that for low values of LF the predominant coefficient is very low, only 0.03 for LF=0.05, what means the efficiency of the inverter is poor. This is the main reason to split the external power demand in two.

**AUTOMATION PROCESS**

The automation process of the power demand is controlled according to the flowchart shown in figure 2.

As it can be seen, the automatic system controls the load factor and switches from one inverter to the other depending on the external power demand. The automatic switching warranties that inverter efficiency is within upper limits, no matter which one is used.

Since the automatic control unit does not use very much power to switch between inverters, the global efficiency is barely modified, thus maintaining the value given by equation 8.

The use of equation 8 requires the knowledge of the power distribution of external appliances as well as the operating time of any of them. Since the external appliances vary from one installation to another, a representative case has been selected for the application of the automation process. The basic characteristics of this case have been presented in table 1.

**LF calculation**

**External power demand (Pext)**

**Maximum power demand (Pext,max)**

**Pext< Pext,max?**

**YES**

**NO**

**LF<0.1?**

**High power**

**Inverter**

**NO**

**Low power**

**Inverter**

**YES**

**Automatic switching control unit**

*Figure 2. Flowchart of automatic control system*

Table 1. Characteristics of the testing prototype

|  |  |  |  |
| --- | --- | --- | --- |
| ***Appliance*** | ***Max. power (kW)*** | ***Appliance*** | ***Max. power (kW)*** |
| Aerothermal heat pump | 6 | Induction cook | 3.25 |
| Convection oven | 2.6 | Microwave | 1 |
| Washing machine | 1.8 | Dishwasher | 1.5 |
| Water heater | 0.6 | Fridge  | 0.5 |
| Convection heater | 2 | Ironing machine | 2.6 |
| LED lights | 0.8 | Other accessories | 1.25 |

Time of using of any of the appliances listed in table 1 also vary from installation to installation; therefore, we have used stochastic and statistical analysis, historical databases and models to set up a standard averaged time for every appliance [58-66]. To make more reliable the developed study, data have been taken from different parts of the World as well as from different social classes.

The results of the application of the aforementioned methodology for the establishment of the time using of every household appliance is listed in table 2. For unicity, the values have been normalized. Since different households appliances can be overlapped, the sum of the normalized value may exceed the unity. Nevertheless, we have adopted as a rule of thumb that the sum of the normalized values for all appliances, except the fridge which operates 24 hours a day, is one.

Table 2. Normalized time of using of household appliances

|  |  |  |  |
| --- | --- | --- | --- |
| ***Appliance*** | ***Time of use***  | ***Appliance*** | ***Time of use***  |
| Aerothermal heat pump | 0.26 | Induction cook | 0.03 |
| Convection oven | 0.04 | Microwave | 0.01 |
| Washing machine | 0.07 | Dishwasher | 0.05 |
| Water heater | 0.10 | Fridge  | 1.00 |
| Convection heater | 0.02 | Ironing machine | 0.03 |
| LED lights | 0.35 | Other accessories | 0.04 |

To apply equation 8 we must also know the overlapping time of the different appliances in a day. Once again, this situation is rather complicated to draw, since resident habits differ from location to location and from high to low social class. As in the case of the time of using, we have resorted to statistical databases, probabilistic approach or developed modelling techniques [67-75]. Figure 3 shows the daily distribution of power demand for standard statistical conditions.

*Figure 3. Daily distribution of power demand for standard statistical conditions*

Results from figure 3 show that the peak power value is 10.936 kW, from which we can establish the load factor points for equation 8.

To make more precise the calculation of the global efficiency, we have obtained the efficiency of the inverter for load factor from 0.1 to 1.0 in o.1 steps obtaining the following results (table 3).

Table 3. Efficiency of the inverter

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| LF | 0.05 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| *η* (%) | 86.0 | 91.2 | 94.0 | 94.6 | 94.1 | 93.6 | 93.0 | 92.2 | 91.7 | 90.9 | 90.2 |

Correlating efficiency and load factor, we obtain a polynomial function of sixth degree of the type:

 (9)

That shows a regression coefficient of *R2=0.9959*

Applying equation 9 to the overall daily period the efficiency of the inverter is 92.7%.

Daily distribution of the load factor can be drawn to evaluate the behavior of the system from the efficiency point of view; the distribution is shown in figure 4.

*Figure 4. Daily distribution of load factor*

Dashed line in figure 4 indicates the threshold that determines the switching process between inverters. All hourly values below this line are operated by the low power inverter, while the ones above the line work with the high power inverter.

In case the system is designed to operate with a single inverter, the high power one, the efficiency of the inverter can be obtained combining data from figure 4 with those of table 3 resulting in (figure 5):

*Figure 5. Daily evolution of the high power inverter efficiency*

Averaging the efficiency for the entire day we obtain a value of 88.5%.

If we now apply the design of a dual inverter system, as it has been mentioned before, taking LF=0.1 as the threshold value, and we draw the daily evolution of the efficiency for each of the two inverters as well as for the combination, we have (figure 6):

*Figure 6. Daily evolution of the efficiency for the single and dual inverter configuration*

If the efficiency of the dual inverter configuration is averaged over the entire day it results of 93.2%, an absolute gain of 4.8% and a relative increase of 5.4%.

**EXPERIMENTAL DESIGN**

To validate the proposed configuration, we have designed and built a laboratory prototype that reproduces at a small scale a real case, based on a PV installation in a semi-detached house where a photovoltaic installation of 11 kWp supplies power to the house and to a thermal heat pump for sanitary hot water and heating. The peak power demand of the electric appliances of the house is 5 kW while the nominal power of the heat pump is 6 kW, for a total of 11 kW, a value that matches the PV array power supply. The installation is designed to operate on the basis of PV panels and the battery unit that stores the excess of power supply during the day to revert the energy flow and supply power to the house at nighttime.

The PV installation has a high power inverter of 12 kW, capable of converting into alternating current all the power generated by the photovoltaic panels, even at the point of maximum power.

The laboratory prototype consists of a dual inverter system, a high power inverter of 1.2 kW, and a low power inverter of 120 W. The load circuit has been simulated by a variable resistance unit that is connected to the dual inverter system as shown in figure 6. Battery is connected to the power analyzer and control unit, which determines if the power demand corresponds to a high load factor (LF>0.1) or to a low one (LF<0.1). A switch device has been intercalated between the PV array and the dual inverter system to commute from one to another depending on the load factor; the switch device is linked to the power analyzer and control unit from which it receives the corresponding signal to switch between inverters (figure 7).

PV array

Power analyzer & Control unit

Power demand

Load circuit

High power inverter

Low power inverter

Switch

Battery

Power meter

Power meter

Power meter

Power meter

Power meter

*Figure 7. Layout of the circuit*

The power analyzer has a built-in power meter that detects active and reactive power to determine the power factor and power losses. Since active power is the only useful part of the global power, this value is taken for the calculation of the load factor and to determine which inverter should be used.

The control unit is based on an Arduino board that controls a set of actuators to open and close the relays; the layout of the control unit can be seen in figure 8.

Arduino board

Mosfet#1

Mosfet#2

Current sensor

High power inverter

Low power inverter

Power meter

Relay

UPS battery

*Figure 8. View of the control unit*

The Arduino module is managed by a program specifically designed for the control of the dual inverter system. The module is used to calculate the consumed power and select which inverter should be used. A view of the Arduino one assembly that has been used as control unit is presented in figure 9.

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*Figure 9. General view of the Arduino One assembly (control unit)*

The mosfet is used to open and close the circuit as a controlled switch. Each of the mosfets play a different role, mosfet 1 is in charge of closing and opening the electric current supply to the inverters, while mosfet 2 opens and closes the relay to selected the appropriate inverter according to the power requirements.

The current sensor uses the Hall’s effect to determine how much current is circulating, thus how much power should be managed by the control unit. Assuming the operating voltage is constant, and using the Ohm’s law, power is calculated from the expression: *P=IV* (10). Depending on the detected current, the sensor generates a voltage between 1.875 VDC and 3.125 VDC, which correspond to the lower and upper limit when maximum current is detected. These voltages are used to activate or deactivate the relay, with the higher voltage corresponding to the opening and the lower one to the closing action.

**EXPERIMENTAL TESTS**

A group of tests aimed at evaluating the performance of the system described in the previous section has been developed. Tests reproduce the conditions previously mentioned to analyze the performance of the prototype and verify the validity of the proposed method. All values in experimental tests at laboratory scale correspond to the real conditions values lowered by a scale factor of 1:10.

Power has been measured using the power meters, both at the inlet and outlet of the two inverters. Two cases have been tested corresponding to the single and dual inverter configuration. In single configuration, for obvious reasons, the high power inverter is the operating one.

Tests have reproduced the profile of power demand of the semi-detached house used as reference, applying the ratio 1:10 to the power values; therefore, the daily distribution shown in figure 3 is applicable as well as the load factor daily distribution of figure 4. The profile of daily power distribution for the single and dual inverter configuration can be seen in figures 10 and 11.

*Figure 10. Daily evolution of inlet and outlet power for single inverter configuration.*

P(in)

*Figure11. Daily evolution of inlet and outlet for dual inverter configuration*

It can be noticed that the dual inverter configuration works better with a much closer profile between inlet and outlet. Translating these results to efficiency drawing, we have (figures 12 and 13):

*Figure 12. Daily evolution of the efficiency for single inverter configuration.*

*Figure 13. Daily evolution of the efficiency for dual inverter configuration.*

It can be noticed that there is good correlation between theoretical and experimental values, what proves the validity of the proposed methodology and of the use of theoretical algorithm to determine the efficiency of an inverter system, single or dual.

The deviation that can be appreciated in figures 12 and 13 is of minor importance with a maximum absolute value of 5% for the dual inverter configuration. The standard deviation of the set of values for the efficiency of the dual inverter configuration is *σ=0.514*, which is a rather low value, indicating the goodness of the correlation. Values for the single inverter configuration are a little bit poorer, with a maximum deviation of 10.4%, and a standard deviation of *σ=1.032*.

On the other hand, averaging the efficiency values over the entire day we have obtained the following results (table 4):

Table 4. Global efficiency for the single and dual inverter configuration

|  |  |  |  |
| --- | --- | --- | --- |
| *Single (Th.)* | *Single (Exp.)* | *Dual (Th.)* | *Dual (Exp.)* |
| 88.5% | 88.6% | 93.2% | 93.5% |

The comparative analysis of results between single and dual inverter configuration (table 4) shows this latter system increases the global efficiency by 4.7% (4.9% for theoretical approach). Furthermore, comparing the maximum and standard deviation of the two configurations, we observe that the single inverter one shows a double value, what means a poorer performance.

**CONCLUSIONS**

A new methodological procedure, based on the use of a dual inverter configuration for non-grid connected photovoltaic installations has been designed and developed. The new design uses a high power inverter for high and medium power requirements, and a low power inverter for low and very low power demand.

The new inverter system uses a control system based on Arduino programming that switches between high and low power inverter depending on the load factor; for load factors higher than 0.1 the high power inverter is activated while for lower values of the load factor the system switches to the low power inverter. The control unit has been designed and built specifically for this system, using an Arduino One board as core of the unit and two mosfets to supply energy and to activate or deactivate the relay that switches from one inverter to another.

Using this methodology the global efficiency has been improved by 5%, from an initial value of 88.5% to an improved one of 93.5%, on average. Theoretical approach has been used and compared to experimental values obtained from experimental tests in a laboratory prototype. The correlation between theoretical and experimental results is of high accuracy with a maximum deviation of 5% and standard deviation of 0.514. These results improve the ones obtained for single inverter configuration where maximum and standard deviation are 10.4% and 1.032.

The high accuracy of experimental results to theoretical approach proves the validity of the proposed design and methodology. Since it has reproduced at small scale the operational conditions in real installations, it can be concluded that the system and methodology can be applied to almost any inverter system.

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