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Comparative Performance Analysis of Photovoltaic Power Plants – a Case Study

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Abstract - **The aim of this paper is the comparative study of the behavior and performances of two photovoltaic power plants of different installed power, but which uses identical equipment. The difference in size is being given by the number of specific equipment used (the power inverters and solar panels). The plant behavior was investigated, as the injected active power is dependent on the available sunlight to the photovoltaic panels (and a larger plant leads to a larger panel area), as well as the influence of the power plants to the power grid, given the fact that a large power plant will inject more active power, and the grid local power transformer must be able to accept this power. The power plants efficiency was also investigated, as typically, the bigger the plant, the higher the efficiency must be. But, the efficiency depends on the generated active power (which must be high, to have a good efficiency) and in the case of photovoltaic power plants, the produced power depends on the available sunlight, and again, the bigger the plant, the bigger the panel area susceptible to be shaded. This gives the fact that although the injected power is higher for the bigger power plant, if the power of each inverter is below the rated power, the overall efficiency is lower compared to the small power plant which works at the rated power.**

Cuvinte cheie: *fotovoltaic, central electrică, radiație solară.*

Keywords: *photovoltaic, power plant, solar radiation.*

I. INTRODUCTION

Nowadays renewable energy is increasingly used due to its potential benefits, meanly the reduction in greenhouse gas emissions, by reducing the dependence on fossil fuels used in classical power plant (coal and gas) [1].

Although solar energy is considered to be convenient, it has specific costs and issues, given by the solar power plant equipment. On one hand, the investment cost must be amortized, and on the other hand the solar power plant is based on static converters. Therefore, before the plant lifetime is reached and the equipment must be recycled, (resulting in an amount of waste) the solar power plant gives electric pollution during its lifetime. This is because the solar energy is injected to the power grid only by means of power inverters, which are injecting voltage and current harmonics to the grid [2-7].

Another problem is caused by the generated energy availability, which is directly dependent on the solar radiation. Consequently, the solar power plants can produce electricity only during sunny days. When the sky is cloudy the solar plants production drops, and during nighttime the production is halted [8-9].

Considering the convenience of installing solar power plants in Romania region, the country is located in a geographical area which gives good solar coverage, having 210 sunny days per year with a solar energy annual flow between 1000 kWh/sqm/year and 1300 kWh/sqm/year [8][10].

As a function of the intensity of solar radiation (Hi) in the horizontal plane, Romania is in the European sunshine zone B, considered to be advantageous to produce electricity by means of solar energy.

Romania is divided into three areas, dependent to the geographical area [8]:

- The red zone, for Hi>1650 kWh/sqm/year, which includes the southern areas: Oltenia, Muntenia, Dobrogea and the south of Moldova;
- the yellow zone with Hi between 1300 and 1450 kWh/sqm/year: the Carpathian and sub-Carpathian regions of Muntenia and Oltenia, Transylvania, the middle and the northern part of Moldova;
- the blue zone which includes the mountain regions - radiation intensity between 1150 and 1300 kWh/sqm/year.

The paper aims the comparative study of two photovoltaic power plants installed in Romania (low-power and high-power) on the same urban location.

After the introduction, the studied power plants are detailed in the second chapter, and in the third chapter, the experimental data is presented and evaluated. Finally, the conclusions are drawn.

II. THE POWER PLANTS

The two photovoltaic power plants taken into consideration are both located in the urban area of Tg. Jiu, Romania, in the Gorj County.

The first plant is residential, connected to the public power grid, at about 250 m from the power transformer, among home consumers, mainly apartment flats. However, the rated power is relatively high, for a residential plant. The main parameters of this plant are:

- Rated power: $P_N = 50$ kW;
- Number of panels: 108;
  - Panel rated power: 540 W;
- Number of inverters: 1;
  - Inverter rated power: 50 kW.

The second studied power plant is also located in Tg. Jiu area, but in the industrial zone, and is connected to the power grid directly to the power transformer. The main parameters of this power plant are:

- Rated power: P_N = 250 kW;
- Number of panels: 466,
  - Panel rated power: 540 W;
- Number of inverters: 5;
  - Inverter rated power: 50 kW.

The photovoltaic panel type used for both plants is LR5-72HPH-540M, with the following rated parameters:

- Max power: P_{max} = 540 W;
- Open circuit voltage: V_{0C} = 49.5 V;
- Max power voltage: V_{mp} = 41.65 V;
- Short-circuit current: I_{SC} = 13.85 A;
- Max power current: I_{mp} = 12.97 A;
- Efficiency η = 21.1 %.

The power inverter used for both plants is SUN2000-50KTL-M0, with the following rated values:

- output power: S_N = 50 kVA;
- output voltage: U_N = 220/230 V (3f+N);
- output current: I_N = 76/72.2 A;
- power grid frequency: f_N = 50/60 Hz;
- max harmonic distortion: THD = 3%;
- max input voltage: U_{dcN} = 1100 V;
- max MPPT input current: I_{dcN} = 22 A.

The 50 kW power plant uses one power inverter with the corresponding 108 photovoltaic panels organized on 6 rows each with 18 panels.

The 250 kW power plant uses the same configuration of panels, for each of the 5 inverters.

III. Experimental Results

The electric and energetic parameters of the two considered power plants had been recorder in August, 2023. It can be seen that the data was recorded during the "good" period of the year, when the solar radiation is the highest.

The analyzed data was recorded by the power inverters, given their capability to measure, compute and record (for a time step of 5 minutes) a comprehensive number of quantities:

- The power grid RMS voltage (phase and line voltages);
- The power grid RMS current;
- Active power injected to the power grid;
- Reactive power;
- Power factor;
- Generated energy to the power grid;
- Frequency;
- Photovoltaic panels voltage;
- Photovoltaic panels current;
- Inverter efficiency.

The data was recorded when the power inverters had been online, therefore, when the solar radiation was sufficient for the inverter to start and connect to the power grid. The time intervals when the inverters had been disconnected from the power grid (during night time for example) had not been recorded. Therefore, each daily recording starts after the sunrise (the solar radiation is high enough for the inverters to start), and stops at dusk (the solar radiation is too low and the inverters stop).

The first recorded quantity, the three-phase power grid current RMS values are illustrated in Fig. 1. It is observed that the RMS values of the three-phase currents are practically equal, no differences being observed qualitatively. As expected, the current RMS value is pulsing, having its maximum value at each mid-day, and the corresponding minimum values at each morning and evening. Moreover, the cloudy days can be identified, from the switching like pattern. It must be noticed that although the both plants are located in the same town, the injected current is not the same (keeping the proportions) – not only that the production evolution in time is not the same, but the switching due to clouds is different.

The power grid voltages are illustrated in Fig. 2. One can see that the phase voltages are not symmetrical, although the currents are, showing the fact that the power grid voltage is asymmetrical.

This does not mean that the photovoltaic plant does not affect the power grid. To better observe the voltage and current daily evolution, a detailed view is illustrated in Fig. 3.

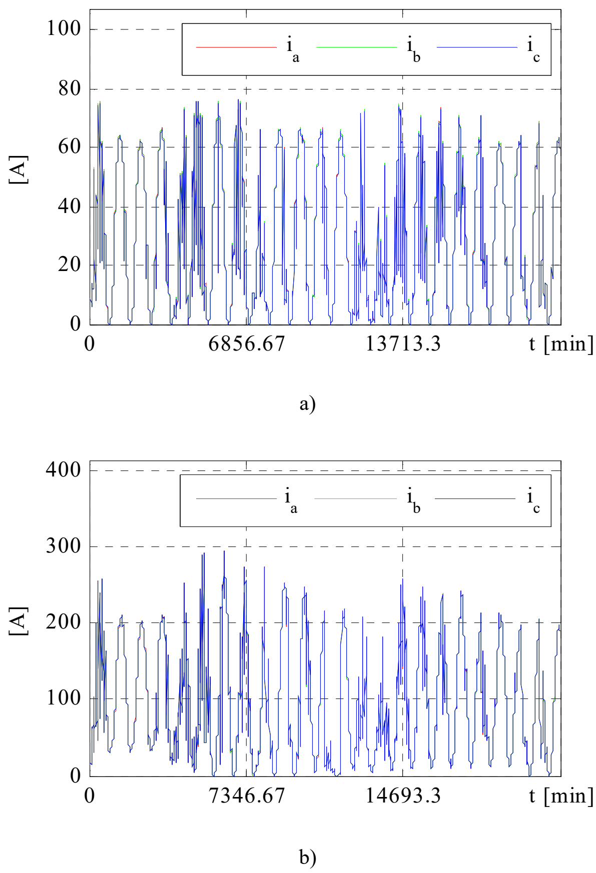


Fig. 1. The RMS current injected to the power grid for one phase: a) 50 kW plant, b) 250 kW plant.

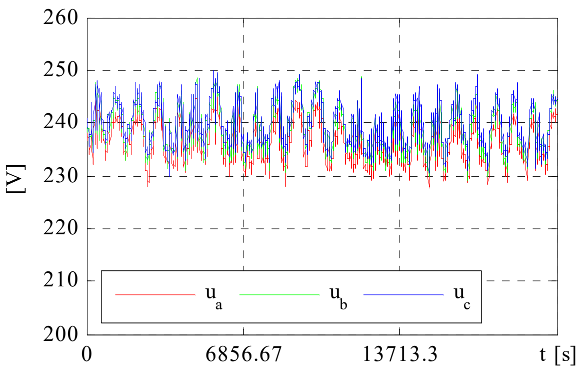
An interesting fact is the effect of the current affecting the voltage as a function of plant coupling point to the power grid. It results that although the current injected to the grid by the 250 kW plant is greater, because the plant connects directly to the power transformer, the voltage increase is lower, compared to the 50 kW power plant which is connected to the grid at considerable distance from the power transformer. In fact, for the latter, the voltage variation and asymmetry are considerable higher, given the long lines and the single phase residential consumers.

A similar conclusion can be drawn regarding the current switching due to shading, for which the voltage is more affected by the low-power plant.

The active power injected to the power grid is illustrated in Fig. 4. Because the voltage variation is low, the active power shape reflects the injected RMS current shape.

On the other hand, the measured reactive power at the point of coupling to the power grid is practically zero, as it can be observed in Fig. 5.

The power factor is illustrated in Fig. 6. For most of the time, the power factor is unitary, except for some short moments. Comparing the low values of the power factor with the active and reactive power (for the same moments of time) it appears that the low value of the power factor coincides with very low values of active power. Also, considering the fact that this low-power factor values are scarse and with no cyclic repetition, they are probably measurement errors.



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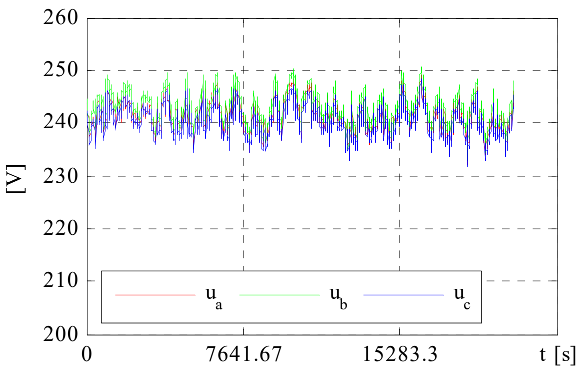

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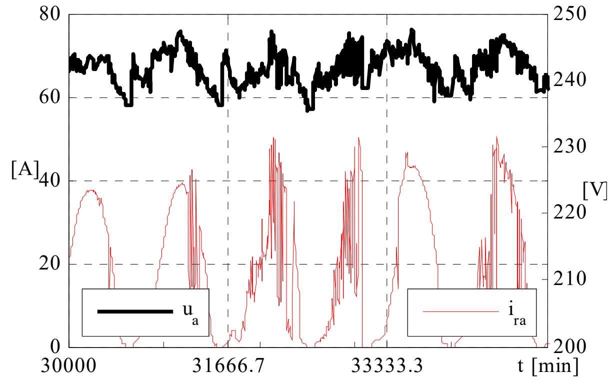
Fig. 2. The power grid voltages: a) 50 kW plant, b) 250 kW plant.



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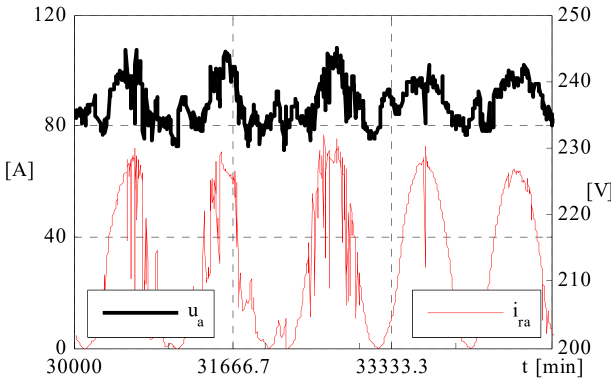
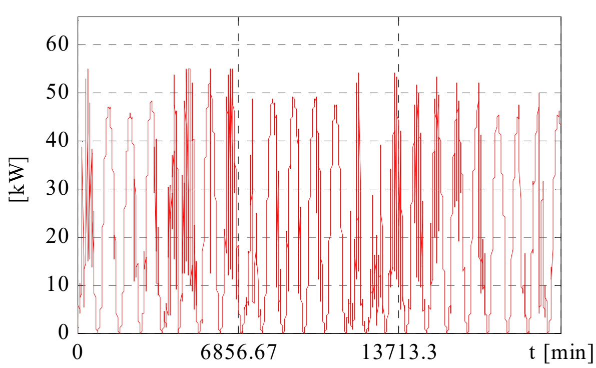


b)

Fig. 3. Detail of the grid current and voltage on phase a: a) 50 kW plant, b) 250 kW plant.



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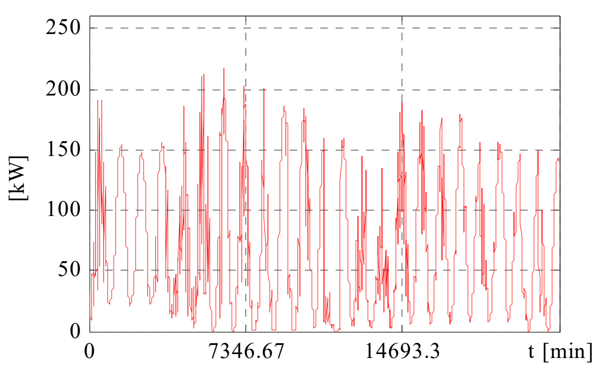


b)

Fig. 4. The active power injected to the power grid for the recorded timespan: a) 50 kW plant, b) 250 kW plant.

The produced energy by the two power plants is illustrated in Fig. 7. The typical daily evolution of the injected active power is visible, given the produced energy ripple. Also, the successive cloudy days are visible, when the produced energy is slackened.

The voltages corresponding to the rows of photovoltaic panels for the 50 kW plant are presented in Fig. 9. It can be seen that the voltages corresponding to the 6 rows of panels are relatively equal, with little differences, except for the cloudy days, to which bigger differences appear as only some of the panels are shaded.

The conclusion is confirmed by the current of each row of photovoltaic panels, given in Fig. 9. It shows that the voltage ripple and difference between rows is higher when the panels are shaded, so the current is low value and high ripple.

The voltages corresponding to the rows of photovoltaic panels for the 250 kW plant are presented in Fig. 10 and the currents are given Fig. 11.

In this case, the number of illustrated voltages and currents is considerably higher, as the plant uses 5 inverters, each with 6 rows of panels.

At the same time, because of the high number of panels, the probability that some of the panels are shaded while other is not, increases. Therefore, the panel row voltage variation as well as the current row variation is much higher for the case of the 250 kW plant.

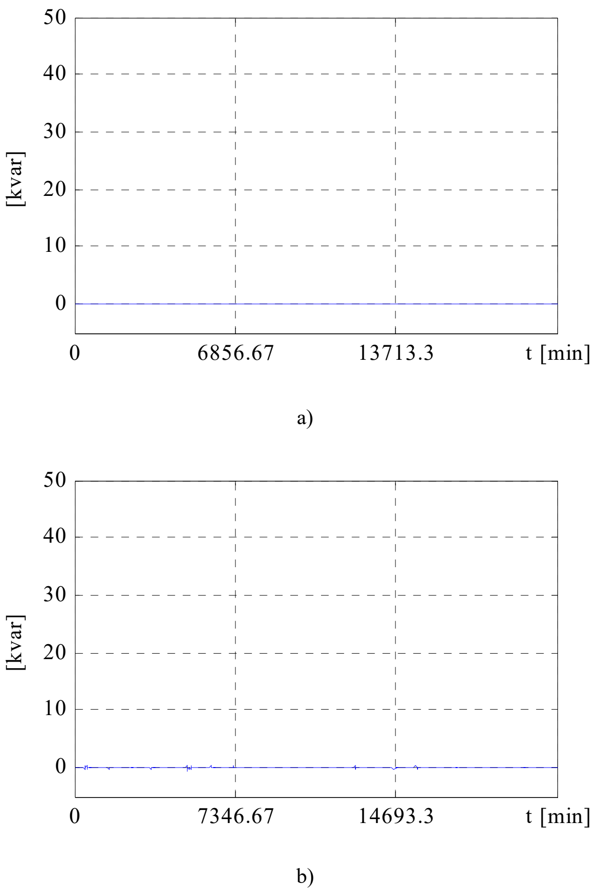


Fig. 5. The reactive power injected to the power grid for the recorded timespan: a) 50 kW plant, b) 250 kW plant.

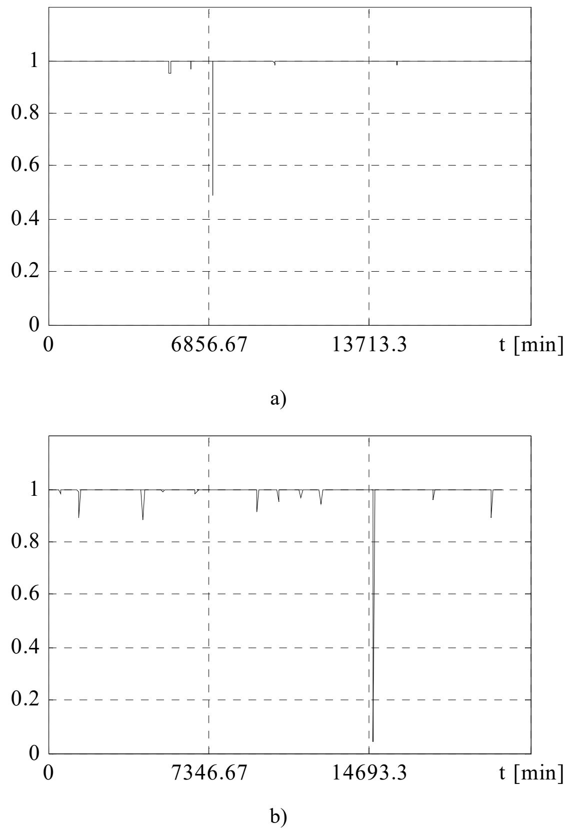


Fig. 6. The power factor for: a) 50 kW plant, b) 250 kW plant.

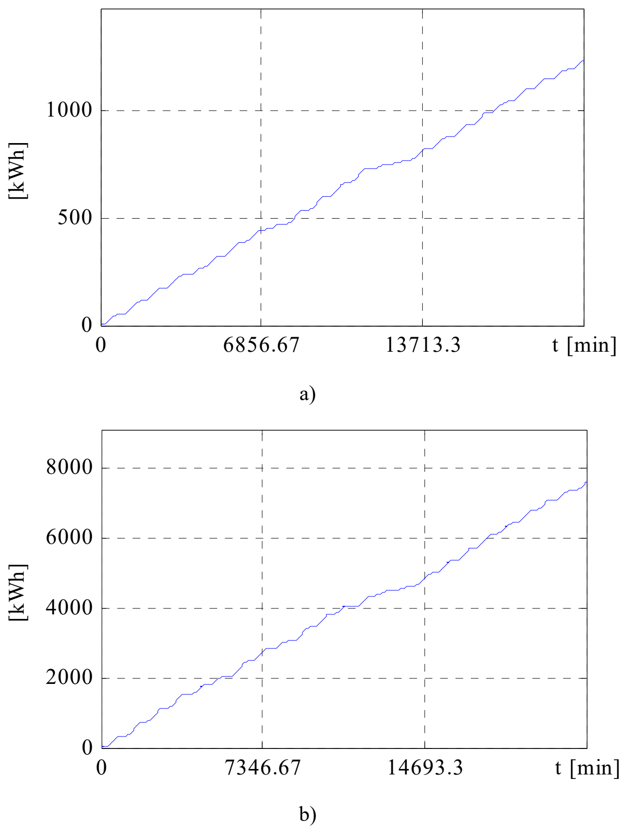


Fig. 7. The produced energy for the recorded timespan: a) 50 kW plant, b) 250 kW plant.

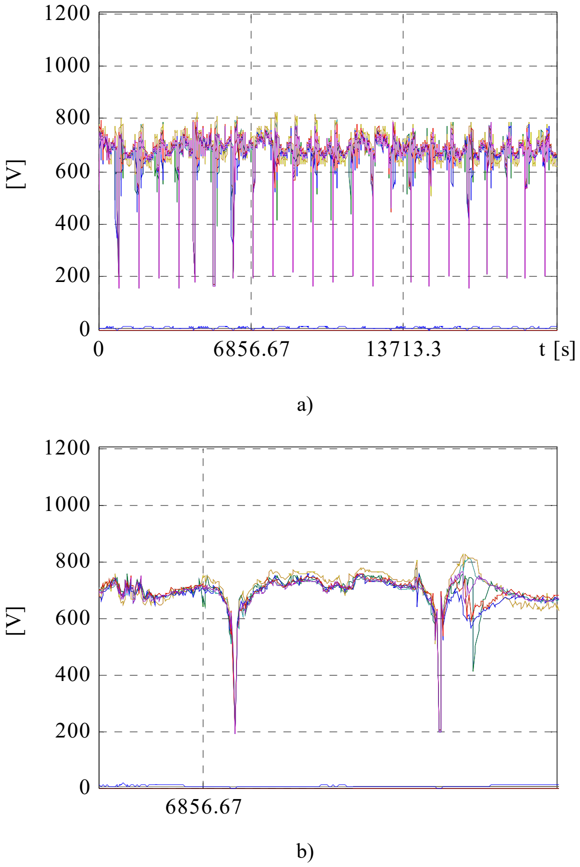


Fig. 8. The output voltage of each row of photovoltaic panels for the 50 kW plant: a) for the recorded timespan, b) detailed view.

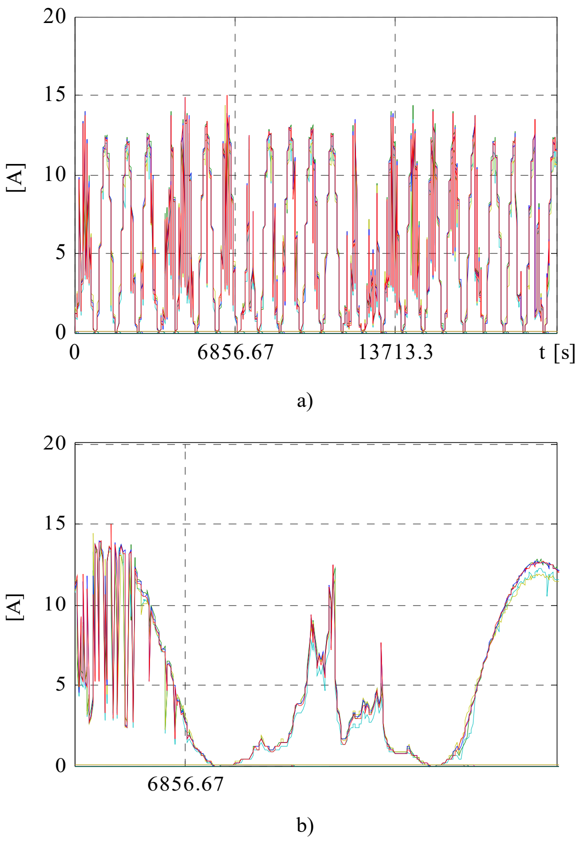


Fig. 9. The output current of each row of photovoltaic panels for the 50 kW plant: a) for the recorded timespan, b) detailed view.

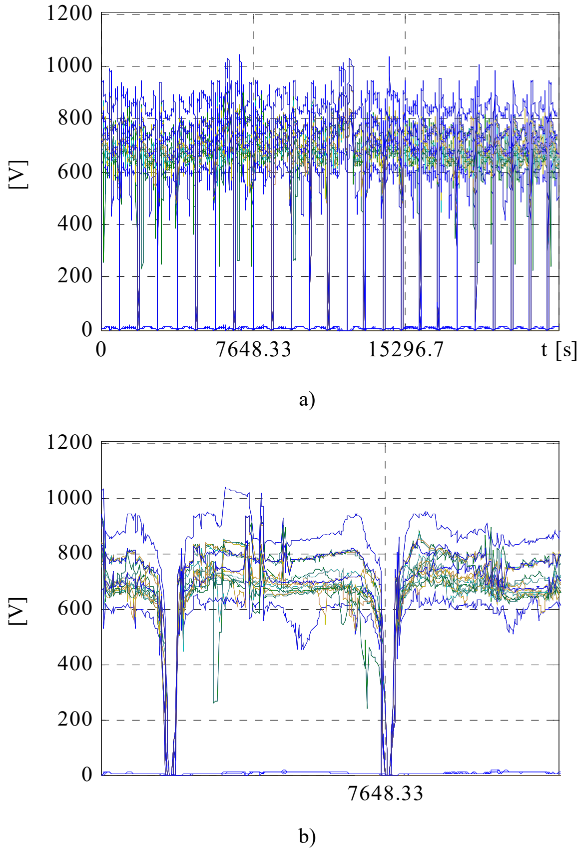


Fig. 10. The output voltage of each row of photovoltaic panels for the 250 kW plant: a) for the recorded timespan, b) detailed view.

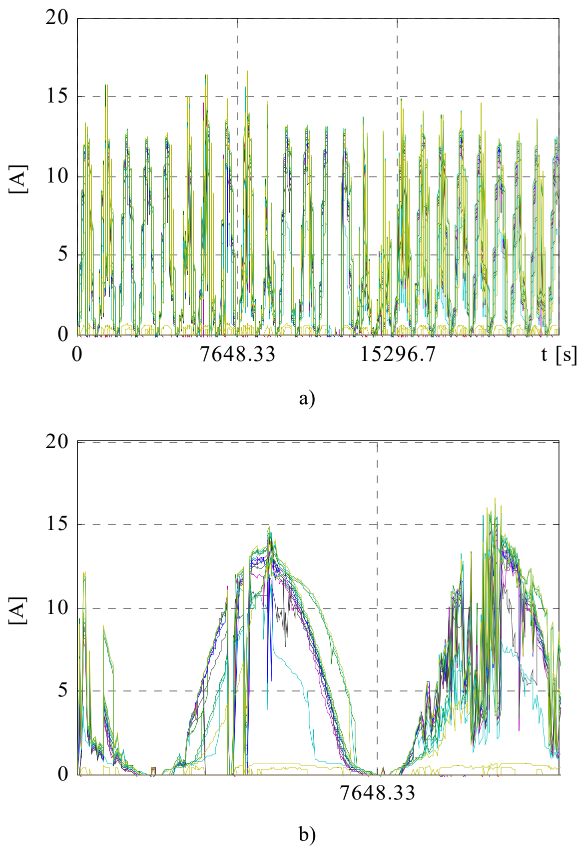
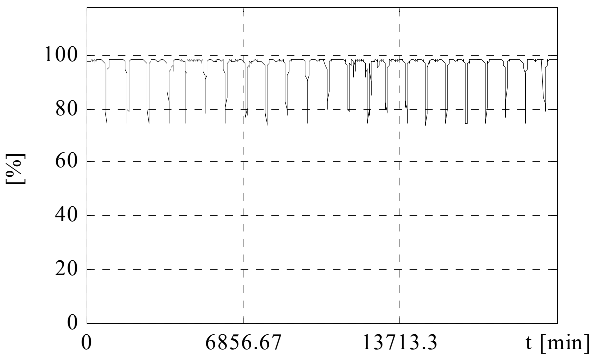


Fig. 11. The output current of each photovoltaic row of panels: a) for the recorded timespan, b) detailed view.

Another issue which is due to the plant size is the higher rate of breakdowns which is shown by the panel rows voltage and current. Because of the high number of panels, some of the connections are broken, so the row voltage increases to the open circuit value.

The power inverters efficiency is illustrated in Fig. 12, for the two considered power plants. The efficiency is high, close to 100% when the produced power is high, close to the rated value, and it lowers when the inverter approaches the idle regime (at the start and the end of each day, or in cloudy days). The efficiency of each of the plant 5 inverters is shown in Fig. 12-b. The efficiency evolution during the day, and during the month, is not identical for the 5 inverters, as the high area of panels is differently shaded. The highest efficiency of the low-power plant is 98.7% and the lowest is 74.3%. For the high-power plant, the highest efficiency is 95.5% and the lowest is 61.6%, although the average minimum is 64.9%.

The typical efficiency of a power plant is higher for higher power, which is contradicted by the obtained results. The explanation of these is given by the two plants injected power. As seen in Fig. 4, a and b, it results that the small power plant works close to the rated power, even at the maximum datasheet power of 55 kW, for some days. The high-power plant works considerably below its rated power of 250 kW (at an averaged percent of 80% of the rated power), for the same days and day moments, despite the fact that both plants are located in the same town.



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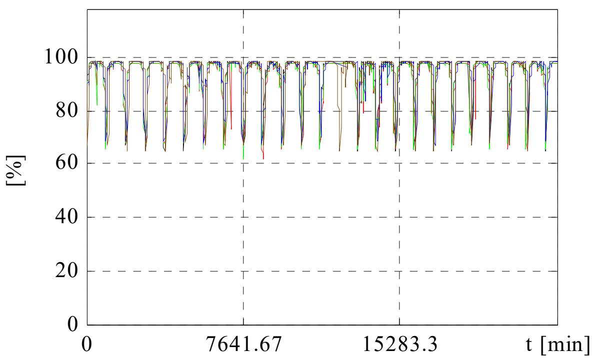


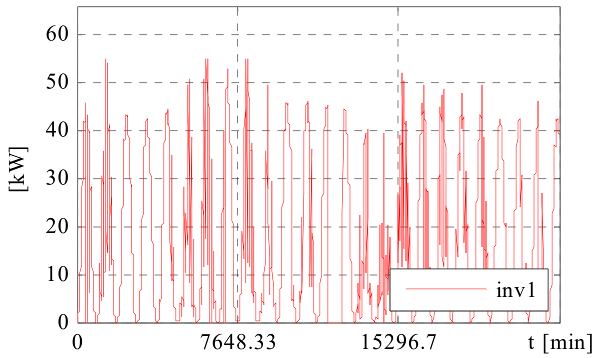
b)

Fig. 12. The inverter efficiency: a) for the 50 kW plant, b) for the 250 kW plant.

This is further explained in Fig. 9 and Fig. 11, which show that the panel row currents are different for the high-power plant, meaning that the solar radiation is not the same for all the panels/inverters.

Therefore, each of the five inverters of the high-power plant is working below its rated power, as proven in Fig. 13 and Fig. 14, respectively.

Another important fact is that the power inverters are pure sine which means that they give sinusoidal voltage at their output (very important for the inverter to work, synchronized to the power grid). At the same time, in order to obtain sinusoidal output voltage, the inverter is connected to its load (power grid) by means of important reactive harmonic filters.



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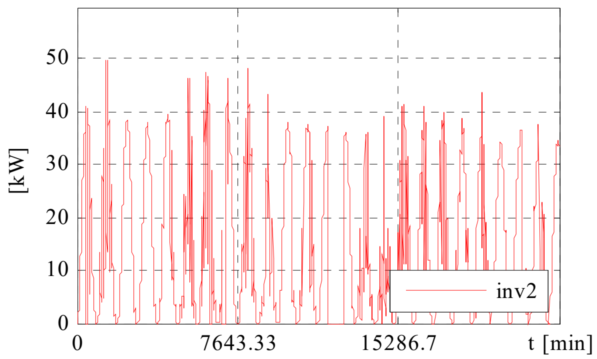

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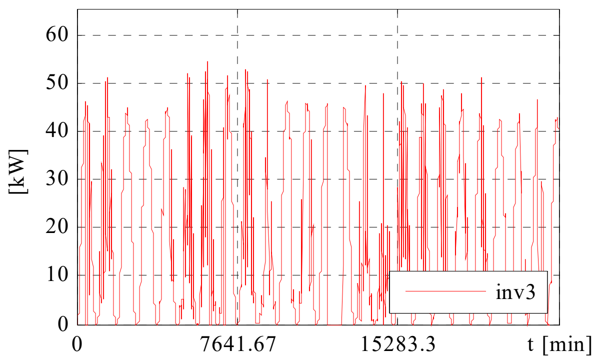
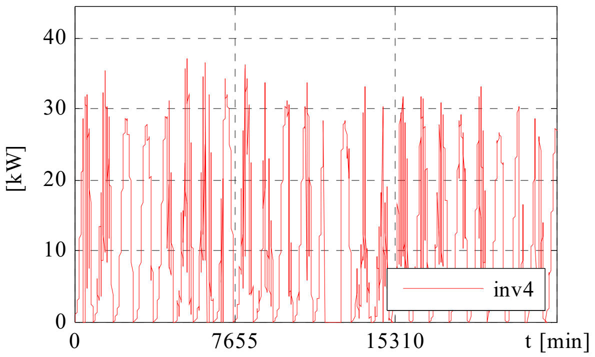


c)

Fig. 13. The power injected to the power grid of the first three inverters of the 250 kW power plant.



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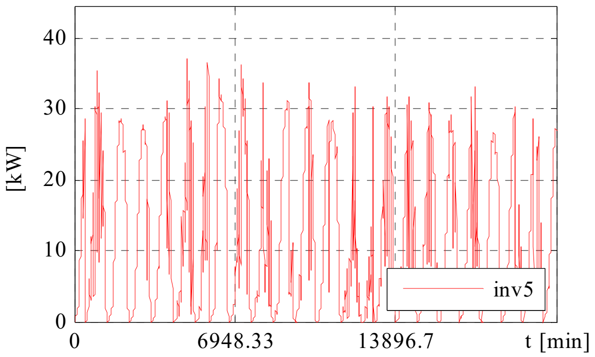

e)

Fig. 14. The power injected to the power grid by the other two inverters of the 250 kW power plant.

The passive harmonic filters give a relatively high value reactive current which flows between the inverter and the harmonics filter, irrespective to the load current (even at idle operation), increasing the inverter conduction and switching losses (compared rectangular wave inverter). This leads to a lower power inverter efficiency, compared to a classic rectangular wave inverter. Moreover, the pure sine inverter uses not only the passive harmonic filters to obtain pure sinusoidal wave, but also a “multipulse” PWM modulation method (like the classical sinusoidal PWM modulation), which gives higher switching losses, compared to the rectangular wave inverter, which output only one pulse per half period.

CONCLUSIONS

The efficiency of a power plant depends on its size, and surprisingly, the smaller plant showed higher efficiency than the bigger plant. For photovoltaic power plants, the efficiency decreases as the plant is low on production and the production is low when the photovoltaic panels are not receiving direct sunlight. The bigger the plant, the higher the total panel surface is, so the higher is the probability that some of the panels to be shaded by thin, scattered clouds. And the injected active power is much lower and unstable in cloudy days.

A demand for photovoltaic power plants consists of the pure sine power inverters which must output sinusoidal voltage with low harmonic distortion, in order to work synchronized to the power grid voltage. Of course, this gives the advantage that the solar power inverter can inject only active power to the grid, with an insignificant amount of reactive and distortion power, At the same time, it gives the disadvantage that in order to obtain pure sinusoidal voltage, large passive harmonic filters are necessary at the inverter output. These filters require an important current to flow from the inverter even at idle operation, resulting in higher inverter losses. Another disadvantage of small distributed photovoltaic power plants is the power grid voltage increase, even more so when the plant is connected to the grid away from the power transformer.

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