CHARACTERIZATION OF A STAND-ALONE PV COOLING/HEATING SYSTEM

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ABSTRACT: Recently, the environmental objectives set by the European Union to reduce CO_2 emissions and to increase the renewable share, together with the reduction of PV prices since 2010, have motivated a great interest in PV heat pump systems for heating and cooling applications. This papers describes the initial characterization test and results of a stand-alone PV heat pump prototype installed in Madrid (Spain), using a water tank as thermal storage instead of batteries as electricity storage (a more expensive and technically complex solution). This initial test has the objective of characterizing the response of the converter that operates the compressor of the heat pump. Such converter was powered by a constant frequency input (the electric grid), in order to quantify the variable frequency output that the compressor demands. In future work, the converter will be powered by a PV array (which means a variable frequency input) and programmed to provide the required output without overcoming any limit value of the system. This way, the heat pump system will be operated completely stand-alone.

Keywords: characterization, heat pump, qualification and testing, refrigeration, stand-alone PV systems.

1 INTRODUCTION

In the last decades, the demand of reversible heating and cooling systems has increased importantly, together with the need of generating energy in a more efficient and sustainable way. According to the European Heat Pumps Agency, heat pumps market increased by 3.5% in terms of units sold in 2014 (which means an installed electrical power of 1.88 GW) [1] and by 12% in 2015 (which means an installed electrical power 2.11 GW) [2]. However, even if heat pumps are one of the most efficient technologies for conditioning applications, the overall power consumption in Europe in this sector keeps increasing every year, so bigger efforts must be dedicated to achieve the environmental objectives of the European Union for the year 2020 –i.e. reducing the CO_2 emissions by 20% compared to 1990, increasing the renewable share to 20% and improving the electrical efficiency to 20% [3].

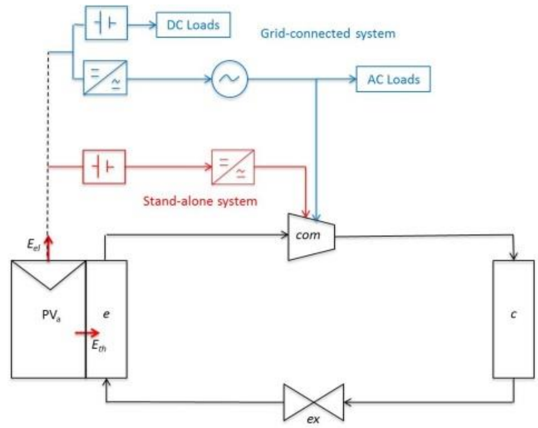
Photovoltaic (PV) energy is one of the most promising renewable energy sources for powering heat pumps and reducing their environmental impact, for several reasons. First, the PV technology can be applied to big and centralized installations, as well as to small and decentralized ones, and its cost is almost independent from the system size and its application. Second, the PV generating cost is similar to the electricity sale price in applications which lack any energy storage system and even lower in large power systems (bids of 1.9 and 2.3 US cents/kWh were approved in China and Abu Dhabi in 2016 [4]), which makes it competitive with almost any other energy source.

Before the PV panels price started dropping in 2010, most research related to solar heat pumps focused on hybrid photovoltaic/thermal (PVT) systems that combined a PV module with a thermal collector on its back surface, which worked as the evaporator of the heat pump. This type of technology is still the dominant one, but the reduction of PV prices has motivated an increasing attention in only PV (OPV) heat pump systems –where the compressor is powered by the electricity generated by a PV array. The objective of this paper is to describe a OPV heat pump prototype installed in Madrid, intended for stand-alone operation with thermal storage, and to discuss the results of the initial experimental works. These have been performed grid-connected, in order to precisely characterize the variable-speed compresor before substituting the grid (which provides constant output frequency) with a PV array (with variable output frequency).

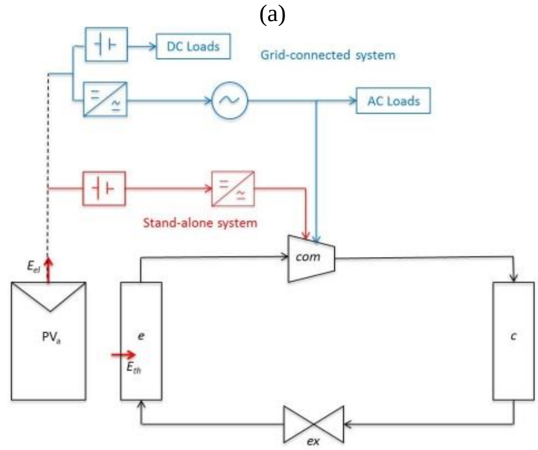
2 CURRENT STATE OF THE ART

Roughly, solar heat pumps can be divided into two categories -hybrid photovoltaic/thermal (PVT) or only photovoltaic (OPV) - that can present two configurations –grid-connected or stand-alone-. Figure 1 shows the schematic of a basic PVT (a) and OPV (b) heat pump system with both configurations. The first experimental study of a PVT heat pump was reported in 1997 and it was a grid-connected system [5], although stand-alone PVT systems have also been widely explored. The biggest inconvenience of this hybrid technology is the high investment and maintenance costs of solar collectors. However, the first work related to OPV heat pump systems was not published until 2010 [6]. Since then, research on this type of heat pumps has been abundant and has explored a wide variety of solutions. The majority of them consists in grid-connected OPV heat pumps for increasing the local self-consumption in buildings. This solution has the inconvenient of forcing the PV array to operate at the voltage of the grid -and not at its maximum power point- unless a back-up storage system is installed in between. The possibility of operating stand-alone OPV heat pumps has been explored only very recently. Reported studies are very few and all of them consider a Battery Energy Storage System (BESS) coupled with the PV array [7], [8]. Such BESS are expensive and might be prone to create technical and security problems.

In conclusion, research in the near future should focus on stand-alone OPV heat pumps that are able to operate without back-up BESS. This solution raises two main technical challenges: managing PV power intermittences due to cloud-passing, and solving day-night generation cycle.



(a)



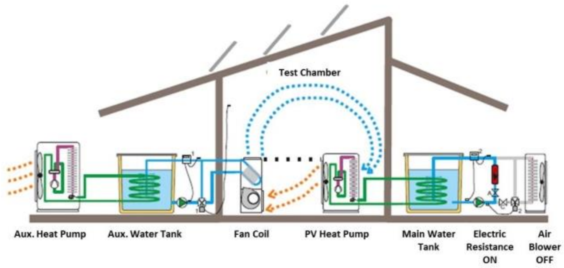
(b)

Figure 1: Schematic of a basic PVT (a) and OPV (b) heat pump system with grid-connected and stand-alone configurations.

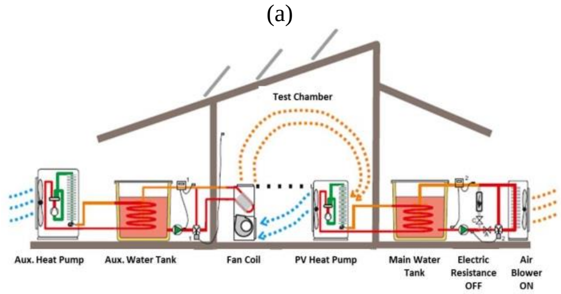
3 EXPERIMENTAL SET

Figure 2 shows the schematic of the PV heat pump installation tested for this work, operating in cooling (a) and heating (b) modes. This installation mainly consists of the following elements:

- <u>PV Heat Pump</u>: a commercial heat pump that needs to be precisely characterized with the electric grid, in order to determine its operating parameters and limits, before powering it exclusively with a PV array.
- <u>Main Water Tank</u>: it simulates the room to be acclimatized, so it is cooled by the PV heat pump when operating in cooling mode and vice versa.
- <u>Electric Resistance</u>: in order to calculate how much thermal energy is extracted by the PV heat pump from the main water tank in the cooling operating mode, an electric resistance is turned on to keep the water temperature constant (see Figure 2.a). This way, thermal loads from the heat pump and the resistance are known to be equal.
- <u>Air Blower</u>: it is used in the heating operating mode for calculating how much thermal energy is provided by the PV heat pump to the main water tank (see Figure 2.b). Such thermal energy is equal to the one extracted by the air blower for keeping the water temperature constant.
- <u>Test Chamber</u>: it is an enclosed and thermally isolated space that simulates the ambient, so its temperature must be kept constant while running cooling or heating tests. The PV heat pump releases heat to the test chamber when operating in cooling mode, and retrieves it in heating mode.
- <u>Fan Coil</u>: it is used for maintaining a constant temperature inside the test chamber, compensating the thermal load of the PV heat pump (the fan coil extracts heat from the chamber when the PV heat pump is in cooling mode, and vice versa).
- <u>Auxiliary Water Tank</u>: heat extracted (or demanded) by the fan coil for regulating the temperature inside the test chamber is transmitted to (or obtained from) the auxiliary water tank.
- <u>Auxiliary Heat Pump</u>: it controls the temperature inside the auxiliary water tank, so the thermal load required by the fan coil can be obtained from water.



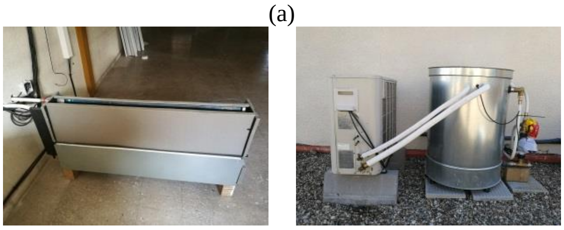
(a)



(b)

Figure 2: Schematic of the PV heat pump installation tested, operating in cooling (a) and heating (b) modes.

(a)



(b)

Figure 3: Images of the PV heat pump prototype installed in Madrid (Spain), composed of the tested system (a) and the auxiliary system (b).

Figure 3 shows real images of the prototype installed in Madrid (Spain). Figure 3.a shows the tested system, which includes the PV heat pumps, main water tank, electric resistance and air-blower, Figure 3.b shows the auxiliary system, including the fan coil, the auxiliary water tank and the auxiliary heat pump. The final objective of this research work is to efficiently operate this prototype, powering the PV heat pump exclusively with a PV array (stand-alone operation) and without any BESS. The auxiliary heat pump, the fain coil, the electric resistance and the air blower are powered by the grid.

4 TEST AND RESULTS

As mentioned before, the compressor of the PV heat pump needs to be characterized before powering it with a PV array, in order to determine its operation parameters and their limit values. This compressor is equipped with a commercial frequency converter that regulates its operating frequency depending on the thermal conditions set for the experiment. The objective of the test described in this paper is to analyze the response of this commercial converter with a constant frequency input (the electric grid in this case). Such converter will be substituted with another one, external to the heat pump, when the compressor is powered by a PV array. Hence, its response needs to be replicated in order to respect all the operation limits of the compressor, but with a variable-frequency input.

Initial tests have been carried out for the cooling mode and forcing a constant temperature of 20ºC in the test chamber. Figure 4 shows the frequency output against voltage for one of the phases of the frequency converter. Both variables present a linear relationship with a slope very close to 1, although frequency is slightly smaller than the voltage. Figure 5 shows the current and the frequency output of the converter against ΔT, i.e. the difference between the temperature in the water tank and the temperature set as target (18ºC for the cooling test). It can be observed that both variables (as well as the voltage, as a consequence of results showed in Figure 4) remain almost constant during the cooling process, with operating values close to 160 Hz, 5 A and 170 V, respectively. Moreover, it can be deduced that when the frequency increases, the current decreases proportionally and vice versa. Finally, Figure 6 shows active, reactive and total power output of the converter versus ΔT. Active and reactive powers have very similar values during the cooling process (cosφ≈0.7), and they remain almost constant (total power varies between 800 and 900 W during most of the test). If comparing Figures 4 and 5, it can be observed that the power follows the current, varying proportionally and opposite to the frequency. In addition, these figures show that the heat pump system is started very fast (frequency, current and power grow from zero to the operation values almost instantly) and stops gradually, slowing down when ΔT≈2ºC.

5 FUTURE WORK

In order to completely characterize the heat pump prototype described in this paper, the same test performed for the cooling process will be repeated for the heating process (with a set temperature in the main water tank of 30ºC). Additionally, both cooling and heating tests will be replicated for different temperatures in the test chamber, which simulates the ambient, for simulating a very warm summer and a very cold winter, respectively.

Once the response of the converter is precisely characterized with a constant frequency input, the compressor of the heat pump will be powered by a PV array, which provides a variable frequency input. Hence, the converter will have to be programmed for providing the output demanded by the compressor at every instant, without overcoming any limit value of the system. For operating the stand-alone system, there are two technical problems that need to be solved when programming the converter: managing the PV power intermittences due to cloud passing, and solving the day-night generation cycle by means of the thermal storage provided by the water tank.

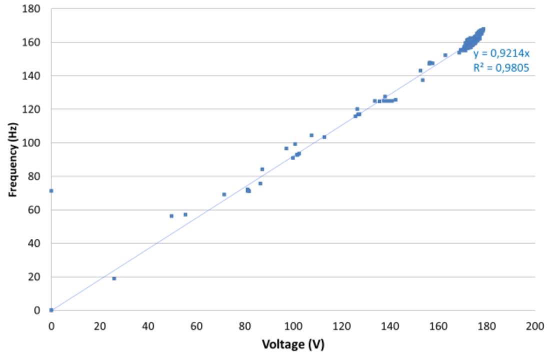


Figure 4: Output frequency versus voltage for one of the phases of the frequency converter.

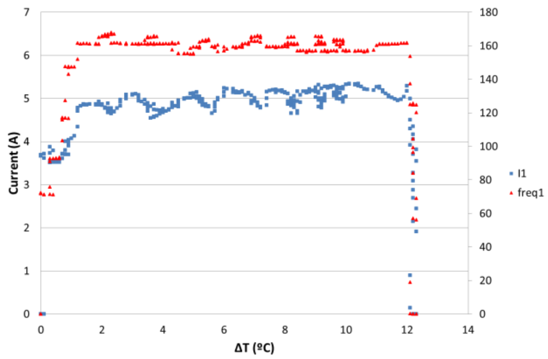


Figure 5: Output frequency and electric current versus ΔT for one of the phases of the frequency converter.

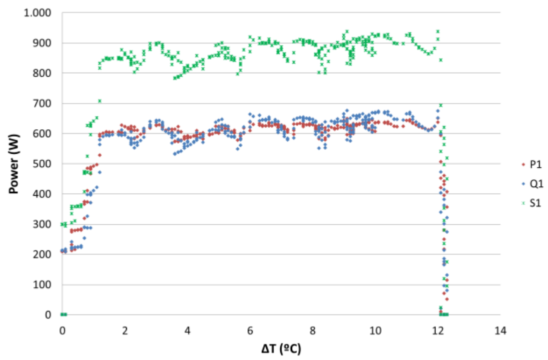


Figure 6: Active, reactive and total power versus ΔT for one of the phases of the frequency converter.

6 REFERENCES

[1] European Heat Pump Agency, *Heat Pump Market and Statistics Report 2015*, November 2015.

[2] European Heat Pump Agency, *Heat Pump Market and Statistics Report 2016*, November 2016.

[3] Oficina de Publicaciones de la Unión Europea, *Europa 2020: la estrategia europea de crecimiento*, Luxemburgo 2013.

[4] J. F. Weaber, *Solar power cost down 25% in five months*, Electrek September 2016, online: https://electrek.co/2016/09/26/solar-power-cost-down-25-in-five-months-theres-no-reason-why-the-cost-of-solar-will-ever-increase-again/

[5] S. Ito, N. Miura, J. Q. Wang, M. Nishikawa, *Heat Pump Using a Solar Collector With Photovoltaic Modules on the Surface*, Solar Energy, Vol. 112 (1997), pp. 147-151.

[6] Kei. Inoue, Y. Iwafune, *Operation of Heat Pump Water Heaters for Restriction of Photovoltaic Reverse Power Flow*, 2010 International Conference on Power System Technology, Hangzhou (2010).

[7] M. Spinnler, L. Hörth, F. Böing S. Wolf, T. Sattelmayer, *Novel heat pump system for highly transient PV operation*, 29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam (2014).

[8] G. F. Abdullah, W. Saman, D. Whaley, M. Belusko, *Life cycle cost of standalone solar photovoltaic system powering evaporative cooler and heat pump water heater for Australian remote homes*, Energy Procedia, Vol. 91 (2016), pp. 681-691.