PV power operation of a solar driven cooling compressor cluster

Battery charging level controlled PV electric energy self-consumption

Omlin L. [1], **Voirol A.** [1], **Gantenbein P.** [1], **Daguenet X.** [1], **Haeberle A.**[1], **Bosshard A.**[2] **and Guentert P.**[3]

[1] SPF Institute for Solar Technology, Eastern Switzerland University of Applied Sciences (OST), Rapperswil

[2] Leutwyler Kühlanlagen AG, CH-8344 Bäretswil (Switzerland)

[3] pg-consult guentert, Colmarerstrasse 14, CH-4055 Basel (Switzerland)

Abstract

A 24 V (voltage) DC driven cooling compressor cluster of two parallel compressors of ($Comp_1$) 1.6 kW_p and ($Comp_2$) 2.5 kW_p cooling power was integrated in a simple cold distribution system for room cooling. A battery and a sensible cold storage allow room cooling in periods of no solar irradiation. The cold distribution is performed through capillary tubes in a cubic duct. The air flow in the duct is sustained through gravitational force i.e. natural convection. To start one of compressors of the cluster the requirement of the min. DC power from the PV field is at least 30 %-50 % of the maximum electric power needed. The compressor cluster operation is battery charging level controlled. A coincidence of available PV power and compressor cluster electric power consumption is in most of the time reached. But at high battery charging level (>75% of max. level) and low PV power the coincidence is interrupted by a switch on of the second compressor to discharge the battery to a level range of 65 % -75 %. Nevertheless a 90 % direct self-consumption of the PV electric energy is reached by the solar compressor cooling system.

Keywords: Cooling cluster, PV solar driven DC compressor, battery level control, natural air convection.

1. Introduction

The cooling demand in the buildings sector will increase in the future and thus the growth of the cooling market is expected. There are many reasons for an increasing building room temperature, such as the growing number of electronic devices, the increased use of large glass facades in the buildings. Due to the climatic changes the share of commercial and residential buildings equipped with cooling systems is expected to increase continuously. To cover the cooling demand in buildings with the available converted solar energy is a sustainable option and has the big advantage of the timely coincidence (IEA SHC Task 53). Fig. 1 shows a close coincidence of solar irradiation, ambient temperature and room air temperature in an office building in Rapperswil (Switzerland). The coupling of a Photovoltaic (PV) field with an electrically driven compressor cooling machine is the concept of solar electric based room air-conditioning (Chen et al. 2020, Liu et al. 2017). PV electrically driven heating and cooling components such as vapour compression heat pumps, chillers or reversible heat pumps in connection with heat and/or cold storages are attractive and sustainable options for the energy supply in buildings. And in case of heating/cooling demand out of solar irradiance a battery can cover the demand if the system is not grid connected. To reduce system costs for example Han et al. 2019 presented a system with impedance matching control strategy without battery i.e. PV direct feed of the compressor. The components comprising a PV electric driven cooling system are market available and the PV market dynamics leads to cost reductions of up to 10 % every year for PV modules. However, still only a few complete system solutions which use photovoltaics for DC driven compressor clusters with a high direct self-consumption are available on the market (Liu et al. 2017).

In this experimental study, the setup of a small scale PV solar cooling system with a DC driven compressor cluster is shown and measurement results are discussed.

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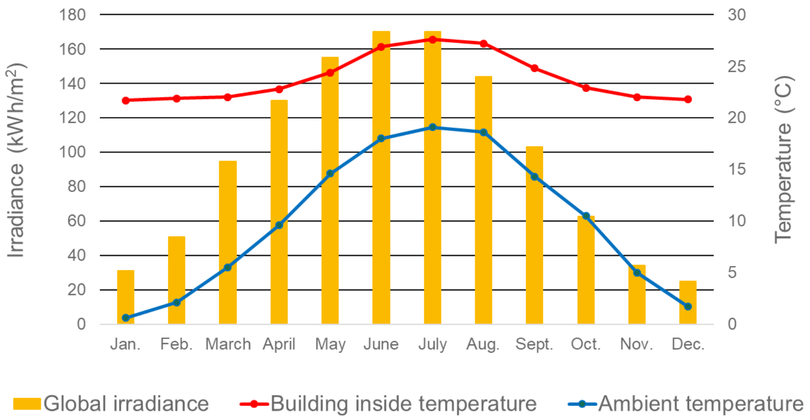

Fig. 1: Weather data and building room temperature: Global solar irradiance, ambient temperature (Meteotest) and the simulated room temperature without cooling of an office building in Rapperswil (Switzerland). A correlation of the temperature curves can be seen and solar irradiation is one of the reasons.

2. Cooling system, system control and data acquisition

An off grid PV driven cooling system (Fig. 2) for room cooling was built in the laboratory. The system consist of a PV field, a DC compressor cluster (two compressors in parallel) which produces the cold energy, a sensible cold storage for shifting the gained cold energy from the day into the night, a battery, and a cold distribution sub-system with two cubic ducts containing capillary tubes. The air flow in the ducts is sustained through gravitational force i.e. natural convection. The battery supplies the DC compressor cluster during short time PV power interruptions due to clouds and to run the cold distribution pump P1 (Fig. 2) during night time i.e. during time of no solar irradiation. In Tab. 1 a summary of the system components, their number in the system and a description is given.

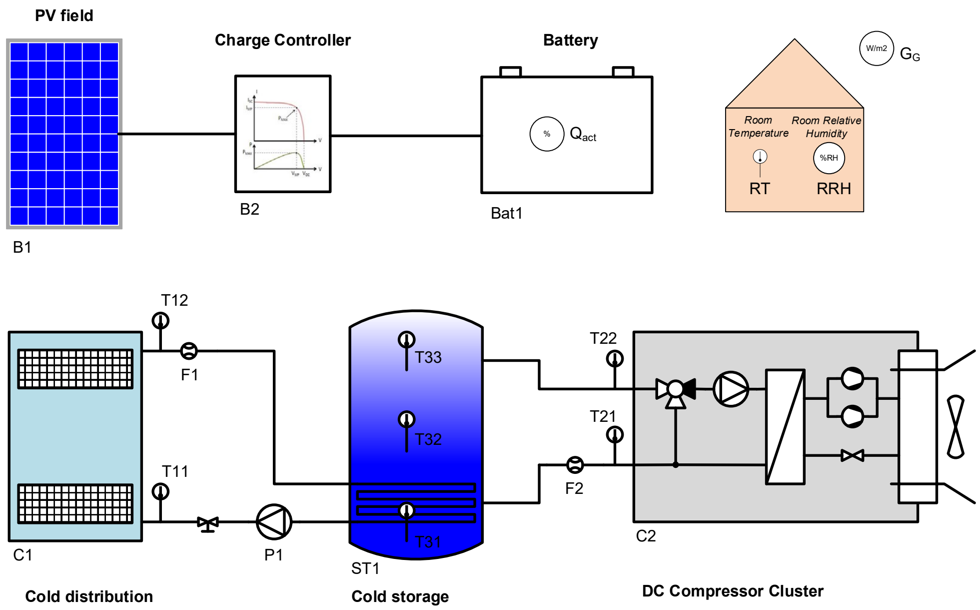

Fig. 2: Schematic of the system: PV field B1, MPP Battery charge controller B2 and Battery Bat1 (above) and cold distribution C1, sensible storage ST1 and DC compressor cluster C2 (below).

Tab. 1: System components

Component	Type and manufacturer	number in the system	Description and parameter
DC compressor cluster (C2)	2 Sierra compressors in parallel (Leutwyler AG)	1	0.5 kW – 6 kW cooling power (modulated)
PV field (B1)	Sky module 270 Wp (Meyer Burger)	6	1.4 kWp (@ STC) [1]
Cold storage (ST1)	Sensible storage TPSK 500 (NIBE)	1	477 liter of water
Battery (Bat1)	Sun power VR M 135/12Volt (Hoppecke)	2	111 Ah / C10 serial connection for 24 V
MPPT battery charge controller (B2)	VT80 (STUDER INNOTEC SA)	1	2500 W
Cold distribution (C1)	cooling shaft (1 x 2 x 0.2 m^3) (Solarfreeze)	2	1 - 4 kW cooling power (16 °C/20 °C; 32 °C / 80 % r.H.)[2]
Distribution pump (P1)	24 VDC solar pump (unknown)	1	800 l/h (max.), Δp 5 m, 22 W
Data acquisition DAQ	LabVIEW® (National Instruments)	1	Own programmed GUI, Computer and I/O hardware

One of the aims of the performed work is a high PV direct self-consumtion, which means, at a defined battery status S, a close to zero I_{Bat} (0 A) current to or from the battery (Fig. 4). And so, to achieve the highest possible direct self-consumption, the current I_{CM} to the cooling cluster has to be close or equal to the current I_{PV} from the PV flied. The measured charging level Q_{Bat} (% of fully charged battery) and battery current I_{Bat} are used as the two input variables for the system control to determine Y_{KM} as the current control output signal (4..20 mA) to the cooling machine. The system control unit regulates the cooling cluster machine (the cooling system) in such a case, that nearly no battery current I_{Bat} is flowing i.e. the current I_{PV} is close to or equal to the current I_{CM}. All the available PV power is used directly in the cooling machine, without temporary storage in the battery.

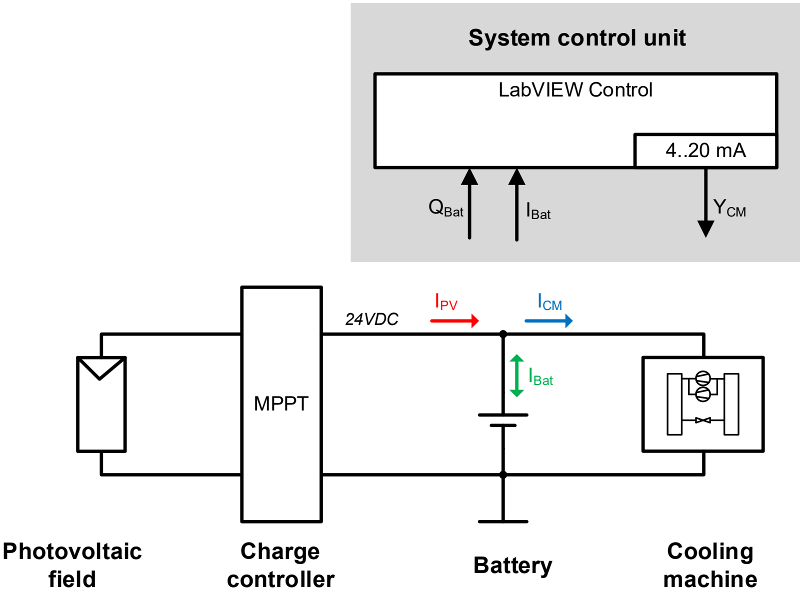

Fig. 4: Schematic of the electric part of the system and the system control unit (PV field current I_{PV}, current to the cooling compressor cluster I_{CM}, current to or from the battery I_{Bat}, battery charging level Q_{Bat}, compressor cluster control current Y_{CM}).

[1] The total peak power of the PV field at standard test conditions (STC) is 1.4 kWp. Due to ageing of the (2nd class) PV modules, the power of the PV field is reduced compared to the initial (new) efficiency indicated in the data sheet.

[2] Cooling fluid temperature inlet to and outlet of the cooling duct capillary tubes heat exchanger, climatic chamber air temperature and relative air humidity.

In case of no solar irradiation and to have an operation of the compressor cluster and/or the cooling fluid pump P1 an arbitrary minimum charging level Q_{Bat_min} of the battery has to be available. This charging level limit is determined according the expected cooling demand after sun set and has the state of charge level SOC = 65 % of maximum of the battery. Due to the behavior (programming) of the solar charge controller, which limits the maximum charge current (I_{PV}) when a certain State of Charge (SOC) level (SOC > 80 %) is reached, it's necessary to keep the SOC of the battery on a lower level, below 75 % of maximum. Summarized, the system control unit keeps the battery level in a range of 65 % - 75 % which corresponds to the battery status S = Okay. Tab. 2 gives a connecting relation of the battery status S, state of charge SOC and the compressor cluster control of the speed n.

There are three battery status S which the battery can assume depending on the SOC. If the battery reaches the battery status "High", the compressor cluster runs at maximum power and thus is reduces the battery level down to the "Okay" range of 65 % - 75 %. And vice versa, if the battery reaches the battery status "Low", the compressor cluster is turned off to charge the battery (from the PV field) up the "Okay" level.

Tab. 2: Control status of the battery

Battery Status S	State of charge SOC	Compressor cluster control
"Low"	< 65 %	"Minimum power, turned off" Comp1(n=0) & Comp2(n=0)
"Okay"	65 % - 75 %	"Controlled power ($I_{PV} = I_{CM}$)" Comp1(n) & Comp2(n)
"High"	> 75 %	"Maximum power" Comp1(n=max) & Comp2(n=max)

The compressor cooling cluster is realized with two parallel compressors of (Comp1) 1.6 kWp and (Comp2) 2.5 kWp cooling power. Both compressors are speed controlled with a minimum switch-on electric power of at least 30 % to 50 % of maximum power. The control of the compressor cluster can be sectioned in three control phases, these are A, B and C. Tab. 2 shows the description and the running status of each compressor and Fig. 5 illustrates this.

Tab. 2: Control phases (time range) of the compressor cluster in operation (Fig. 5)

Phase	Compressor 1	Compressor 2	Description
A	Comp1(n)	Comp2(n=standby)	Comp1 is running in the speed controlled power range but there is not enough energy from the PV field to run Comp2 as well (Comp2 = standby).
B	Comp1(n=max)	Comp2(n=standby)	Comp1 is running on maximum power Comp2 is in standby.
C	Comp1(n=max)	Comp2(n)	Comp1 runs at maximum speed and Comp2 runs at speed controlled range (following the available PV power) .

Fig. 5 shows a theoretical example of the electrical power consumption phases of the compressor cluster. In the control phase A and C the PV power matches the compressor cluster electric power. In phase A compressor 1 (Comp1) runs in a power controlled range, Comp2 is off, and in phase C Comp1 runs at maximum power while compressor 2 (Comp2) runs in a power controlled range. In the control phase B Comp 1 is running on maximum power and the difference to the PV field power is feed into the battery. Comp2 starts (or stops at the end of the day) at the transition from phase B to phase C (transition of phase C to phase B) at a power level 1/3 of its maximum electric power (consumption). In this theoretical example the battery status S is "Okay" for the whole day.

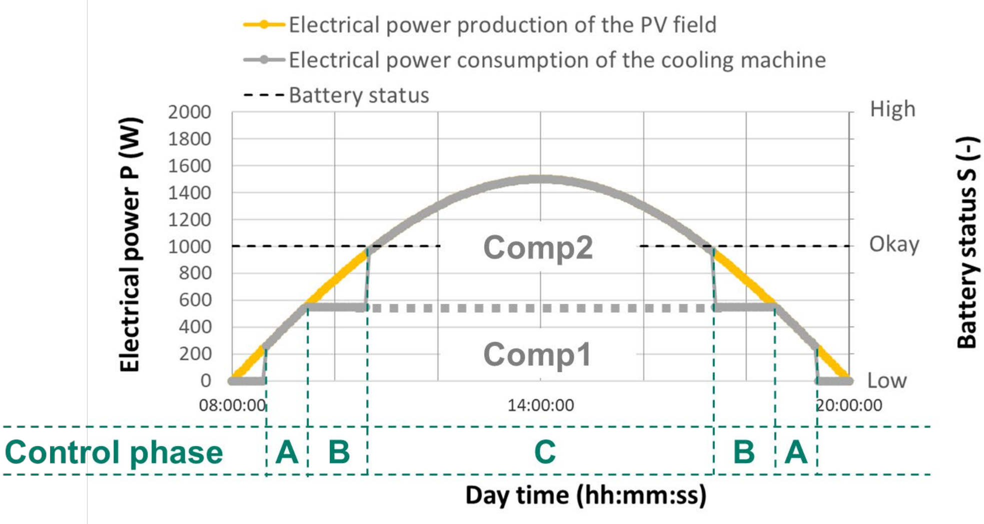

Fig. 5: Performance curve of the cooling cluster: Electrical power production P of the PV field (yellow) and a theoretical possible power consumption curve of the cooling cluster of two compressors (grey) at a sunny day. On the second vertical axis the battery control status S is shown.

3. Measurement results

Fig. 6 and 7 are showing measurement results acquired at the 27th of May from 08:00 o'clock in the morning till 20:00 o'clock in the evening. The compressor cluster is running from 09:00 o'clock until almost 19:00 o'clock in different control phases.

The power consumption of the cooling machine is not congruent with the power production of the PV field. There are many broad peaks during the control phase B, which can be explained by a battery status induced battery discharging (Figure 7) and a running of Comp2. In phase C many negative power spikes of the compressor cluster are visible. These spikes are not finally investigated. We assume that they stem from over temperature and over-pressure compressor cluster turnoffs.

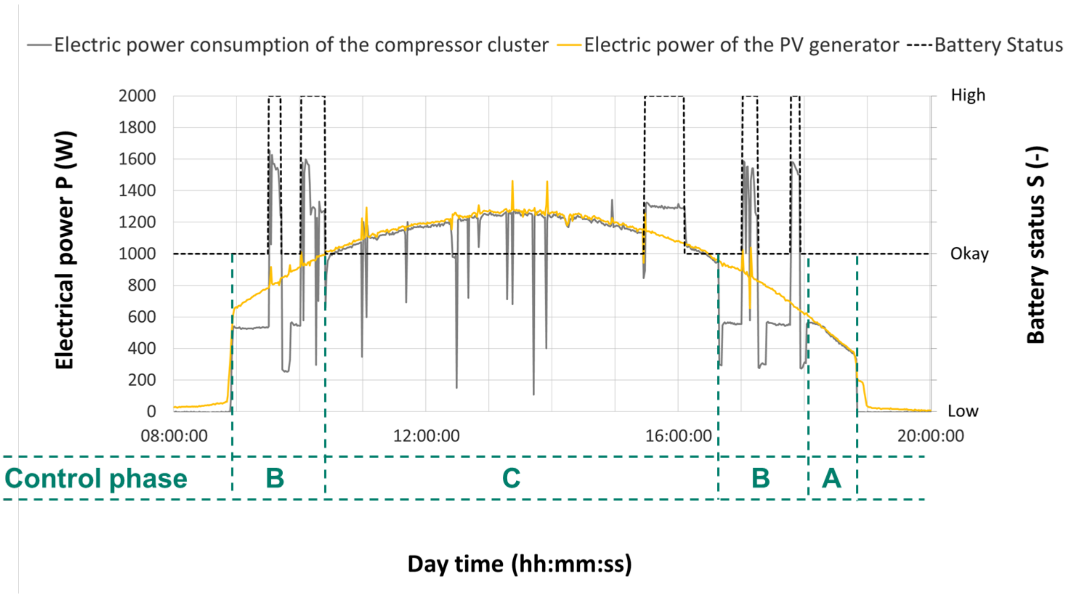

Fig. 6: Measurement results at the sunny 27th of May 2020: The yellow curve shows the PV power production. The grey curve shows the power consumption of the compressor cluster and the dashed grey curve the battery status S.

At the beginning of the first control phase B, when the battery status S is "Okay", we can see that a positive battery current is charging the battery. This leads to an increasing battery SOC until the battery status S changes from "Okay" to "High". After both compressors of the cluster are switched on a negative battery current flows out of the battery and into the compressor cluster. The battery status turns back to "Okay". During the control phase A and C the battery current is controlled to zero with many spikes in phase C. This spikes, which are charching the battery, are the reason for the battery discharging phase in the time range of 15:30 o' clock and 16:10 o'clock.. In times where the battery current I_{Bat} is zero (0) the electric current from the PV field I_{PV} is equal the electric current I_{CM} to the compressor cluster.

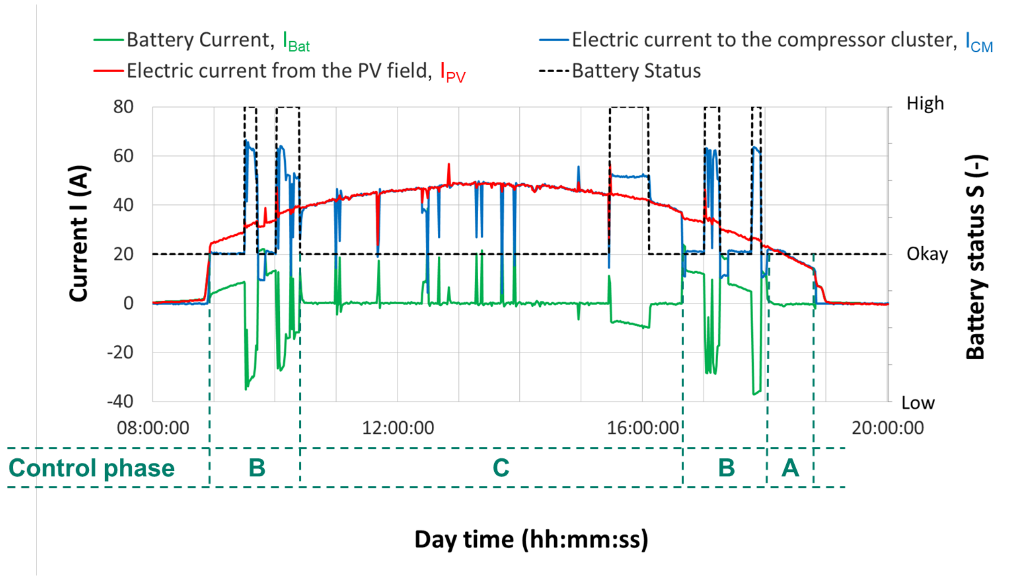

Fig. 7: Electrical currents I and battery status S: Electric current from the PV field (red), electric current to the cooling compressor cluster (blue) and controlled battery current (green) in function of time. In the case of 100 % of direct self-consumption the battery current is zero. The battery status S shows the charging level of the battery – where "Okay" for S can be set arbitrarily.

4. Discussion and Outlook

A solar electric cooling system with a DC driven compressor cluster was set up and measurements were performed. With the battery (storage) to supply the cooling fluid pump with electric energy and the sensible cold storage the option for room air-cooling in times of no solar irradiation is available. The results show electric power peaks during operation (i.e. current peaks) due to battery discharging and compressor over-temperature and overpressure reasons. Most of the operation time, a coincidence of electric current from the PV field and electric current to the compressor cluster was observed. A PV energy self-consumption higher than 90 % was reached.

The operation has to be optimized towards a higher direct self-consumption, through the avoidance of peaks in the electric current, with a better system control program (and adjusting battery size and charging level S "Ok"). A scaling for a pilot system with a power up to several 10 kW – is aimed in the future. And with the help of a numerical model the battery size (Ah) and battery status S (-) will be better adjusted to the systems needs.

5. Acknowledgments

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6. References

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