POLITEHNICA UNIVERSITY OF BUCHAREST
DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

PHD THESIS SUMMARY

CONTRIBUTIONS REGARDING THE EFFICIENCY OF CONVERTING AND STORAGE OF RENEWABLE ENERGY

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1 INTRODUCTION

Doctoral thesis named "C**ontributions regarding the efficiency of converting and storage of renewable energy**" comes as a necessity in the energy sector, which is currently facing a global crisis generated by the continuous development of human society, which, leads to an increase in electricity consumption. The repercussions are increasingly visible and translate into climate changes, rising pollution levels and declining fossil fuel resources.

In this context, the main concerns both nationally and globally are the implementation and the use of systems that supply electricity from renewable sources and in particular the increase rate of energy production through them.

The main objective of the doctoral thesis is the research of electricity generation systems using the sun as a renewable source. Even though photovoltaic energy has grown in recent years, capturing and transforming solar energy into electricity is still a challenge.

The thesis aims to study and develop optimal solutions regarding photovoltaic systems in order to achieve maximum efficiency in the conversion process.

Therefore, this paper addresses a topical issue, namely energy efficiency, which has been, is and will be a strategic goal in energy conversion.

The doctoral thesis, it also aims to research and solve problems referring to electricity storage.

2 CURRENT STATUS IN THE FIELD OF PRODUCTION AND DISTRIBUTION MANAGEMENT OF RENEWABLE ENERGY

The crisis we have been facing lately has accentuated and prioritized increasing environmental protection around the world from climate change. [1]

According to scientists' studies, in conjunction with the Energy Union Strategy, in order to combat climate changes, it is necessary to increase energy efficiency, to reduce greenhouse gas emissions and to maximize production, as well as the consumption of electricity from renewable systems. [2] [3]

Referring to the situation in Europe, the proposed target for 2050 is to neutralize greenhouse gas emissions, thus achieving improvements in several areas, such as agriculture, investments in hydrogen with a role in the energy sector, reduction of carbon emissions from real estate stock, reduction of pollution and decarbonisation of the energy sector.

According to the European Green Pact, the proposed target by 2030 is to reduce greenhouse gas emissions by 50-60% compared to 1990 levels and to become the first carbon-neutral continent by 2050. [4]

Even if the production and consumption of electricity from renewable sources is increasing at EU level, in order to achieve the proposed results, further efforts and the increasing use of renewable energy are necessary and essential. [5]

3 RENEWABLE ENERGY SOURCES. AREAS AND CRITERIA FOR EVALUATION OF OPPORTUNITIES TO PRODUCE ELECTRICITY FROM RENEWABLE SOURCES

The renewable energy term is associated with the types of non-polluting and environmentally friendly energy sources that come from natural resources that are renewed over a relatively short period of time. The role of renewable energy production systems is to generate electricity, heat and transport fuels.

The classification of renewable energy sources can be done as follows: solar, wind, hydropower, geothermal, biomass. [1] [5] [6]

4 CONVERSION OF PHOTOVOLTAIC ENERGY INTO ELECTRICITY

4.1 Characteristics and principles of conversion

Photovoltaic conversion is the conversion of solar radiation into electricity and is currently a key element in the world's energy strategies being the main form of long-term energy available with minimal negative effect on the environment. [7]

The importance of this form of energy is given by the many advantages it has:

- Inexhaustible source;
- Free accessibility;
- Geographical availability in all populated areas;
- Not harmful to the environment.

4.2 Electrical parameters of the photovoltaic cell

The complete electrical diagram for a photovoltaic cell, exemplified in Figure 4.1, takes into account the occurrence of unwanted electrical resistances (parasites), marked with r_s and possible leaks through the cell insulation, noted r_p. [7] [8] [9]

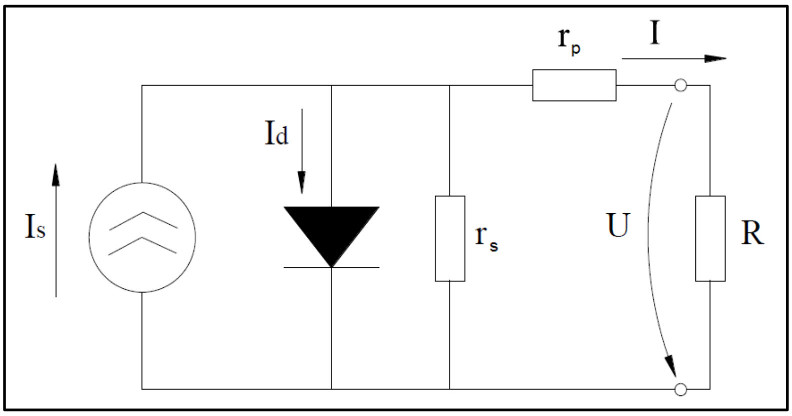

Figure 4.1 Detalied electrical diagram of a photovoltaic cell [8]

- In the presence of resistance r_p:

$$I = I_s - I_0 \cdot e^{\frac{q(U+I\cdot r_p)}{nkT}} \quad (4.1)$$

- In the presence of resistance r_s:

$$I = I_s - I_0 \cdot e^{\frac{qU}{nkT}} - \frac{U}{r_s} \quad (4.2)$$

- In the presence of both resistors:

$$I = I_s - I_0 \cdot e^{\frac{q(U+I\cdot r_p)}{nkT}} - \frac{U+I\cdot r_p}{r_s} \quad (4.3)$$

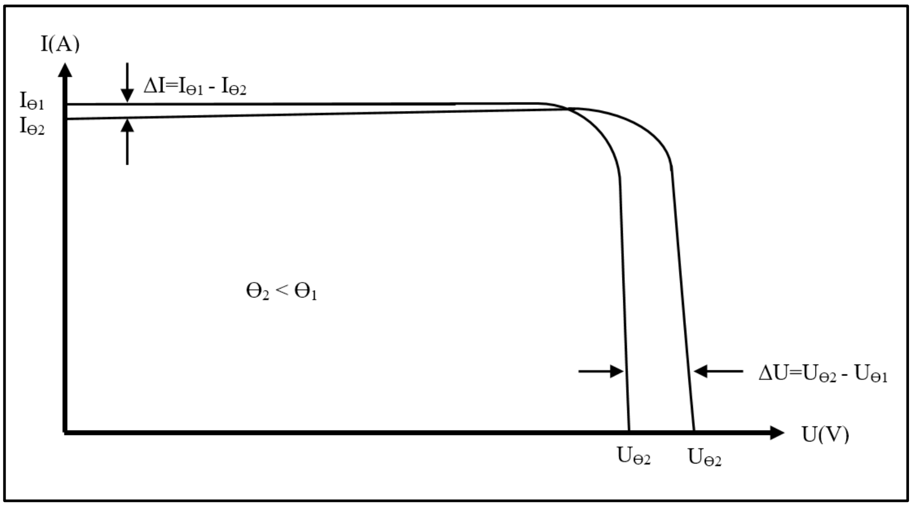

Figure 4.2 The influence of temperature on the operation of photovoltaic cells [10]

According to the graph in Figure 4.2, it can be observed that as the temperature of the environment in which a photovoltaic cell is used increases, the current I increases, but the output voltage U decreases substantially, which suggests the idea that as the temperature increases the efficiency of the photovoltaic cell decreases. [8] [10]

4.3 Energy efficiency of photovoltaic cells

As can be seen in Figure 4.2, a first conclusion regarding the increase of the energy efficiency of a photovoltaic cell, respectively of a photovoltaic system, is related to their construction technology with the significant decrease of r_p values and by maximizing r_s.

In the same idea, the maintenance of photovoltaic cells is very important, in the sense of decreasing r_p, respectively increasing r_s.

An important factor that influences energy efficiency is the final efficiency, noted with Y_f. It is described as the ratio between the energy generated in alternativ current and the rated power of the photovoltaic panels P_{max}.

$$Y_f = \frac{E_g}{P_{max}} \quad (4.12)$$

4.4 The simulation model of a photovoltaic cell

In the MATLAB program I simulated the operation of a photovoltaic cell.

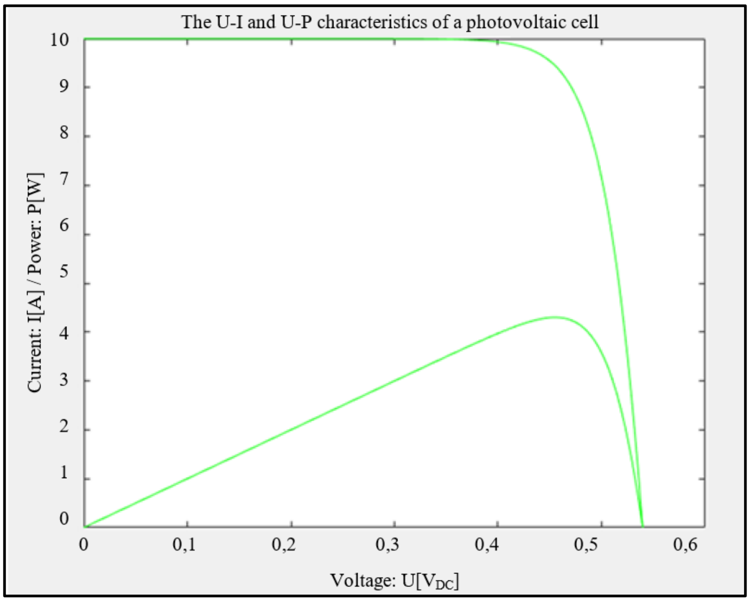

Figure 4.3 Simulation model for a reference photovoltaic cell (ideal)

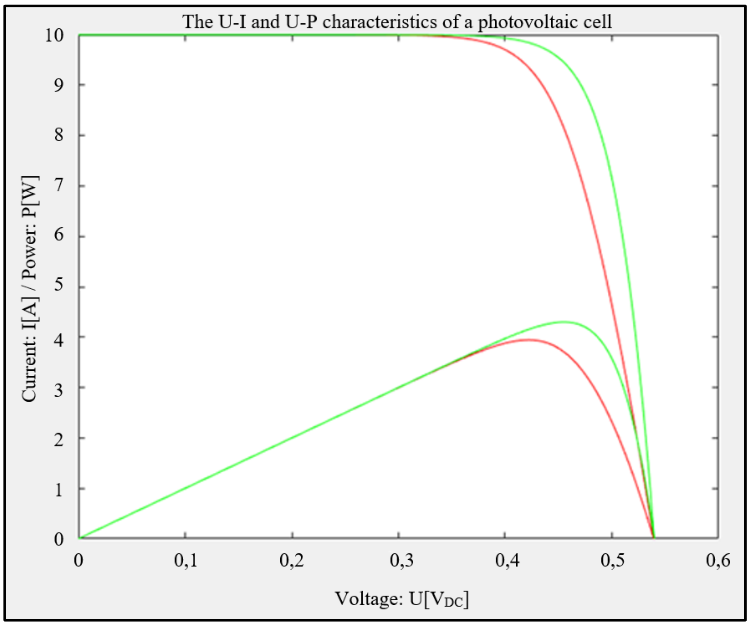

Figure 4.4 Simulation model for a photovoltaic cell with increased parasite resistance

It can be observed deviations from the reference curves I=f(u) and P=f(u), marked with green color.

The area between the two curves P=f(u) represents the losses that lead to the decrease of the energy efficiency of the cell by increasing the value of r_p.

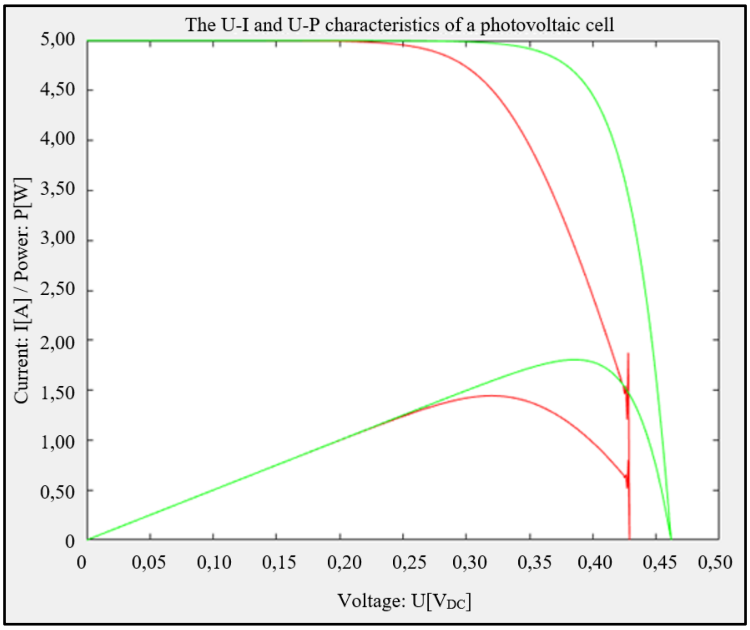

Figure 4.5 Simulation model for a photovoltaic cell with reduced shunt resistance

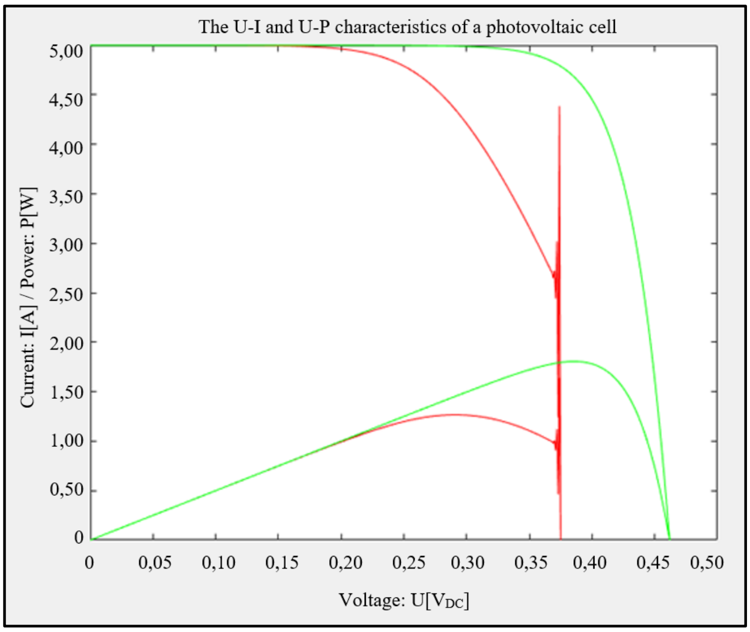

Figure 4.6 Simulation model for a photovoltaic cell with increased parasite resistance and reduced shunt resistance

Consequently, the three aspects developed theoretically above have been emphasized, so that:

- The drastic decrease of the efficiency, respectively of the energy efficiency of the photovoltaic cell operation by increasing the area between the two curvesP=f(u);
- The drastic decrease of the no-load voltage of the cell;
- The periodic amortized regime amplified by increasing the overadjustment of the debited power.

4.5 Experimental results

Validation of the theoretical aspects studied and developed both in this chapter and in the following ones, was possible through the the photovoltaic plant from ICPE ACTEL headquarters, where I am working. The plant was designed and purchased as part of two European-funded research projects and the electrical diagram is presented in Figure 4.7.

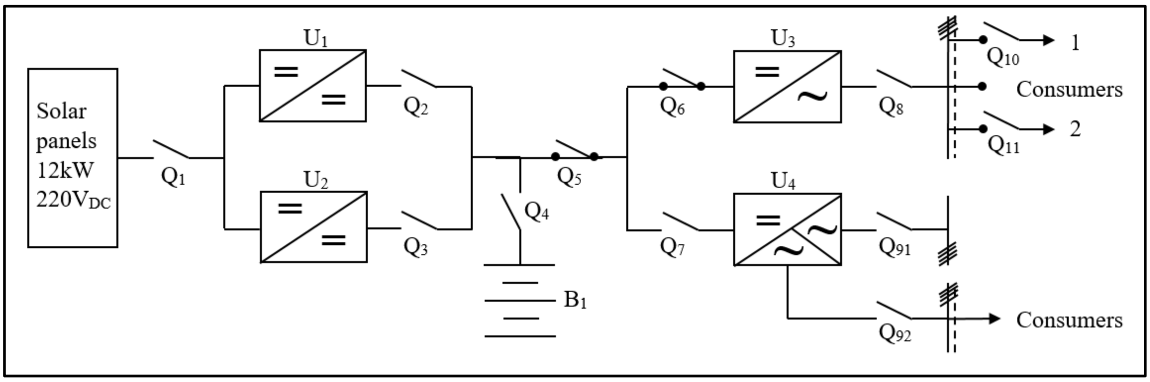

Figure 4.7 Electrical diagram of the photovoltaic power plant – SIPAMASRE and SICEEIF

An overview of the structure comprising the photovoltaic panels, which are a component of the plant, as well as the electrical panel to which these panels are connected are shown in Figure 4.8.a and Figure 4.8.b.

Figure 4.8.a Photovoltaic panels - component of the ICPE ACTEL SA photovoltaic power plant

To characterize the photovoltaic panels in the ICPE ACTEL plant and to validate the simulation study presented in the paper, I realized a set of measurements at the output of the plant.

Under different irradiance conditions were measured the output voltage of the photovoltaic panels and the load current for variable load achieved with real consumers from the company's endowment.

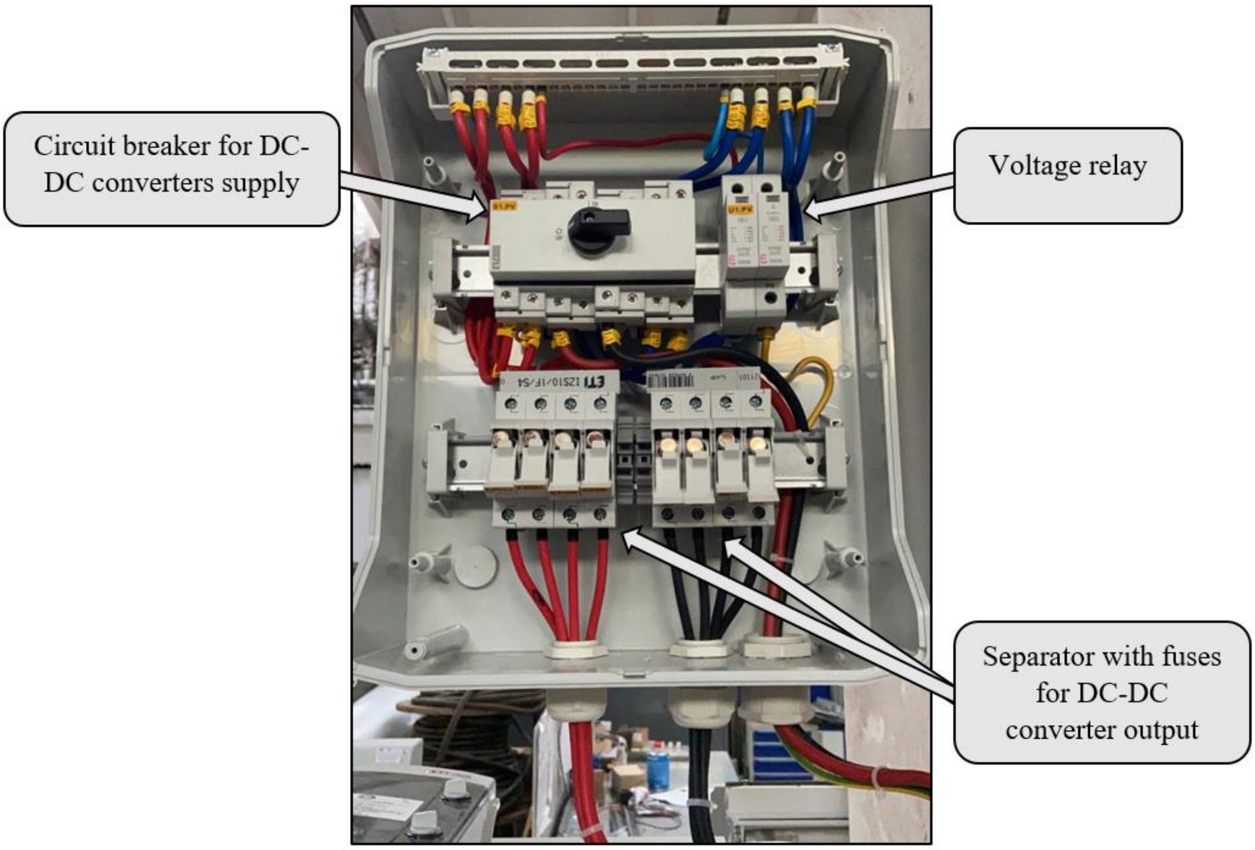

Figure 4.8.b Electric panel – component of the ICPE ACTEL SA photovoltaic power plant

Table 4.1

No. Crt.	Irradiance	U_{DC} (V)	Is (A)
1	Higher irradiance (sunny day)	221	0
2		219	9,6
3		217	11,9
4		215,7	13,15
5		213,5	16,55
6		203	25,5
7		190	30,9
8	Less irradiance (less sunny day)	221	0
9		218,8	9,5
10		216,5	11,4
11		215,2	12,9
12		210	15,4
13		198	20,1
14		188	24,2

Figure 4.9 exemplifies the experimental characteristics U=f(I) related to the ICPE ACTEL photovoltaic plant, values measured at the output of the photovoltaic panels.

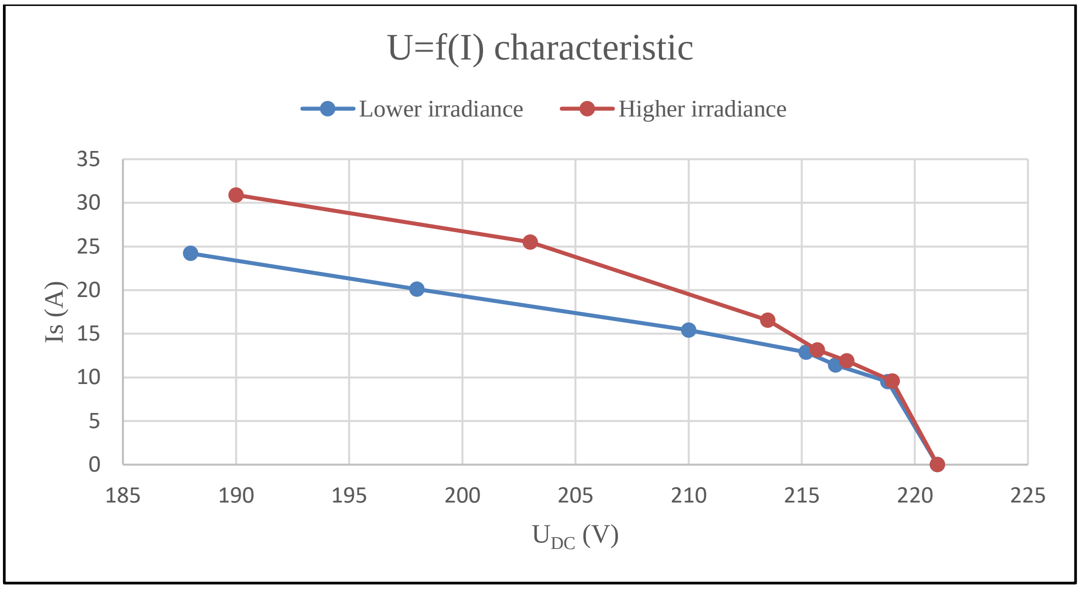

Figure 4.9 Experimental characteristic U=f(I)

The characteristics from Figure 4.9 suggest the following conclusions::

- The value of the no-load voltage, regardless of irradiance, is the same;
- The photovoltaic power plants, being new constructions, the values of the series resistance, respectively of the parallel resistance from the equivalent scheme of the photovoltaic power plant, have ideal values;
- The experimental characteristics in figure 4.9 complete the theory regarding the mathematical model of photovoltaic cells;

A new problem in the characterization of photovoltaic cells is their behavior in a dynamic regime. In this sense, I studied the behavior of photovoltaic cells when coupling and uncoupling the load. The result of this behavior is represented in the graphs in figure 4.10, respectively 4.11.

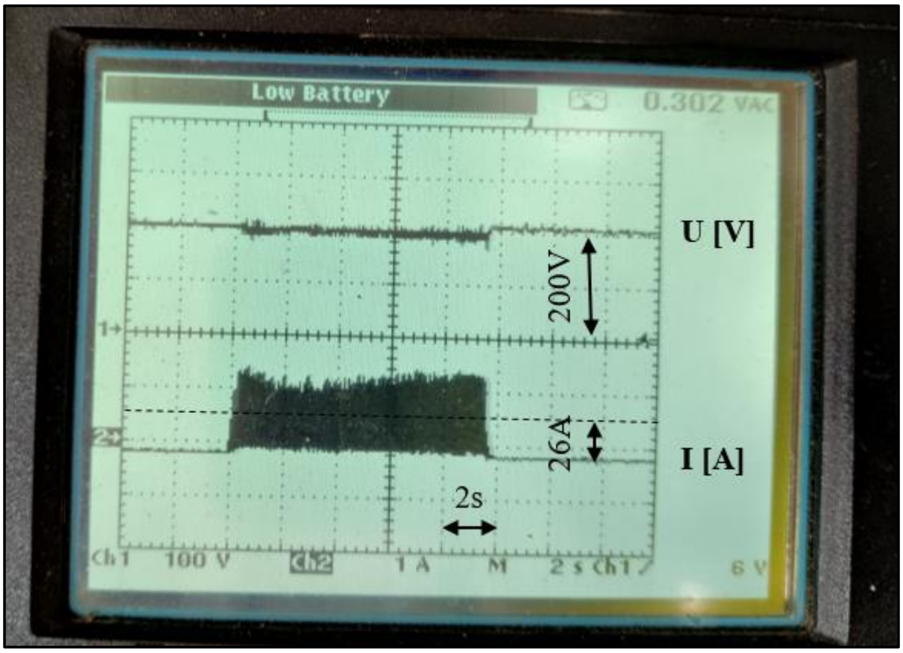

Figure 4.10 The photovoltaic cell operating in no-load regime when a load is coupled

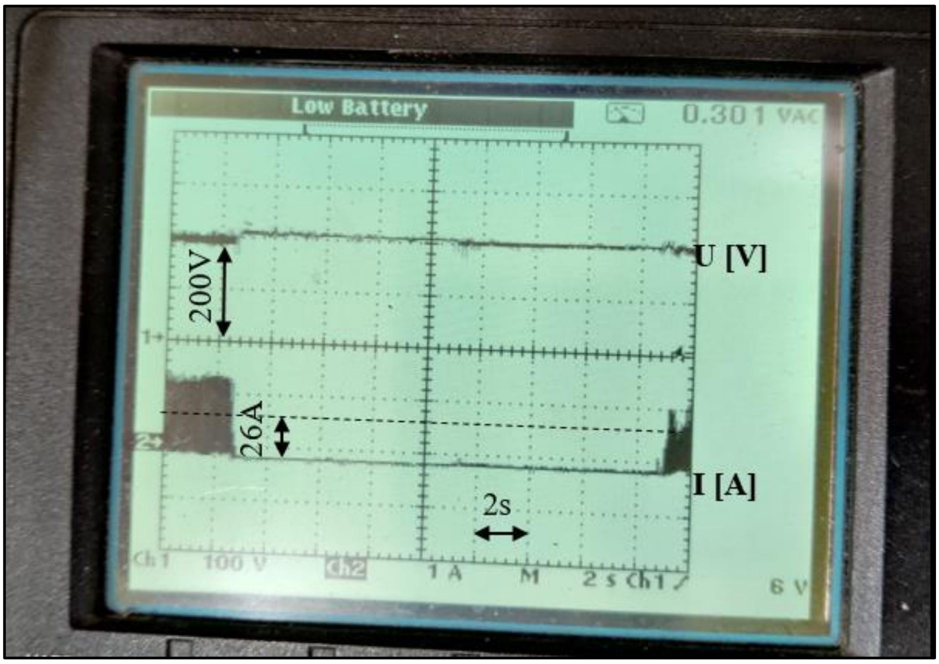

Figure 4.11 The photovoltaic cell operating on load when it is disconnected

The characteristics U=f(t), I=f(t) from the above graphs, lead to the following conclusions::

a) I associated with the coupling / decoupling regimes of the load, the dynamic regimes related to the modification of the irradiance during a short period of time;
b) The graphs show the following:
    - When coupling or decoupling the load, at the nominal value of the current generated by the photovoltaic panels, the voltage at the output of the panels decreases by about 10V, suggesting the character of a voltage source;
    - The source response is aperiodic, with a response time of about 0.4 s.
c) The increase or decrease time of the voltage at decoupling / coupling of load is about 0.32 s;
d) The alternative component, the voltage ripple at the output of the photovoltaic plant is about 0.3V, this value being insignificant in the system.

4.6 Conclusions

Achieving increased efficiency is largely based on the construction technologies of photovoltaic panels with minimum parasite resistance and maximum shunt resistance.

Increasing the energy efficiency of photovoltaic systems is based both on increasing the efficiency of photovoltaic cells, but also on the elements of concentrating light radiation on the surface of photovoltaic panels and their careful maintenance. The simulation of the operation of the photovoltaic cells was performed starting from their equivalent scheme, the distinguishing parameters being those related to the construction of photovoltaic panels (r_s și r_p). The measurements performed on a photovoltaic plant validated the simulation models and strengthened the qualitative and quantitative aspects regarding the solutions for increasing the energy efficiency for the photovoltaic cells, in the structure of the panels, respectively the photovoltaic systems.

5 BATTERY CHARGER REGULATOR. THE ROLE AND PLACE OF CONTINUOUS VOLTAGE CONVERTERS IN PHOTOVOLTAIC SYSTEMS.

5.1 General aspects

The battery charger regulator is constructively a DC/DC voltage converter and represents the "brain" of the system, which ensures: the hierarchy and safety of the operations that the energy storage system must guarantee, parameters requested by the consumer, correlation of loading / unloading regimes, blocking in case of deviations.

5.2 The proposed technical solution for the DC/DC converter used in the conversion of photovoltaic energy

Wiring diagram of the proposed DC/DC converter is described in Figure 5.1, with the following mentions: [11] [12]

- Converter operation in a single quadrant because the energy flow is entirely from the photovoltaic panels to the storage circuit;
- Operation in $U_{ieșire}$>$U_{intrare}$ regime, because the output voltage of the photovoltaic panels is lower than the voltage value at the battery terminals.

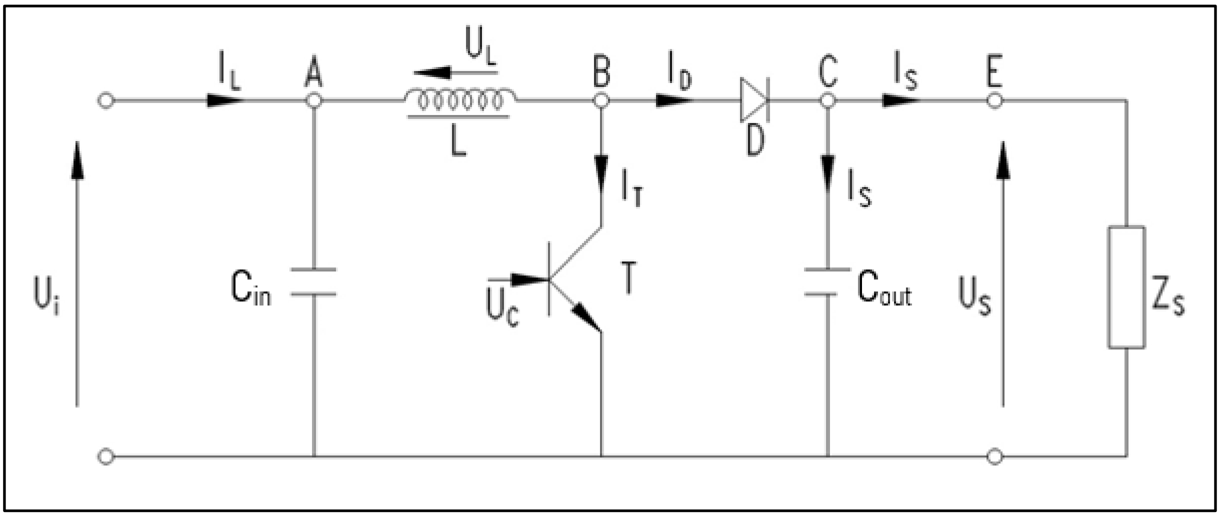

Figure 5.1 DC/DC Converter - proposed technical solution

For maximum energy efficiency I dimensioned the elements from the electrical diagram represented in figure 5.1, as follows:

- Inductance L, minimum winding resistance, magnetic circuit with characteristic B=f(H) able to ensure minimum losses;
- Transistor T, type IGBT with a maximum switching frequency of approx.30kHz;
- Capacitors C_{in} and C_{out} with appreciable internal resistance (very high).

5.3 Simulation model of DC/DC converter

In the PSPICE program I simulated the operation of the DC/DC converter presented above.

After defining all the parameters, I performed the actual simulations. The detailed wiring diagram through which the simulations were realized is shown in Figure 5.2, with the mention that the switching transistor is a MOSFET. The graphs obtained will be presented on the followings.

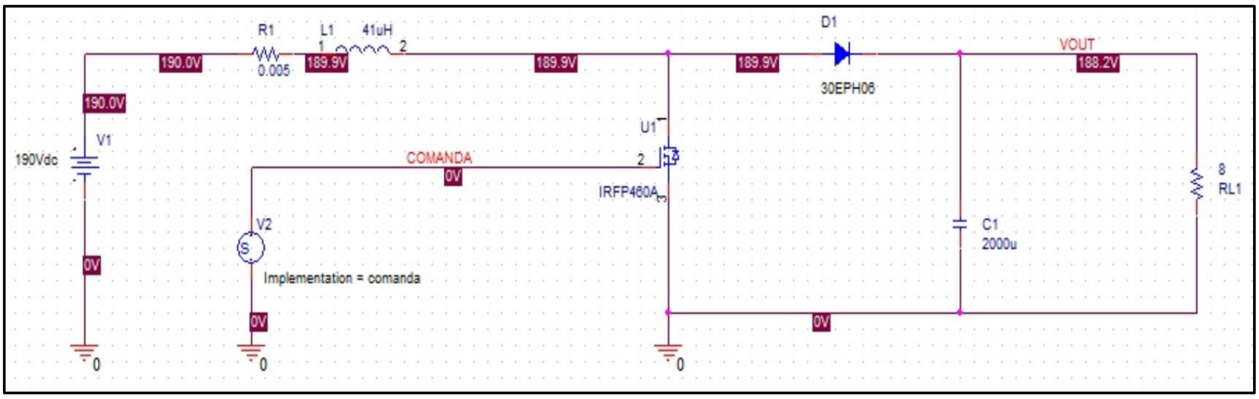

Figure 5.2 Simulated wiring diagram

In figure 5.3, by simulation at a input voltage value of Ui = 190Vdc, it is obtained a variation of the output voltage in load within the limits of 219, 875V ± 0,1%.

Figure 5.3 Simulation result U_i = 190VDC

In figure 5.4, by simulation at a input voltage value of Ui = 210Vdc, it is obtained a variation of the output voltage in load within the limits of 220,435V ±0,1%.

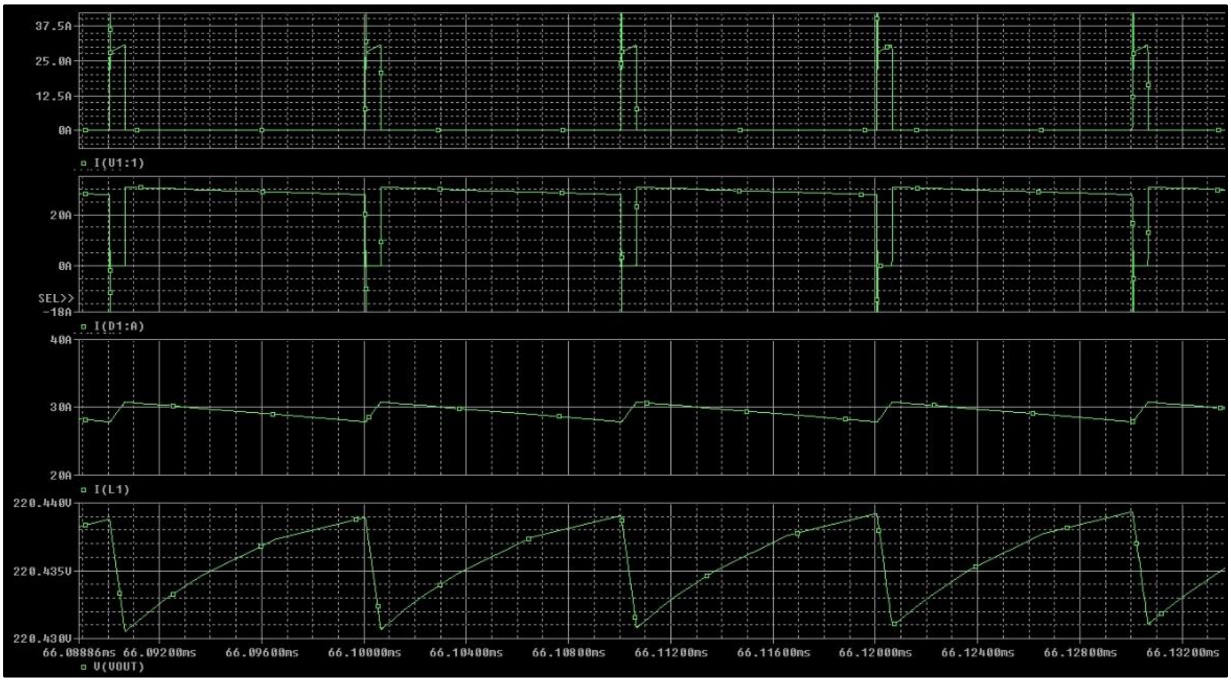

Figure 5.4 Simulation result U_i = 210Vcc

In the simulations, in figure 5.3, respectively figure 5.4, are presented the evolution in time in the switching process of the transistor T. The following quantities are represented in order on the ordinate axis:

- Current through transistor T, expressed in amperes;
- Current through diode D, expressed in amperes;
- Current through inductance L, expressed in amperes;
- Converter output voltage, expressed in volts.

I mention that the abscissa of the graph represents time expressed in ns.

It is also noted that the switching frequency is:

$$f_c = \frac{1}{T_c} \tag{5.1}$$

Where:

$T_c = 10^{-8}$s

f_c = 100MHz, the switching frequency characteristic of a MOSFET transistor

We can conclude that by choosing the adequate inductance L, will obtain a convenient variation of the output voltage U_s of 2-3% at a much wider variation of the input voltage, U_i.

5.4 Experimental results

Measurements performed on the ICPE ACTEL photovoltaic, using the DC/DC converter U_1, ICPE ACTEL production, according to figurie 5.5, and a load of about 8Ω, are shown in table 5.1.

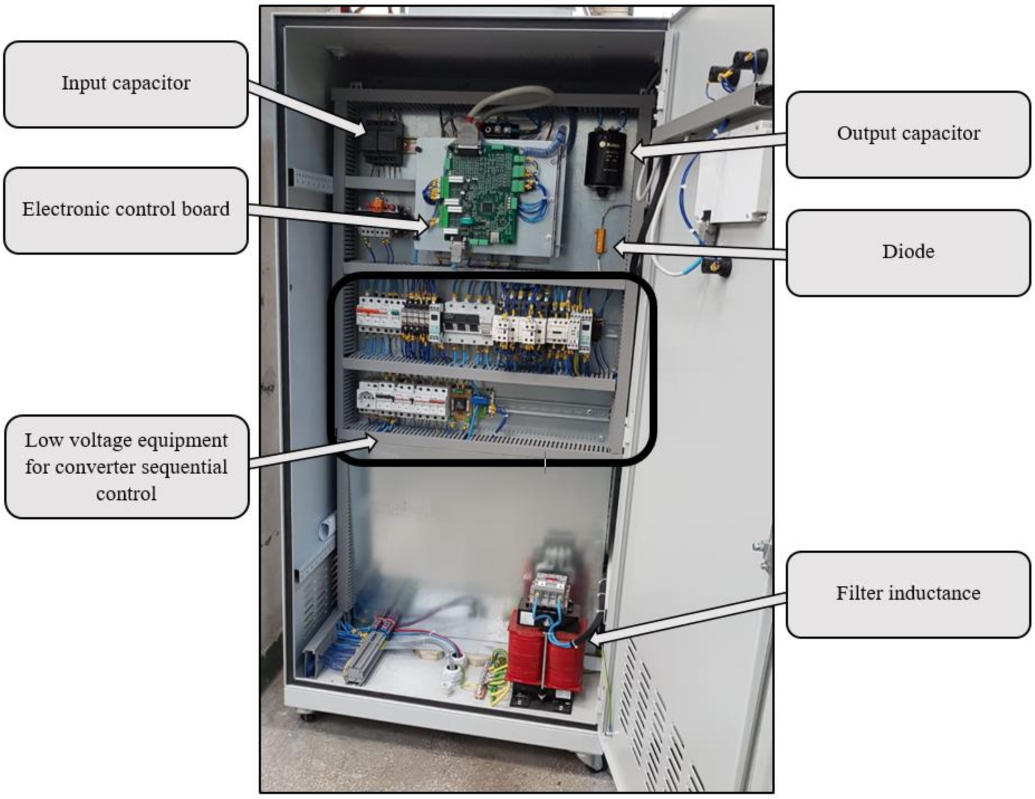

Figure 5.5 DC/DC Converter

Table 5.1 Experimental results

Nr. Crt.	Input voltage U_i [VDC]	Output voltage U_s [VDC]
1.	190,0	219,6
2.	203,0	219,8
3.	213,5	219,9
4.	215,7	220,1
5.	217,0	220,1
6.	219,0	220,2
7.	221,0	220,2

Figure 5.6 shows the variation of the output voltage U_s as a function of the input voltage U_i in the DC/DC converter.

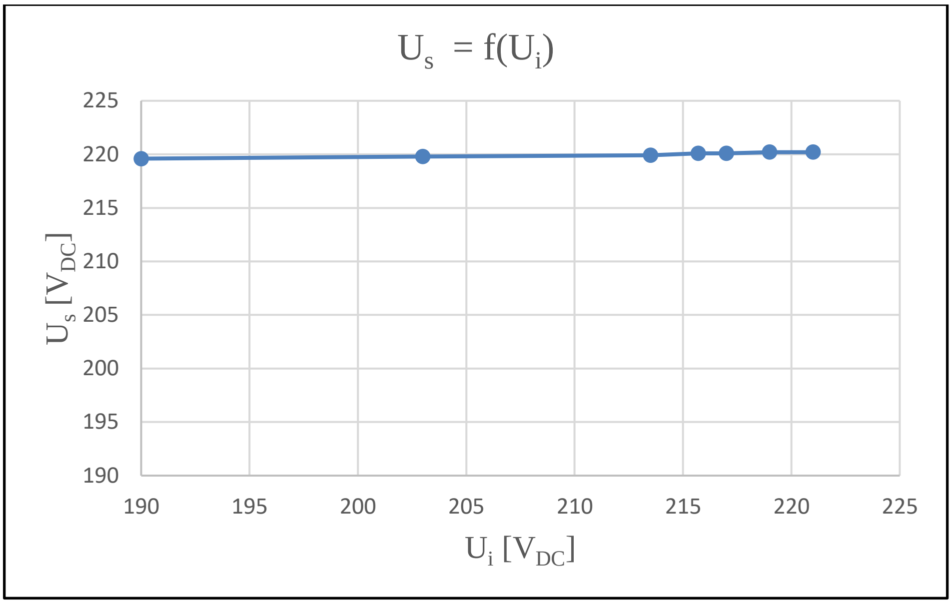

Figure 5.6 Output voltage variation depending on the input voltage

It is observed from table 5.1, respectively from the graph U_s=f(U_i) presented in figure 5.6, that the DC/DC converter used at a load close to the nominal value, demonstrates::

- The stabilizing character of the output voltage that is applied on the storage battery circuit, respectively of the DC/DC converter;
- The values of the output voltage U_s at the load of approximately 8kΩ, show that the operating point (U_s, I_s) is that of the maximum power developed by the photovoltaic panels;
- The measured values of U_s were performed in the absence of the battery, which is the best filter for any DC source, and is very close to the values in the simulated models.

5.5 Conclusions

In this chapter, on the line of conversion of photovoltaic energy into electricity, I have study the aspects related to:

- The necessity of using the DC/DC converters in order to ensure a stabilized output voltage strictly necessary for the storage battery circuit and for c.c.-c.a conversion;
- The implementation of a technical solution that ensures the operation of the photovoltaic-electricity conversion in conditions of maximum energy efficiency;
- The simulation of chosen DC/DC converter in load regime close to the nominal conditions for two situations of input voltage variation;
- Measurements of the characteristic parameters of the DC/DC converter, namely the output voltage under quasi-nominal load conditions and the verification of the static operating point at maximum power;
- Validation of the results of simulated regimes by experimental measurements performed on a photovoltaic plant.

6 STORAGE OF ENERGY PRODUCED BY PHOTOVOLTAIC POWER PLANTS. PRINCIPLES. STORAGE ELEMENTS. STORAGE EFFICIENCY.

6.1 General aspects

Starting from the management of electricity production and taking into account the surplus produced electricity, given that we are experiencing a decline in both industrial and domestic consumption, the main concern is the storage of excess energy in order to be used when needed.

Energy storage is an important element in the range of functions that a smart grid needs to provide. Electricity has the particularity that without a storage system, it must be consumed at the time it is produced, so without storage the energy generated must be equal to the energy consumed.. [10] [13]

6.2 Types of batteries used in electricity storage

In the case of storage systems, the most used solution is the one based on batteries, which in these applications are of special construction and are characterized by a high number of charge-discharge cycles and lack of maintenance.

The most common types of batteries for electrical energy storage projects are:

1. Lead (Pb);
2. Nichel – cadmiu (NiCd);
3. Nichel – metal (NiMH);
4. Lithium – ion (Li-ion).

Each technology has advantages and disadvantages and their performance is influenced by several factors, including: storage capacity, state of charge, temperature, charge-discharge cycles, lifetime. [14-25]

6.3 Battery sizing

The battery capacity is sized according to the daily consumption requirements and energy autonomy.

Energy autonomy is defined by the number of days without solar radiation, during which the battery must provide energy to power the load. [14-27]

$$Battery\ capacity = \frac{\sum_{k=1}^{n} L_k\ x\ t_k}{Ubat}, \tag{6.1}$$

where,

C_k = necessary consumption [kWh]

t_k = required time for power supply [hours]

U_{bat} = nominal voltage battery [V]

The second step in the process of sizing a battery is to determine the number of elements, which depends strictly on the required voltage and the capacity of the battery.

The construction of the battery tray is made from either series, parallel or series-parallel connections.

Connecting the batteries in series allows the increase of voltage generated by the battery.

The number of elements, denoted by N, is determined as follows:

$$N = \frac{U_n}{u_n} \ , \tag{6.2}$$

where:

U_n = nominal voltage of the consumer

u_n = nominal voltage of a cell

Connecting the batteries in parallel, as opposed to connecting in series, contributes to higher capacity. The calculation formula for the required number of cells is:

$$N = \frac{C_t}{C_{elem}} \ , \tag{6.3}$$

where:

C_t = required battery bank capacity

C_{elem} = capacity of a cell

6.4 Experimental results regarding the sizing and the operation of the battery from the ICPE ACTEL photovoltaic power plant

The experimental measurements were realized on the UCG250-12 battery, consisting of 18 cells 250Ah 12V each, through which we have experimentally highlighted three of the main characteristics of the battery in terms of characterizing the storage process:

- Dependance $C_{Ah} = f(t_{discharge})$, the discharge is performed at constant current for ten hours; table 6.1 and figure 6.1;
- Dependance $C_{Ah} = f(I_{discharge})$, the discharge is performed during two hours; table 6.2 and figure 6.2;
- Dependance $U_{battery} = f(t_{discharge})$, the discharge is performed at constant current; table 6.3 and figure 6.3;

Table 6.1 – Dependence of battery capacity on discharge time

No. Crt.	$I_{discharge}$ [A]	Battery capacity [Ah]	$t_{discharge}$ [h]
1.	25,00	250,00	0
2.	25,00	241,45	2
3.	25,00	232,93	4
4.	25,00	224,43	6
5.	25,00	215,90	8
6.	25,00	207,40	10

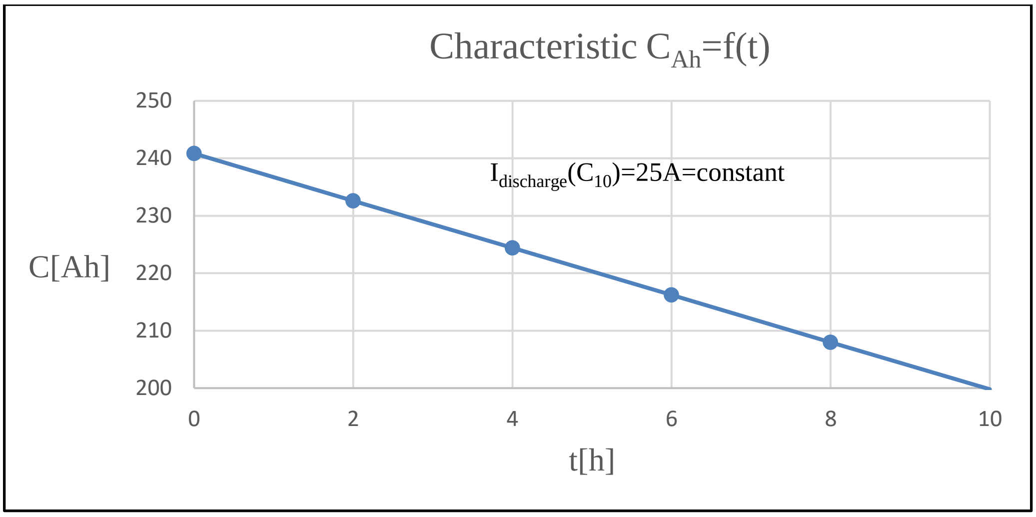

Figure 6.1 C_{Ah} dependence on time

Table 6.2 – Dependence of battery capacity on discharge current

No. Crt.	Battery capacity [Ah]	$I_{discharge}$ [A]	$t_{discharge}$ [h]
1.	250,00	0,00	2
2.	230,80	22,50	2
3.	198,00	55,00	2
4.	186,00	82,50	2
5.	180,00	110,00	2

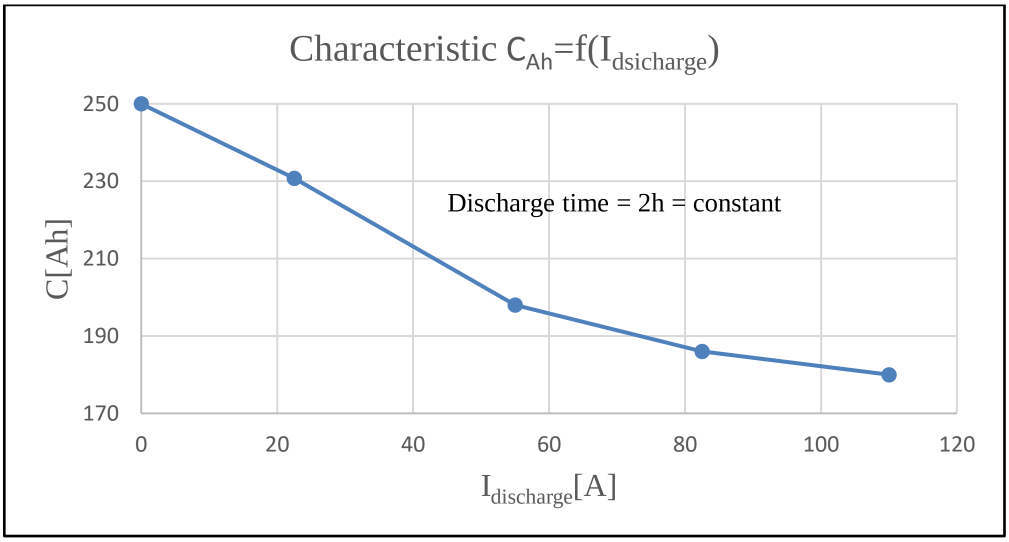

Figure 6.2 C_{Ah} capacity dependence on discharge current

Table 6.3 – Dependence of battery voltage on discharge time

Nr. Crt.	$I_{discharge}$ [A]	Battery voltage [V]	$t_{discharge}$ [h]
1.	25,00	242,64	0
2.	25,00	225,22	2
3.	25,00	216,36	4
4.	25,00	209,16	6
5.	25,00	202,86	8
6.	25,00	195,48	10

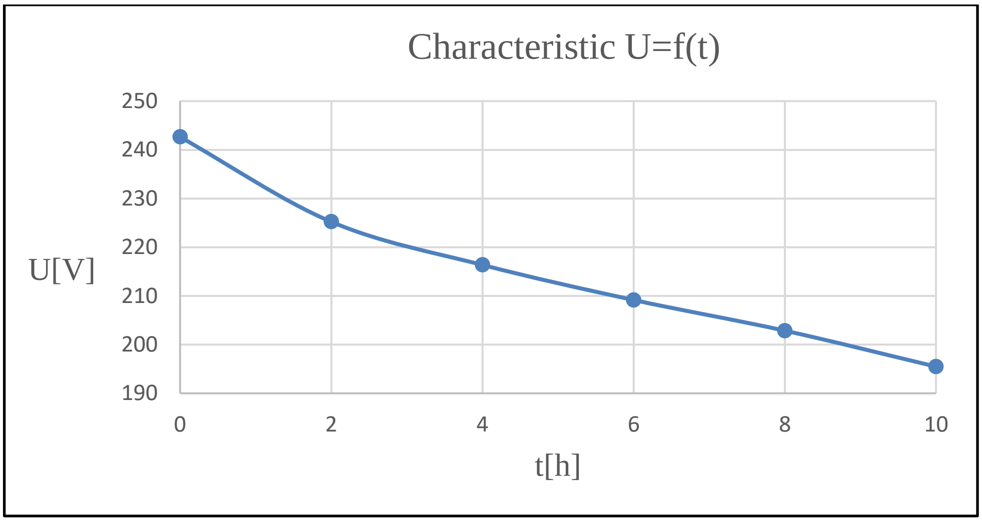

Figure 6.3 Dependence of battery voltage on time

From the examination of the three characteristics reveals the following:

- The characteristics have similar features in terms of the dependence of the capacity as a function of time at constant discharge current in C10 mode, respectively depending on the discharge current when the discharge time is constant, respectively the dependence of the voltage at the battery terminals depending on the discharge time at a constant discharge current;
- Significant loss of battery capacity occurs due to significant increase of discharge current;
- Regardless of the symmetry, it is very important in the discharge process not to exceed the value of the 1.8V / element voltage, given the fact that the electrochemical processes at the battery level in this case can be irreversible;
- In the storage process it is very important that it occurs under the presence of voltage-current-time protections;

6.5 Mathematical simulation and modeling of batteries used in the storage of electricity produced from renewable sources

Experimentally, to highlight the dependence between the voltage at the battery terminals and the state of charge, respectively its relative state of discharge, I used the 250Ah, 220VDC battery (18 cells of 12V each).

The experimental results can be found in Table 6.4 and in the graphs in Figures 6.4 and 6.5.

Table 6.4

No. Crt.	State of Charge [%]	Battery voltage [V]	
		Charging regime	Discharging regime
1	0	208,80	208,80
2	20	213,41	213,37
3	40	218,03	217,94
4	60	222,62	222,52
5	80	227,23	227,09
6	100	231,84	231,66

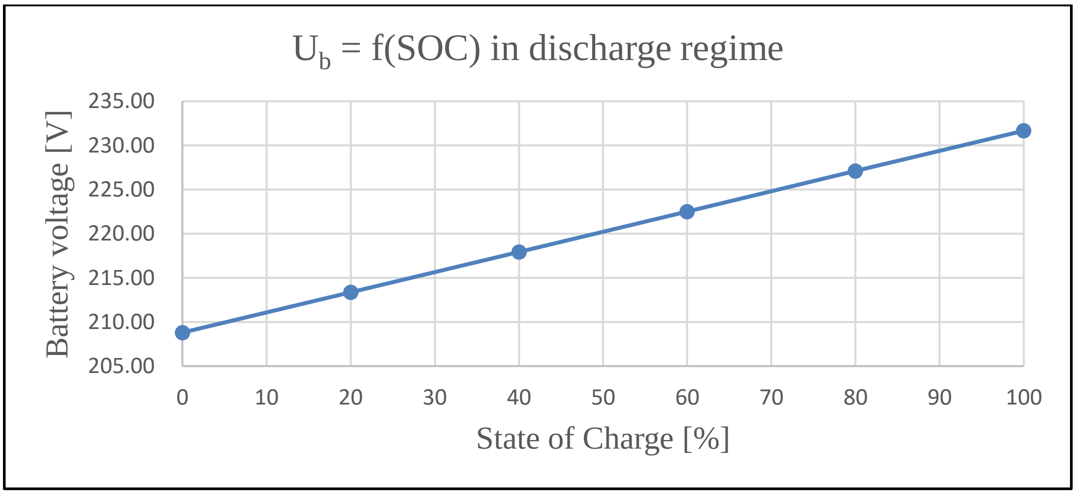

Figure 6.4 Dependance $U_b = f(SOC)$ on discharge battery

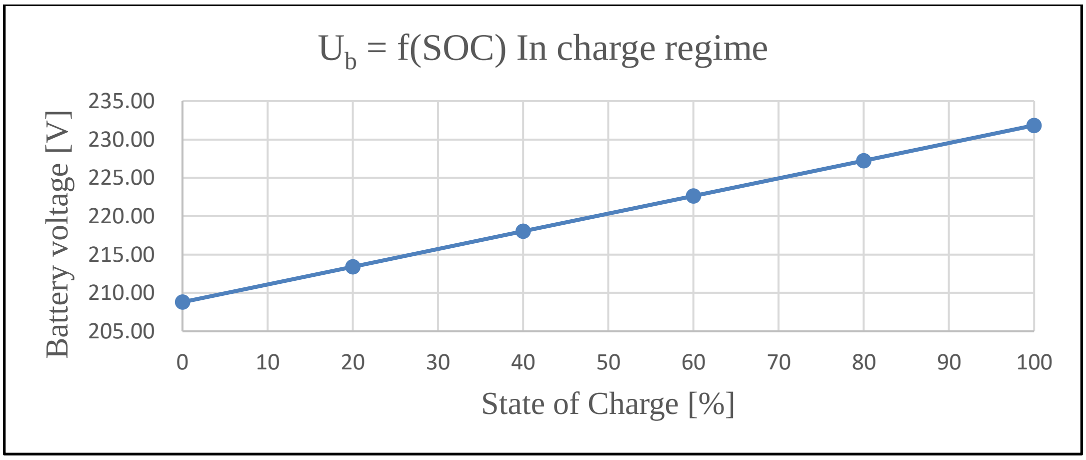

Figure 6.5 Dependance $U_b = f(SOC)$ on charge battery

As can be seen from the graphs above, both in charging and discharging mode, the voltage at the battery terminals is directly proportional to its charging level, so in discharging mode the battery voltage decreases with reduce the charge level and increase with the charging of the battery in case of charging mode.

6.6 Conclusions

Of all the battery types on the market for storage applications in photovoltaic systems, Pb, NiCd, NiMH and Li-ion batteries stand out.

Lead-acid batteries are the most widely used batteries in renewable energy storage systems with the advantage of low price, technological maturity, low self-discharge rate, reliability, high number of charge-discharge cycles. However, this type of battery also has many disadvantages as low specific density and negative impact on the environment.

Nickel-cadmium batteries have the main advantage of a long life of up to 1500 cycles, followed by fast charging time and the possibility of recycling. The disadvantages of this solution are the low self-discharge, low specific energy and the presence of the memory effect.

NiMH batteries have a higher specific energy compared to NiCd batteries, they are environmentally friendly but the number of charge-discharge cycles is considerably lower.

Li-ion batteries are characterized by the higher value of the cell voltage, the highest specific energy, the ability to withstand a large number of charge-discharge cycles, but their main disadvantage is the high cost of purchase.

The objectives of the modelling are related to achieving optimal energy storage, both in terms of energy efficiency and cost optimisation.

The battery modelling proposed experimental tests and measurements to define the parameters that characterize energy storage.

7 THE USE OF STATIC CONVERTERS IN RENEWABLE ENERGY CONVERSION SYSTEMS. PRINCIPLES. DEFINITIONS. CLASSIFICATIONS.

7.1 General aspects. The role of static converters in photovoltaic systems

Static power converters are complex energy equipment that performs the static conversion of electricity, changing the parameters of the electricity generated by the source, like voltage and current values, frequency, number of phases, etc., taking into account the requirements of the receiver. Static power converters also ensure the conversion of significant amounts of energy.

The converters are located between the power source and the consumer, having for the power source the role of receiver and the role of power source for the load.

7.2 The proposed technical solution for the DC-AC converter used in the conversion of photovoltaic energy

For the ICPE ACTEL photovoltaic plant, we chosen as a solution for the DC-AC converter a three-phase voltage inverter, with PWM control, bidirectional, with IGBT transistor valves, whose block diagram is exemplified in figure 7.1.

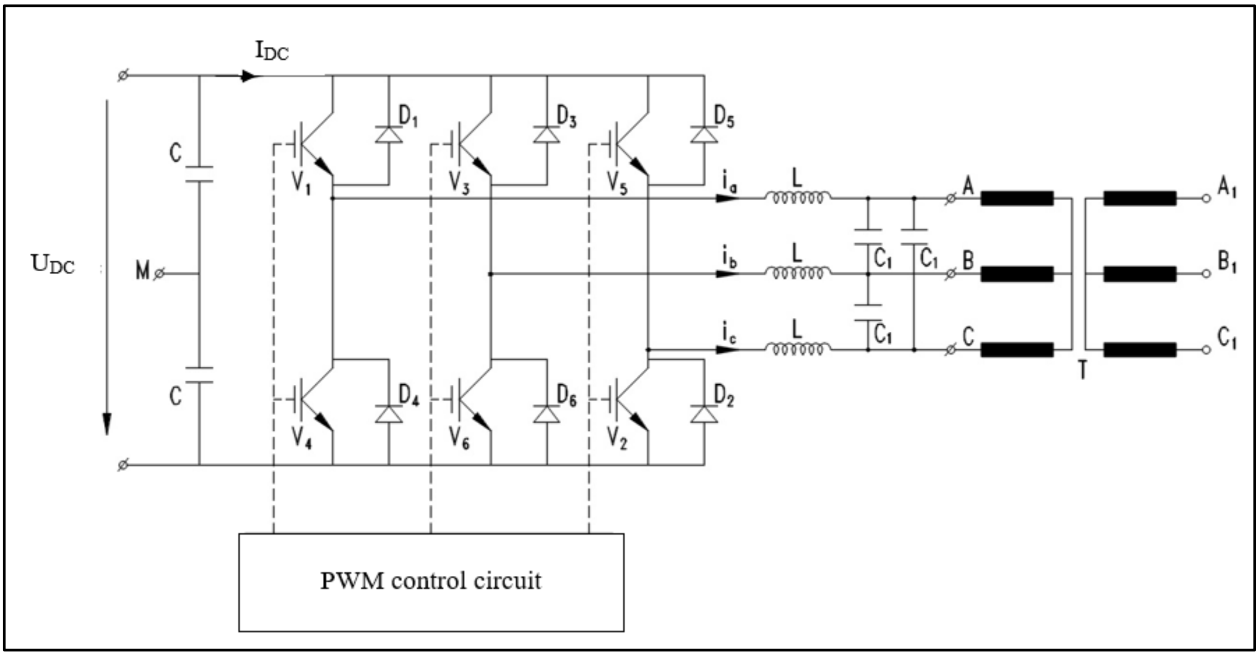

Figure 7.1 Wiring diagram of an inverter with PWM control

Although this type of three-phase inverter could be made with 3 single-phase inverters, we did not choose this solution because:

- The different single-phase loads would produce an asymmetry of power on each phase and thus we could have an important homopolar component;
- A double number of valves (power transistors) would be used;
- Nu întotdeauna avem acces la nulul sarcinilor trifazate.

I chose the variant of an inverter with 6 valves $v_1 \div v_6$ in Graetz bridge with PWM control.

It is observed from figure 7.1 that the voltage U_{AM} has the amplitude $\frac{U_{cc}}{2}$ when the transistor v_1 is in conduction, respectively $-\frac{U_{cc}}{2}$ when the transistor v_4 is in conduction.

It follows that:

$$U_{AB} = U_{AM} - U_{BM} \quad (7.1)$$

$$U_{BC} = U_{BM} - U_{CM} \quad (7.2)$$

$$U_{CA} = U_{CM} - U_{AM} \quad (7.3)$$

7.2.1 PWM control principle of three-phase inverters

The control of DC-AC converters is based on the width modulation technique of the control pulses of IGBT transistors, named in the technical literature specialitate PWM (Pulse Width Modulation).

The principle of generating PWM control pulses consists in obtaining pulses of fixed amplitude and variable width, depending on a variable control voltage, principle shown in figure 7.2.

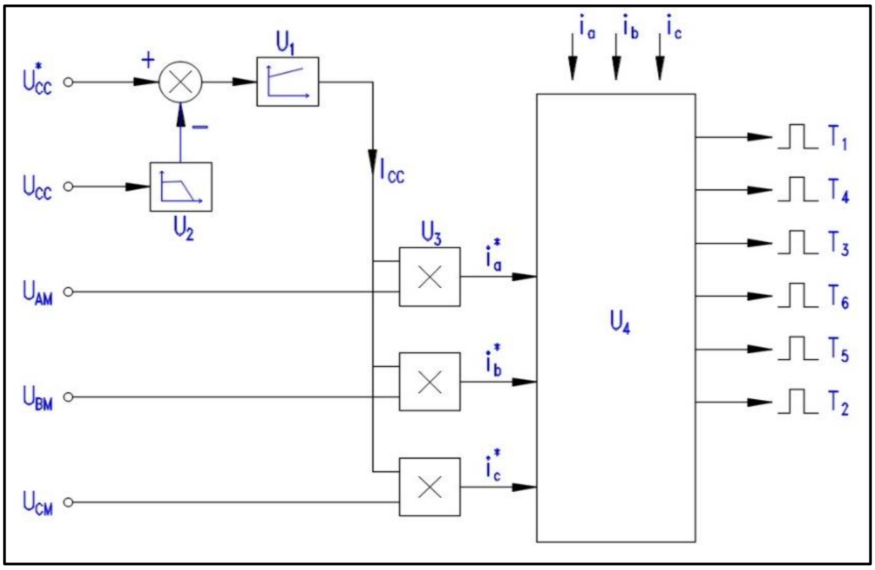

Figure 7.2 PWM pulse generation for a three-phase inverter

7.2.2 Sizing calculation of the DC-AC converter used in the photovoltaic plant

The value of the installed power of a photovoltaic unit is in accordance with the rated output power of the inverter, defined as the power that the inverter is capable of continuously transmitting in the national grid taking into account the temperature of 25°C.

As a rule, the sizing of the inverter takes into account that the input power is 5% higher than its normal power. Regarding the nominal power of the inverter, it must be ± 20% of the standard power of the photovoltaic panels.

The ratio between the two powers is the sizing factor of the inverter k_{inv}:

$$k_{inv} = \frac{P_{PV}}{P_{PV\ inv}} = [0{,}83 \ldots 1{,}25] \qquad (7.4)$$

Where:

P_{PV} = Power of photoelectric panels at STC;

$P_{PV\ inv}$ = inverter power.

In the inverter sizing process, a power factor of at least 0.9 must also be considered. If the technical solution regarding the structure of the installation provides separate sources for compensating the reactive power, the choice of the inverter does not depend on the necessary reactive power. Otherwise, the rated power of the inverter must be dimensioned so that it represents 110% of the rated power of the panels.

Single-phase or three-phase sources can be chosen depending on the installation power. For powers higher than 5kW it is mandatory to use the three-phase solution which has the following constructive elements:

- voltage control device;
- network transformer;
- controlled PWM inverter bridge;
- device for identifying the maximum power point;;
- public network monitoring circuit;

7.3 Simulation model of the DC-AC converter

The principle scheme used in the theoretical simulation of a DC-AC converter is the one shown in Figure 7.1, and with an appropriate IGBT control, it can work as follows:

- In rectifier mode: the power transfer is from AC to DC side, ensuring a sinusoidal regime for phase currents ia, ib, ic and a power factor equal to 1;
- In inverter mode: the power transfer is from DC to AC side, ensuring a sinusoidal regime for phase currents ia, ib, ic and a power factor equal to 1;

We further propose to analyze the inverter regime. In this situation the DC side is supplied with a constant voltage, Vcc, and the AC side connects to the three-phase sinusoidal system ea, eb, ec. The AC side can also be the primary of a three-phase transformer whose secondary is connected to a three-phase network.

The diagram shown in Figure 7.1, including the controller and generation of control signals, was simulated in SIMULINK (MATLAB).

The simulation was realized using a series of modules from the SIMULINK library and some created specifically for this simulation.

The simulation file contains the following blocks:

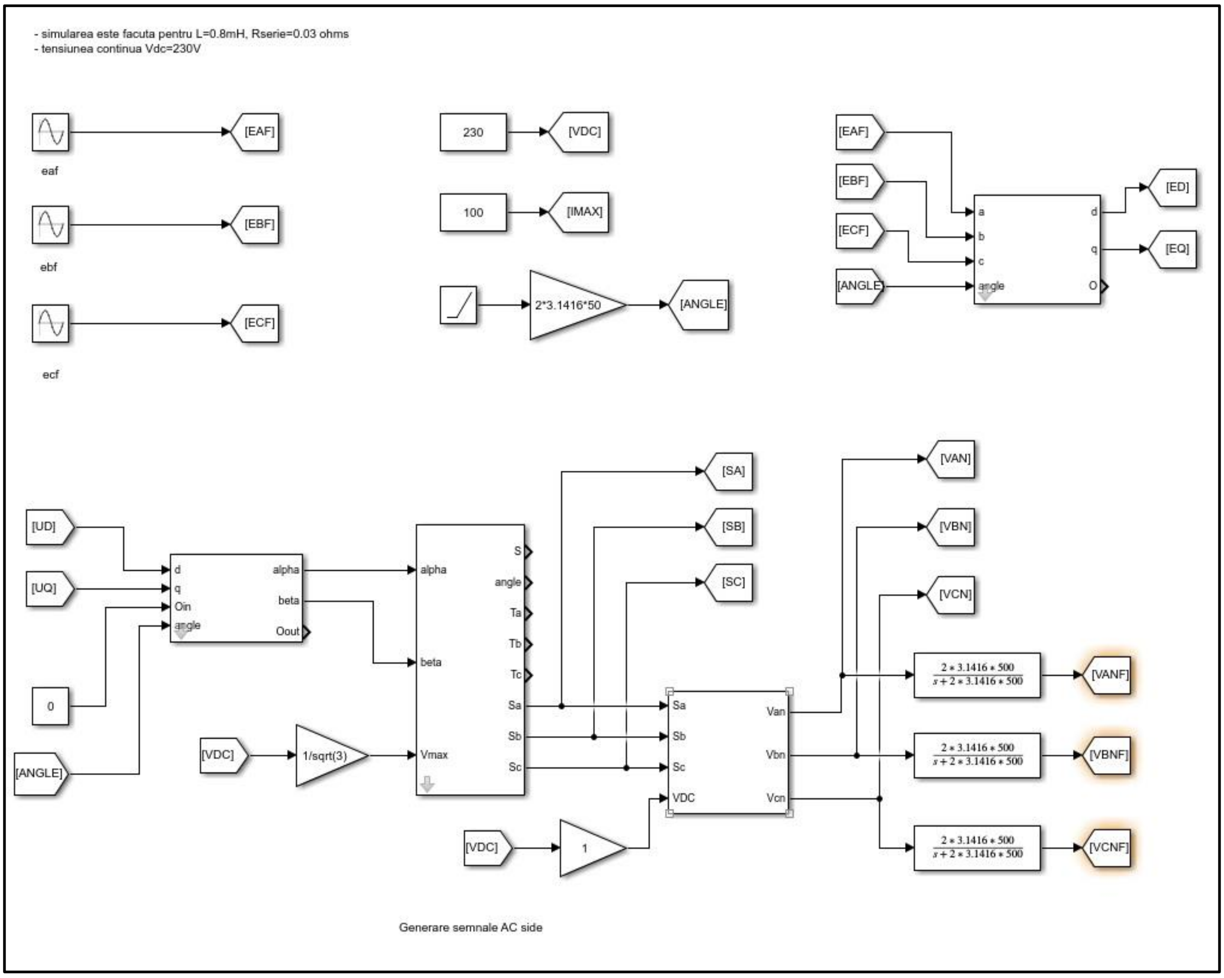

Figure 7.3 Signal generation AC side

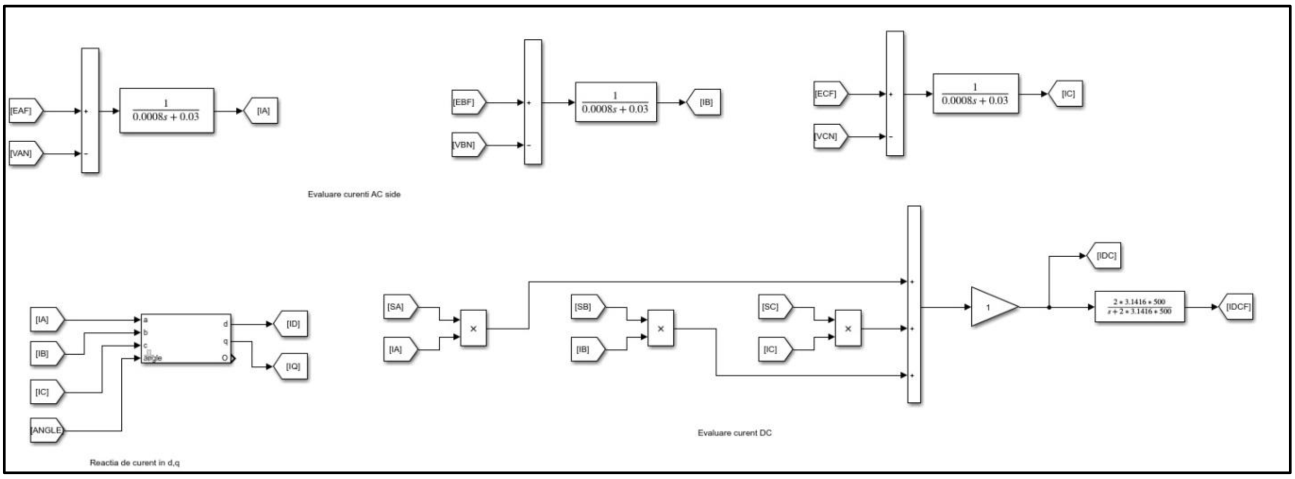

Figure 7.4 Currents evaluation from AC and DC sides

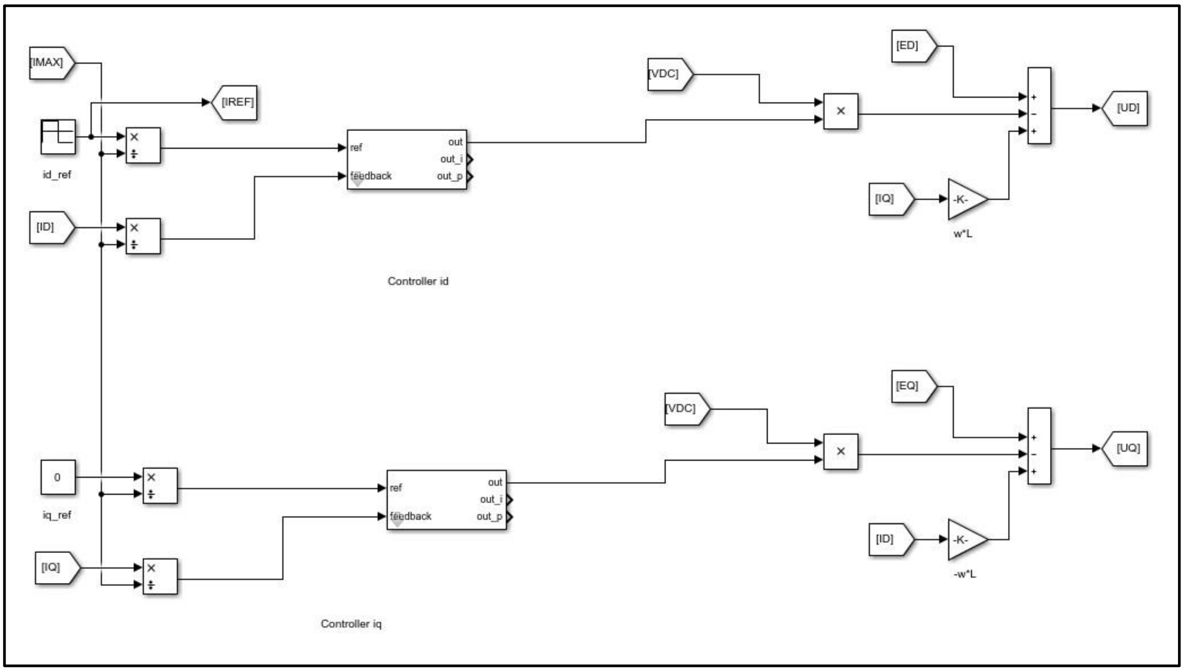

Figure 7.5 Current regulators

The simulation results are shown in Figure 7.6.

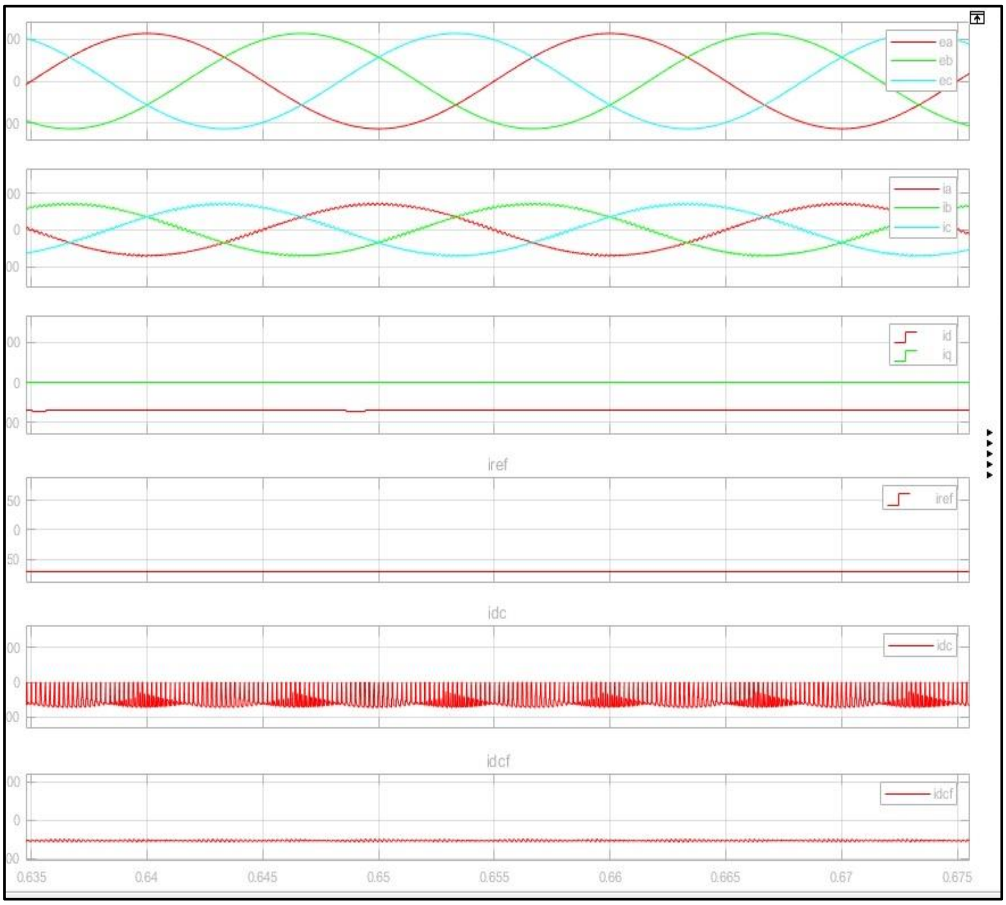

Figure 7.6 Simulation results

The figure above shows the followings:

- The first graph shows the voltages of phase ea, eb, ec. Their effective value is 80V;
- In the second graph are the phase currents ia, ib, ic. Their effective value is 49A; Phase currents, as can be seen, are in phase with phase voltages (the power transfer is from the direct current side to the alternating current side);
- In the third graph are represented the components id, iq of the currents on the AC side (the regulation of the current in the AC part is done with these components which are obtained by the Park transformation applied to the components ia, ib, ic). It is observed that id = -70 A, iq = 0.06A, which corresponds to a peak value of the phase currents equal to 70A. The minus sign of id and the value very close to zero of iq indicate a power factor equal to 1;
- The fourth graph shows the current reference for the id regulator (equal to -70A);
- The fifth graph shows the current absorbed from the DC source. It is a pulsating current with values between 0 ...- 73A and a frequency of 5kHz;
- The sixth graph shows the average current from the DC side, equal to -52A. The minus sign indicates that the power transfer is from the DC side to the AC side.

7.4 Experimental results

The measurements for highlighting the experimental results were made on the DC-AC ICPE ACTEL converter, type INV12_220/400, a component of the photovoltaic system.

I mention that this converter is constructed as a metal cabinet and is shown in Figure 7.8 below. The values obtained from the measurements are shown in Table 7.1

Table 7.1

No. Crt.	U_{cc} [V]	I_{cc} [A]	U_{A_1N} [V]	U_{B_1N} [V]	U_{C_1N} [V]	$U_{A_1B_1}$ [V]	$U_{B_1C_1}$ [V]	$U_{C_1A_1}$ [V]
1	235,30	0	245,90	245,80	245,90	425,40	425,23	425,40
2	231,50	51,84	245,10	245,00	245,10	424,05	423,85	424,05
3	229,50	52,28	244,70	244,60	244,80	423,33	423,16	423,50
4	225,30	53,26	237,90	237,70	237,80	411,56	411,22	411,39
5	223,30	53,74	234,80	234,60	234,70	406,20	405,85	406,03

A relevant block diagram to exemplify the measurements presented in Table 7.1 is shown in the figure below:

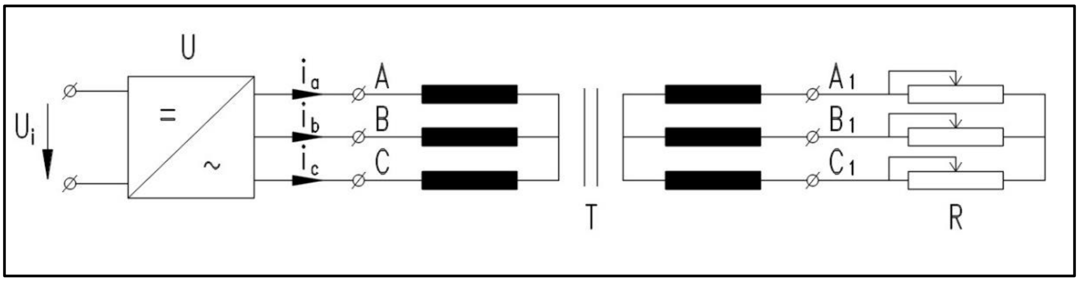

Figure 7.7 Three-phase inverter block diagram

In figure 7.7 the symbol R represents the variable resistance that has a value between 0 ÷ 8Ω, 60A

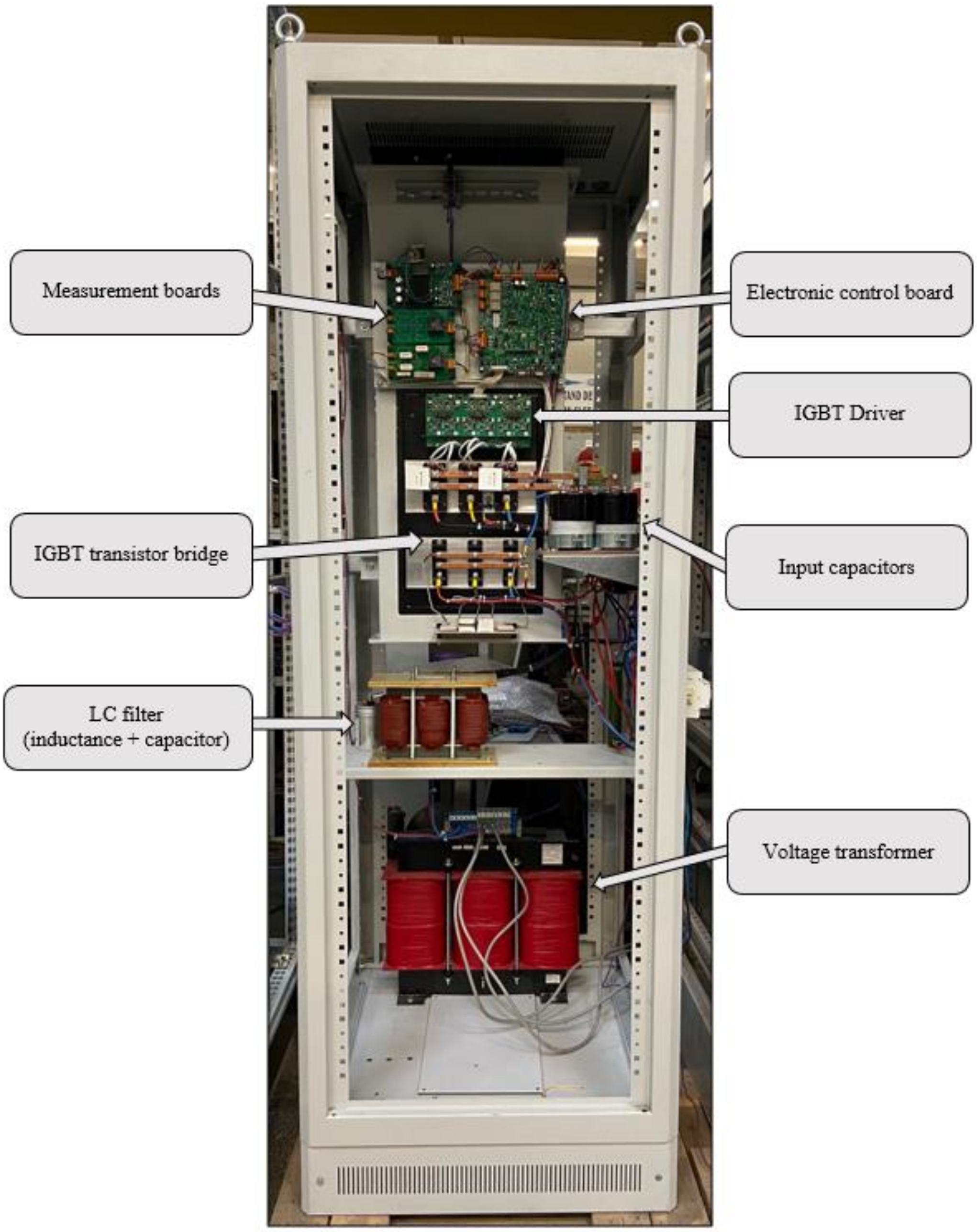

Figura 7.8 Dulap invertor

Representative measurements U_{cc}, respectively U_{A_1N} were visualized with an oscilloscope. Figure 7.9 shows evolution over time of this measurements:

- U_{cc} is the voltage obtained from the photovoltaic panels in buffer with the battery;
- U_{A_1N} (U_{B_1N}, U_{C_1N}) are the phase voltages used both for consumers, in the case of off-grid power plants, and for the public network for on-grid power plants.

To highlight the operational stability of the PV power plant, in figure 7.10 I graphically represented $U_{cc} = f(I_{cc})$, and in figure 7.11 $U_{A_1N} = f(I_{cc})$.

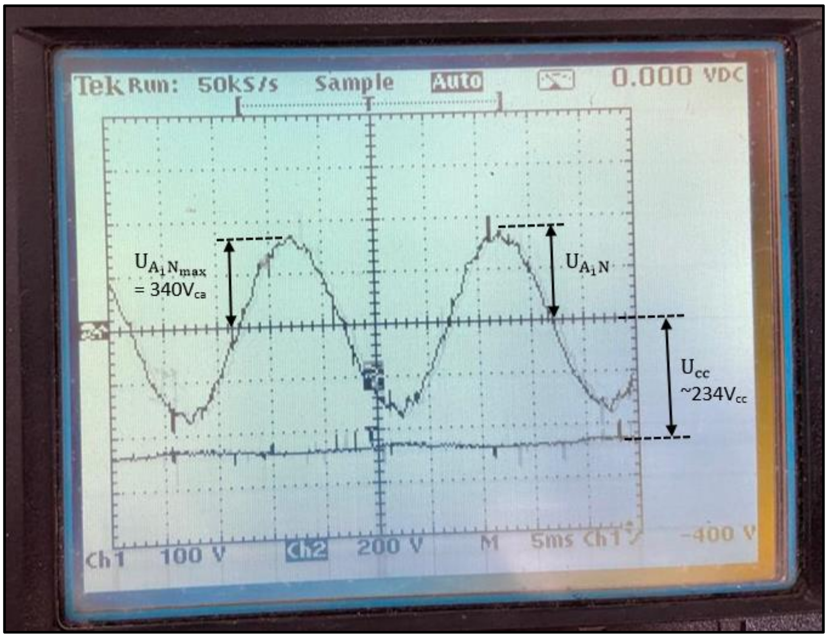

Figure 7.9 The evolution over time of the measured voltages

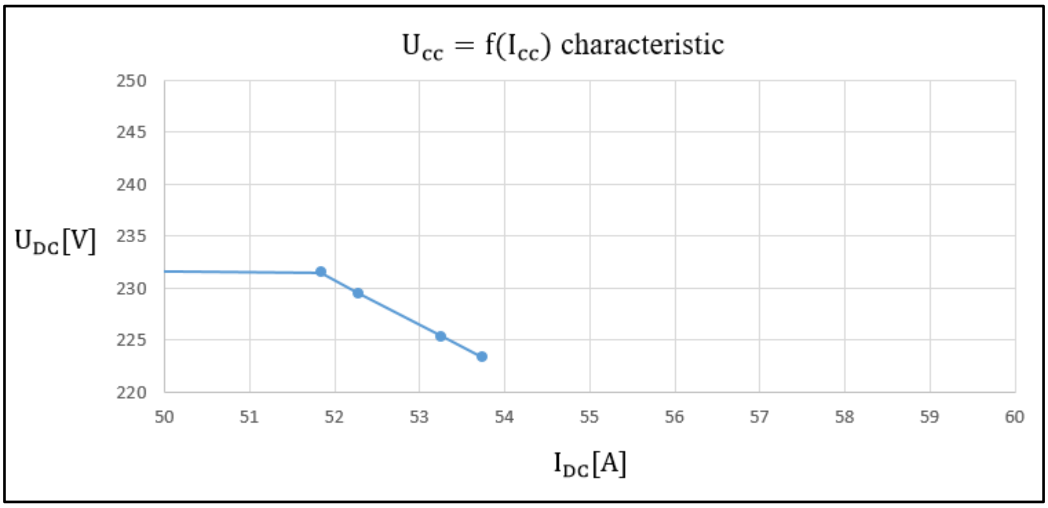

Figure 7.10 Dependence of input voltage on input current

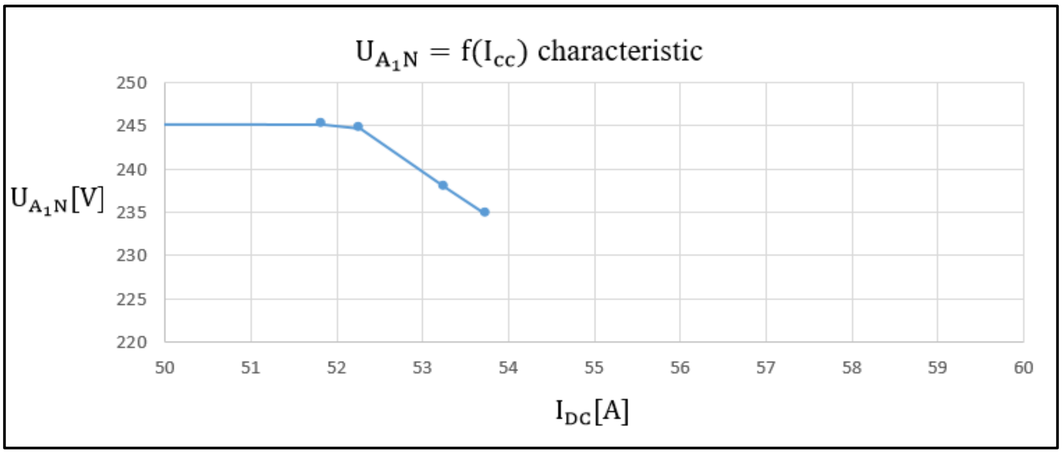

Figure 7.11 Dependence of phase voltage on input current

The following conclusions can be deduced from the two graphs:

- As the load current increases, the evolution of the U_{cc} voltage is slightly declining.
  The reasons are related to:
  - The use of the power plant at rated power;
  - The use of the power plant after a day of operation in which the light radiation was not at its maximum level, and in this case the battery is not fully charged;
- As the load current increases, the output voltage of the inverter has a slight decrease, due to the same reasons listed above.

7.5 Conclusions

By comparing the simulation results, the experimental ones and by visualizing the waveforms, the following can be highlighted:

- Operational stability of the inverter in the PV power plant;
- Choosing a constructive solution and optimal sizing of the inverter with PWM control;
- The voltage-current characteristics of the inverter are similar, confirming its optimal choice.

Regarding quality of the energy supplied by the photovoltaic power plant, the following can be seen from the oscillogram shown in figure 7.9:

- The supplied voltage is very close to a sinusoid, the deviations from it, caused by the switching phenomenon at 5kHZ frequency, being minimal;
- The frequency of the supplied voltage is 50Hz, a stable value regardless of the load;

8 FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. PERSPECTIVES.

This chapter summarizes the research activity carried out during the study years, focusing on the contributions on the contributions to the energy efficiency sector of the conversion of photovoltaic energy to electricity, as well as on the recommendations for further research to improve current methods and those identified in the thesis. .

8.1 General conclusions

One way to increase energy efficiency is to act on component of the photovoltaic system, so that, during the chapters, the thesis approached the solutions for the efficiency of the equipment studied individually, namely: photovoltaic panels, battery charging regulator, storage system, DC-AC static converters.

Within each chapter dedicated to the research of PV system components, the following were made:

- Elaboration of the theoretical study in order to propose and develop an optimal technical solution in the process of photovoltaic energy conversion;
- Realization of electrical diagrams and sizing calculation;
- Carrying out simulation studies through Matlab - Simulink and PSpice programs, with the aim of analysing the functionality of the photovoltaic system components;
- Making out experimental measurements in order to verify and validate both the studied theoretical aspects and the simulated ones;
- Identifying possible problems and proposing solutions to remedy or prevent them.

The conclusions of the studies and analyzes presented above are:

1. **Photovoltaic panels**

The results obtained after the simulation contribute on the one hand to the confirmation of the developed data from the theoretical study, and on the other hand lead us to the following conclusions:

- If the value of one of the two resistors changes, there is a marked decrease in cell efficiency. The no-load voltage value is also reduced, which contributes to a regular damped regime of power evolution near the no-load value;
- If the values of the two resistors are changed at the same time, there is a drastic decrease of the energy efficiency. As in the first situation, the no-load voltage value also decreases, but this time it is much more pronounced. As for the periodic regime is concerned, it is amplified by increasing the overregulation of the power flow.

The conclusions reached from the measurements and processing of the data obtained are:

- The voltage characteristic as a function of output current is similar to those obtained from the theoretical and simulation study;
- The value of the no-load voltage remains constant regardless of irradiance;
- For current generation power plants, the values of shunt and parasite resistances are close to the ideal ones;

2. **Battery charger regulator**

The simulations consisted of obtaining and visualizing the following: current through the switching transistor, current through the diode, current through the inductance and the output voltage.

Two simulations were performed, at an input voltage of 190Vdc and at an input voltage of 210Vdc. The resulting conclusion is that sizing and choosing the appropriate inductance, according to the above criteria, contributes to obtaining a convenient variation of the output voltage, within the limits of 2-3%, for a wider range of input voltage variation.

Accepting a wider range of input voltage variation while keeping the output voltage within permissible limits, has a significant role in the functionality and reliability of the system, because the voltage from the photovoltaic panels oscillates depending on external environmental factors. All this translates into increased energy efficiency.

Experimentally, in order to plot the output voltage characteristic as a function of the input voltage, measurements were made when operating the converter at different input voltage values ranging from 190 ÷ 221Vdc.

Following these we can conclude:

- The results obtained confirm the hypotheses elaborated in the theoretical and simulation study, more precisely, the stabilizing character of the output voltage for a wide variation of the supply voltage is confirmed; moreover, the measurements were performed in the absence of the battery, which is the best filter for any DC source, and the results are very close to the simulated models.
- The measured values for the output voltage show that the operating point is the maximum power developed by the PV panels;

Therefore, the measurements of the parameters considered in characterizing the operation of the DC-DC converter, namely the output voltage under quasi-nominal load conditions and the verification of the static operating point at maximum power, confirm the veracity of the proposed technical solution and the correctness of the principles of choice and dimensioning of the converter components. All this ultimately contributes to increasing the energy efficiency of the whole system.

3. Storage system

The conclusions deduced after processing the experimentally obtained data and making graphs corresponding to each of the three simulated situations are:

- The resulting characteristics confirm the theoretical notions related to the fact that the reduction of the battery lifetime is closely related to the way of its exploitation;
- Battery capacity is inversely proportional to the value of the discharge current. Thus, significant loss of battery capacity occurs when the discharge current value has a significant increase;
- The voltage at the battery terminals decreases with increasing discharge time. To avoid damage to the battery it is recommended that discharging should only be done up to the minimum voltage per cell (depending on the battery type), otherwise electrochemical processes in the battery may be irreversible.

The results show that regardless of the operating mode, the output voltage is directly proportional to the charge level of the battery, indicating an efficiency at the charge-discharge cycle level, which is a performance scale in evaluating battery efficiency.

4. DC-AC static converter

In order to obtain the maximum performance of an inverter, in practice correction devices are used to reduce or even block higher order harmonics, for example:

- Filters for blocking high frequencies;
- The installation of the inverter is done at a distance as far as possible from the consumer so that the high frequency wave does not propagate to the consumer.

The simulation study resulted in six graphs of voltage-current characteristics. The derived conclusion relates to the veracity of the sizing calculation resulting from the simulation graphs showing a power factor of 1 and the similarity of the characteristics;

In the structure of a photovoltaic power plant, the DC-AC converter has a decisive role in achieving its use value. Therefore, the following aspects are taken into account in the design and construction of the converter:

- Sizing to the theoretical maximum power of the PV plant;
- Ensuring a stable output voltage within the maximum allowed tolerance of ±10% of the nominal value, which is strictly necessary especially for off-grid plants;
- Ensuring a stable output voltage frequency as close as possible to 50Hz and within the standard tolerance allowed;
- In the case of on-grid operation, the DC-AC converter, being driven by the public voltage network with a higher net short-circuit power, must support statically and dynamically the bidirectional conversion of active power for deviations from the mains frequency, respectively of reactive power for deviations from grid voltage. Therefore, the chosen solution ensures the optimal operating parameters.

All these features contribute to increasing the energy efficiency of both the inverter and the photovoltaic plant.

The literature defines a performance factor characteristic of a photovoltaic plant, defined as the ratio between the energy supplied by the plant and the maximum energy that the plant can supply under favourable standard conditions, irradiance 1000 W/m^2 and temperature 25°C.

The performance report highlights the effect of losses caused by various factors.
Its value is indicative as it can vary significantly depending on the technical solution chosen or the location of the plant. The estimation of the performance factor is reported in the figure below:

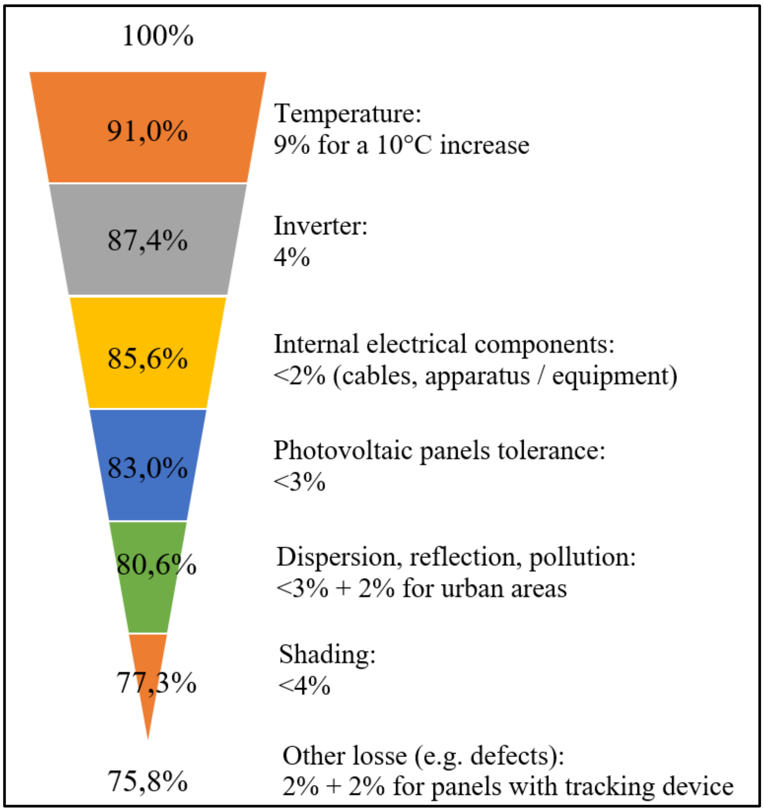

Figure 8.1 Estimation of the performance factor of a photovoltaic system

Maximizing energy efficiency, in addition to the ways developed above, occurs through:

- Choosing the optimal installation site taking into account low temperatures;
- Choosing an inverter with high efficiency and equipped with the function of tracking the maximum power point;
- Choosing photovoltaic panels with a tolerance of ±3%;
- Ensuring the maintenance of photovoltaic panels by removing residues;
- Avoiding shading by reducing the distance between the rows of photovoltaic panels;
- Choosing conductors of higher section than necessary in the case of long routes with large voltage drops;
- Reducing faults through preventive maintenance..

Current concerns in the field of photovoltaic power plants are directed towards reducing costs, increasing efficiency and identifying new technical solutions for the main components, which consistently aim to increase their energy efficiency.

The doctoral thesis followed these needs and I believe that the implementation of the developed principles brings a seminificant contribution to the operation of a photovoltaic plant at maximum energy efficiency.

8.2 Original contributions

The doctoral thesis *„Contributions regarding the efficiency of converting and storage of renewable energy"* represents a theoretical and practical approach to maximizing the energy efficiency of a photovoltaic system in terms of design, sizing, installation, operation, both the entire system and each component of its structure.

The main objective of the research activities is the integration of photovoltaic renewable energy sources for off-grid power generation as well as in electricity grids at maximum energy efficiency.

The own and original contributions of the thesis consist mainly in:

- Elaboration and realization of theoretical studies:
    - Making a synthesis on the current state in the field of renewable energy management and distribution, presenting the basic theoretical aspects related to the thesis objective as well as a bibliographic study regarding the photovoltaic sources made so far;
    - Carrying out a documentary study on renewable energy sources and highlighting their main advantages and disadvantages in order to identify the favourable application areas for each type of renewable source.
    - Identifying and finalizing the constructive elements of a photovoltaic system.
    - Carrying out a theoretical study of the elements that are composing the conversion system in order to identify the operating principles and their integration into the photovoltaic plant.
    - Modelling and analysis of the components of the same conversion system;

- Identification and presentation of component selection criteria so that the efficiency of the photovoltaic system increases.
- Conducting the study on achieving operational reliability in case of dynamic, transient regimes occurring between source and consumer;
- Carrying out a study and an analysis regarding the opportunity of the energy storage system in both off-grid and on-grid PV power plant operation modes;

❖ Simulation of electrical equipment:
- Sizing of the main elements involved in photovoltaic energy conversion;
- Proposing a sizing solution to achieve maximum efficiency;
- Elaboration of electrical diagrams for static converters;
- Mathematical modelling, construction of electrical diagrams and development of simulation programs in Matlab-Simulink and PSpice.
- Simulating the functionality of photovoltaic panels, battery charge controller and inverter under various conditions and operating regimes.
- Simulation and mathematical modelling of batteries used for energy storage;
- Highlighting through simulation the elements that contribute to increasing energy efficiency for each component element of the photovoltaic system;

❖ Testing and validation of an experimental model:
- Realization of the experimental model by connecting and developing the functionality scheme using a part of the electrical equipment related to large research projects within the ICPE ACTEL company.
- Proposing and implementing testing and verification methods for equipment.
- Performing experimental measurements to identify how equipment works in real situations.
- Realization of experimental characteristics;
- Implementation of a method to build graphs based on data files obtained from measurements.
- Theoretical validation of energy efficiency conversion principles using experimental results on the photovoltaic plant of ICPE ACTEL.
- Mechanical design for battery integration.
- Implementing and performing validations and performance verifications by presenting experimental results and interpreting them.
- Presentation of problems encountered in practice that are not found in the literature and proposals for their solution.
- Proposing the use of atmospheric surge protection in the operation of photovoltaic power plants with direct application for the experimental plant;
- Defining a unitary formula for the presentation of results for all the studied and tested equipment.

- Results dissemination:
  - Verification and validation of the proposed solutions following the theoretical study by simulation analysis and implementation on an experimental model.
  - Performing a comparative analysis between the theoretical models, the simulation study and the obtained results based on the experimental model.
  - Interpretation of the obtained results, identification and proposal of new solutions to increase energy efficiency, developed from simulations and experimental testing.
  - Identifying the factors that contribute to the decrease of energy efficiency and the designing/developing solutions to prevent, reduce or stop them.
  - Identifying performance indicators and defining solutions to increase energy efficiency.
  - Design and presentation of methods for connecting the elements of a photovoltaic system, choosing and sizing them so that they are functionally compatible and can work as a unitary system.
  - Development and implementation of an integrated solution;
  - Participating in the dissemination of research results by publishing scientific articles in specialized journals.

8.3 Perspective ulterioare de dezvoltare

The ideas developed in the doctoral thesys can be the starting point for new research in this highly topical area with great implications in the field of renewable energy production under conditions of increased performance and especially under conditions of increased energy efficiency.

In this sense, I believe that a number of future research activities can be found in the following directions:

- Performing an analysis of the transient regimes in the operation of each component of the experimental photovoltaic plant and the array developed by any renewable energy producer;
- Improving and deepening the influence on the maximum power point of other environmental factors;
- Integrating resonant converters into the structure of photovoltaic power plants to increase their energy efficiency;
- Carrying out the study on the large-scale integration of domestic photovoltaic power plants or those used by local communities into the national energy system;

9 PUBLISHED SCIENTIFIC PAPERS AND CONFERENCE PARTICIPATIONS

1) **Mădălina Lupașcu**, Valentin Năvrăpescu, Ion Potârniche, “*Energy efficiency of solutions developed by ICPE ACTEL in collaboration with SIEMENS SRL Romania and ICPE CA Bucharest*”- INCDIE ICPE-CA & SIEMENS Romania Scientific Conference – SPECIAL GUEST DECEMBER 6, 2018;

2) **Mădălina LUPAȘCU**, Valentin NĂVRĂPESCU, Ion POTÂRNICHE, “*Study regarding the optimization of the regulation of ac/dc converters used in the operation of dc motors driving the drilling winch*”– SME 2018;

3) Ion POTÂRNICHE, Mina GHEAMALINGA, **Mădălina LUPAȘCU**, Cristiana POPA, “*Traditions and perspectives in the field of electric motor drive equipment in the structure of drilling rigs made in Romania*”– ZASTR 2018;
Univers Ingineresc nr. 20/2018 - 16-31 October 2018

4) Ion POTÂRNICHE, **Mădălina LUPAȘCU**, Mina GHEAMALINGA, “*ICPE ACTEL's concerns for the development of energy-efficient solutions and products in the field of electrical drives and automation*”– ZASTR, Chișinău 2019;

5) **Mădălina LUPAȘCU**, Valentin NĂVRĂPESCU, Ion POTÂRNICHE, “*Study regarding frequency control for isolated sources using photovoltaic energy storage systems*”– ATEE 2019 (Published in 30 May 2019);
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Electronic ISSN: 2159-3604;
Print on Demand(PoD) ISSN: 2068-7966

6) **Mădălina LUPAȘCU**, Valentin NĂVRĂPESCU, Ion POTÂRNICHE, “*Considerations on voltage control for storable photovoltaic energy sources integrated into the national energy system*”– ATEE 2019 (Published in 30 May 2019);
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