Architecture and Performance of a Power Management System for Multiple Compressor Solar Ice-makers

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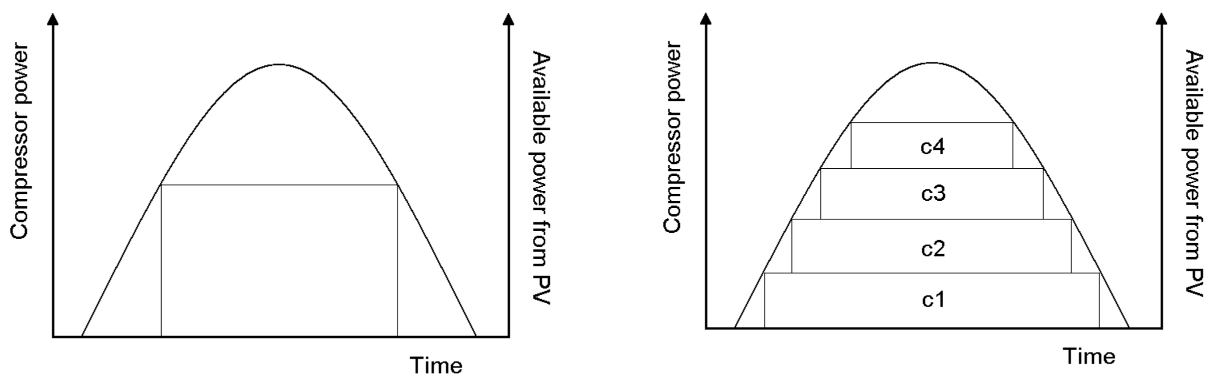
Abstract: - A power management system is presented for the control of multiple compressors driven by photovoltaic panels, which allows for maximum exploitation of the solar energy. The system finds application in batteryless refrigeration/heating arrangements with variable speed compressors. The operation of the system is based on an efficient compressor startup circuit, a maximum power tracking subsystem and a smart control pattern for the number of operating compressors and their speed. A prototype system was built for a solar ice-maker and exhibited near-excellent energy utilization.

Key-Words: - Compressors, ice-maker, refrigeration, solar, photovoltaic, control

1 Introduction

Direct-current (DC), variable speed compressors are becoming increasingly dominant in small scale refrigeration and heat pump systems, especially in photovoltaic (PV) panel operated ones [1-4]. It has been shown in [5] that commercial models of such compressors might not, although meant to, operate efficiently when used directly with solar panels; startup difficulties and power management issues arise in this case. In the same work, a control system was proposed for the enhancement of the efficiency of these compressors when driven by solar panels. In the current work a control system is proposed for the operation of multiple compressor systems.

There is a number of reasons why multiple compressor systems may present advantages over single compressor systems. One advantage is that a much wider control range can be achieved. Even with fixed speed/power compressors, the utilization of energy from a variable power source, like PVs, is increased dramatically when using many small compressors instead of one large compressor (Fig.1). The same applies to systems with variable speed compressors. For example, a single variable speed compressor can operate at a minimum power of 50% of its rated power. A system of four small, similar compressors, each rated at ¼ of the single compressor power, will have a total minimum power of operation of 12.5% of the total rated power, since it is possible to operate only one compressor at 50% of its rated power. Another advantage is that the static friction of small compressors is lower than that of large compressors and, as a result, a multiple compressor system has lower startup power requirements. This is of great importance to solar



(a) (b)

Fig.1. Energy utilization with multiple compressors. (a) Large compressor, (b) multiple small compressors. Thick line: solar irradiance, thin line: compressor power.

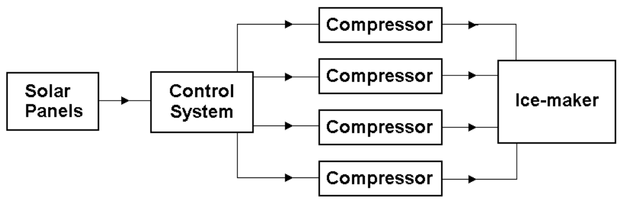


Fig.2. Block diagram of the arrangement under study.

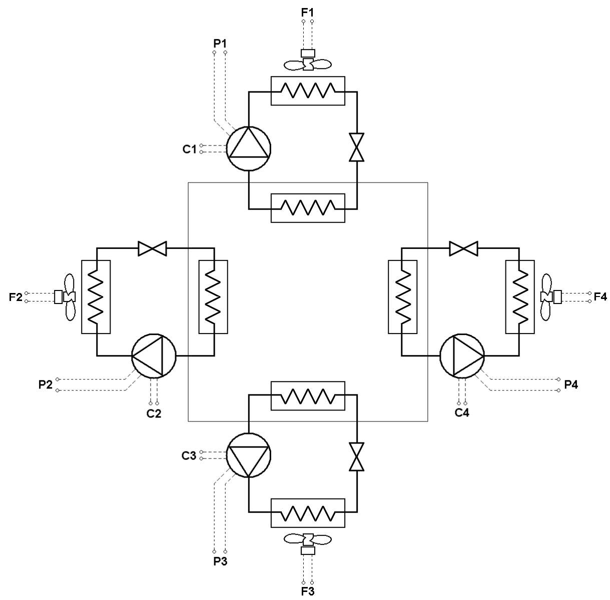


Fig.3. Schematic representation of the refrigeration system.

systems, where there is a need for maximum exploitation of the available solar energy. Finally, a multiple compressor system exhibits a much higher degree of fault tolerance than a single compressor one since it will sustain the presence of a number of compressor faults before it becomes inoperative.

The proposed control system for the operation of multiple compressor systems was developed for a solar driven ice-maker. The system is generally based on that presented in [5], however with some enhancements and with a developed control strategy and circuit architecture for multiple compressor operation.

Figure 2 shows the block diagram of the entire system. Four compressors make up the refrigeration system (see Figure 3 for details) and are being driven by a control system, which in turn is fed by the solar panels.

2 The Refrigeration System

Figure 3 shows the refrigeration system. Four cooling circuits are used to cool down a tank within which water is gradually converted to ice. Each cooling circuit consists of a compressor, an evaporator, an expansion valve and a condenser with its fan. The fan is of the brushless type and has a supply voltage of 12Vdc.

2.1 DC compressors

The compressors are the BD35Fsolar from Danfoss and have an input voltage range of 10-45Vdc (supplied at P1-P4 in Figure 3). This compressor has a speed control input (ports C1-C4 in Figure 3). A resistor connected to this input will set the compressor speed. Resistor values of 170 Ω to 1.7 kΩ correspond to speeds of 2000 rpm to 3500 rpm respectively. In our previous work [5] a 16-step digitally control resistor was used for speed control. In the current work a 2-step resistor is used along with a hysteretic control scheme. Figure 4 depicts the principle this of operation. A resistor that corresponds to the highest compressor speed is connected to the control input. When the compressor speed exceeds the desired mean speed by a determined hysterisis band, the computer connects a resistor that corresponds to minimum speed. Again, when the compressor speed falls below the desired mean speed by the hysterisis band the computer sets the control resistor to its maximum value, and so on. This process is mainly sustained due to the appreciable delay of speed change of the compressor, largely dependant on the compressor's embedded electronic unit.

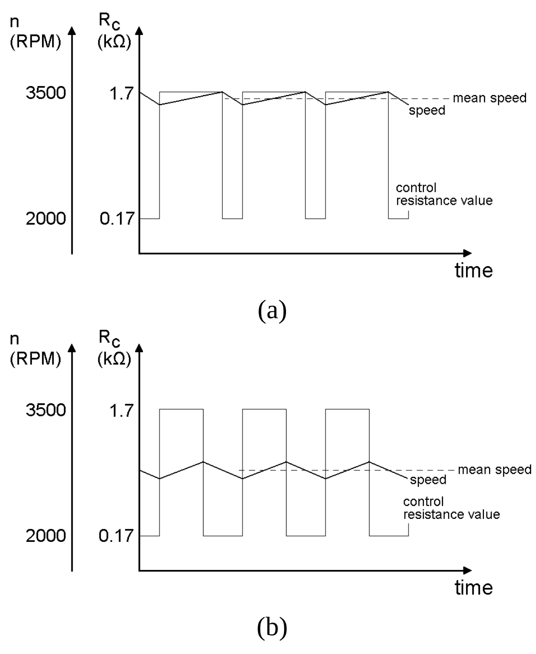


Fig.4. Hysteretic control of the compressor speed.

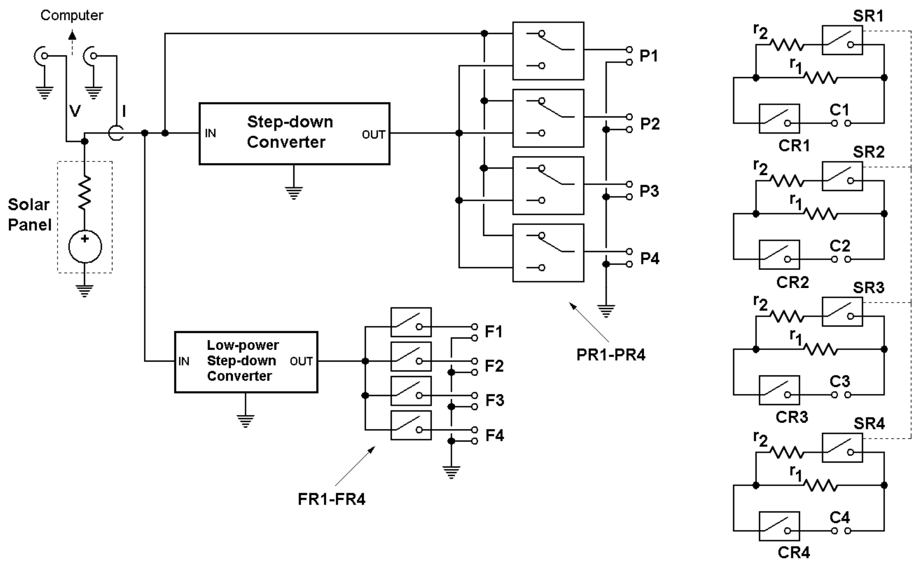


Fig.6. Schematic representation of the control system.

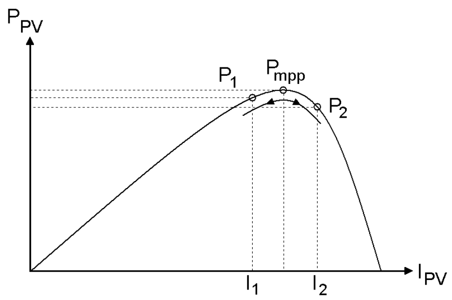


Fig.5. Maximum power traking.

Figure 4(a) shows a situation where the speed setting resistor is 1.7 kΩ for most of the switching period and so the compressor speed is high, whereas Figure 4(b) shows a situation where the speed setting resistor switches between 1.7 kΩ and 170 Ω almost every half-period and so the compressor speed is medium.

In fact, it is not the average speed that is being controlled rather than the average compressor current, which is roughly proportional to the compressor speed. The computer controls the current in order to achieve maximum power transfer from the solar panels. Figure 5 depicts the process. The computer injects perturbations in the compressor speed and therefore in the compressor current. It then measures the solar panel power (see sensors in Figure 6) and using a dedicated algorithm tracks the value of the current (eventually of the speed) for which the maximum power point occurs.

3 The Control System

Figure 6 shows the schematic of the control system. At the left side of Figure 6 lie the solar panel and the measuring points for the panel's voltage and current, used to determine the power drawn from the PV panel.

A low-power Step-down converter is used to convert the solar panel voltage (36V nominal) into the 12V needed for the condenser fans. The fan relays, FR1-FR4, are controlled by the computer and are used to enable each fan only when the corresponding compressor is in operation. Each fan requires around 3W of electrical power. The voltage conversion performed by the low-power Step-down converter is highly efficient (>85%) as it is based on a switch-mode circuit.

3.1 Speed control relays

On the right side lie the relays that control the compressors' speed. All these relays are controlled by a computer. Ports C1 to C4 are connected to each compressor speed control input (see Figure 3). The control relays, CR1-CR4, are used to enable/disable each compressor separately. The speed relays, SR1-SR4, are used to vary the speed setting resistance from 0.17 Ω to 1.7 kΩ (Fig.4). These relays are ultimately responsible for controlling the compressors' speed and therefore for tracking the maximum power from the solar panels. These relays are required to sustain a very large number of ON/OFF cycles. This leads to the use of solid-state type of relays. The dashed line connecting SR1 to SR4 reveals that all four relays are controlled by the same signal from the computer, which means that all four compressors are driven at the same speed. The reason for choosing this kind of operation will be explained in Section 4.

Step-down converter

A very important part of the system is the Step-down converter, used for the startup of the compressors. It was shown in [5] that this converter considerably aids the startup of the compressor by compensating for the startup transients and by performing an impedance conversion. By matching

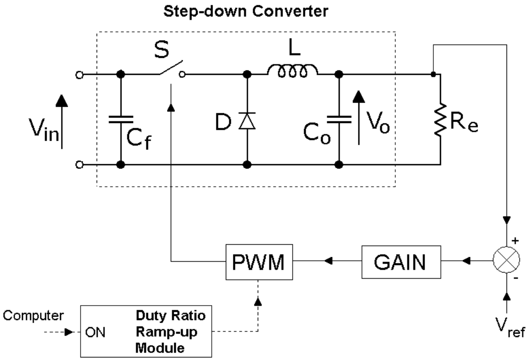


Fig.7. Step-down converter

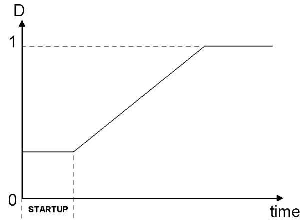


Fig.8. Duty ratio ramp-up.

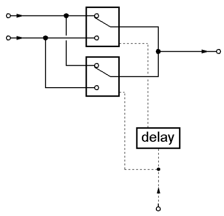


Fig.9. Detailed schematic of a power relay.

the solar panel's effective output impedance to the compressor's effective impedance at startup, the latter can start operating without the use of large capacitors or oversized solar panel and with a relatively low value of solar irradiance.

Figure 7 shows the schematic of the converter. A closed-loop, Step-down converter, fed by the solar panel (V_{in}), supplies the effective compressor load, R_e. It has been found that, for the specific compressor model, the optimum way to compensate for the startup transients is to design the converter to deliver 10 V at the compressor using a proportional only control loop of relatively high gain.

Although based on a switch-mode circuit, the converter does not exhibit 100% efficiency. The same applies for the low-power converter used to supply the fans. However, the power handled by that converter is very low compared to the power delivered by the solar panels. There needs to be a way for the main converter to be overridden after each compressor startup so as to avoid the electrical power losses associated with its operation. The compressors can then be connected directly to the solar panels, since they can handle an input voltage range of 10-45 V (a switch-mode converter for this purpose is already built inside the compressor unit). Apart from increasing the overall system efficiency, this method lowers the cost of the converter, since the latter will be used to start one compressor at the time and will only be required to handle the power drawn by one compressor only.

Overriding the converter with a simple relay contact between input and output would cause a significant compressor input voltage transient, from 10 V to whichever the solar panel voltage would be at that time. The best way to override the converter is to raise its output voltage until it becomes equal to the input voltage. A changeover relay contact (power relays PR1-PR4 in Figure 6) can then be used to disconnect the individual compressor from the converter and to connect it directly to the solar panel. This process must be performed after startup, since during startup the converter output voltage must be maintained at around 10 V, as explained above. A dedicated control unit, named 'duty ratio ramp-up module' in Figure 7, is responsible for interrupting the converter's closed-loop and imposing a slow increase of the converter's output voltage by means of increasing the duty ratio (Fig.8) of the switch *S*. This operation is performed upon a computer-generated command.

3.3 Power relays

As explained in the previous section, the power relays, PR1-PR4 in Figure 6, are used to perform the overriding of the main Step-down converter. The symbol for the relays in Figure 6 does not represent the actual circuit. A simple changeover contact would not be sufficient to perform the operation because of the finite time spent for the contact to travel between the two positions. This time is normally in the order of a few tens of milliseconds, typically 20 ms. During this time the compressor is not actively supplied and relies on its internal capacitor in order to keep operating. This capacitor is not sufficient to maintain the compressor's operation; a relatively large external capacitor is required. The relay configuration shown in Figure 9 is used in order to avoid the use of an external capacitor at all. When the control signal arrives one contact travels from the converter output to the solar panel while the second contact remains unaffected, thus leaving the compressor supplied from the converter while the first contact is 'dead time'. After a preset delay the second contact travels too to the solar panel position. This is done after the first contact has settled, so that during the 'dead time' of the second contact the compressor is supplied by the

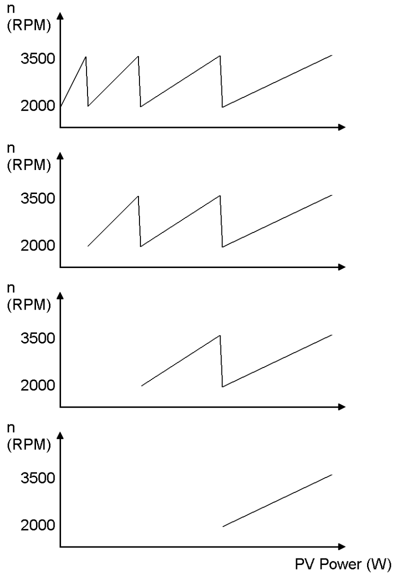


Fig.10. Compressor speed control pattern.

COP (EN 12900 Household/CECOMAF)

rpm \ °C	-30	-25	-23.3	-20	-15	-10	-5	0	5	7.2	10	15
2,000	0.90	1.02	1.06	1.15	1.31	1.48	1.67	1.87	2.08	2.17	2.29	
2,500	0.87	0.97	1.01	1.09	1.24	1.41	1.60	1.80	2.02	2.12		
3,000	0.75	0.90	0.95	1.06	1.22	1.39	1.58	1.78				
3,500	0.73	0.84	0.89	1.00	1.17	1.36	1.55					

Fig.11. Coefficient Of Performance (COP) variation with speed for a given evaporation temperature.

solar panel. After the changeover from the converter to the solar panel has completed the converter is completely disconnected by the individual compressor, its closed-loop control is recovered and it is ready to perform the startup of another compressor. One should take into account that, although all the compressors are initially connected to the converter output, only the compressor whose control relay (CR1-CR4 in Figure 6) is activated will start operating.

4 Control Algorithm

4.1 Speed control pattern

The power drawn by each compressor is roughly proportional to its speed. Therefore, in order to adapt the compressors to the solar panel one needs to modify the compressors' speed according to the available power. For a single compressor this function can be performed through the maximum power tracking control mentioned above. However, when multiple compressors are operated at the same time, one needs to consider a suitable pattern of operation, along with maximum power tracking.

Figure 10 shows the proposed compressor control pattern. At low PV power levels only one compressor can be started and operated. As the power level increases the compressor's speed is increased automatically by the maximum power tracking control. At some point in time the compressor reaches its maximum speed. In order to start a second compressor one would have to wait until the PV panel provided another 50-60 Watts, which are required for the second compressor startup. In the mean time the first compressor would not be capable of utilizing the extra energy since it is driven at maximum speed, which means that there would be underutilization of the PV generated energy. If, for instance, the first compressor reached maximum speed and then the PV supplied an excess power of only 40 W for one hour (due to environmental conditions) there would be 40 Whr unused. It is therefore proposed here that the first compressor speed should fall to minimum (right after it reaches maximum speed) in order to leave an available power level for the second compressor to start. In this way the second compressor can start immediately after the first one reaches maximum power (Fig.10). If excess power is available, both compressors will speed up to their maximum speed and the previous procedure will be repeated with the third compressor. Figure 10 shows that the speed-up rate (with regard to power increase) decreases as more compressors become active.

The above described operation is more efficient not only due to better energy utilization but also due to the characteristics of the compressors. The compressors are characterized by a higher value of Coefficient Of Performance (COP) at low speeds. Figure 11, [6], shows the variation of this coefficient with speed for a given evaporation temperature. Since this temperature remains roughly constant throughout the ice-maker operation, it is desirable to have all compressors driven at the same speed rather than having some at their maximum speed and modifying the speed of the last one according to the available power.

4.2 Main algorithm

Figure 11 shows a general view of the main control algorithm for the system. This algorithm is run by a computer. The computer measures voltage and current from the system and outputs commands to it via a National Instruments interface card.

The first program stages handle the compressors' startups and cutouts. First, the solar irradiance is measured via a pyranometer (this is not shown in the previous figures). The number of compressors that

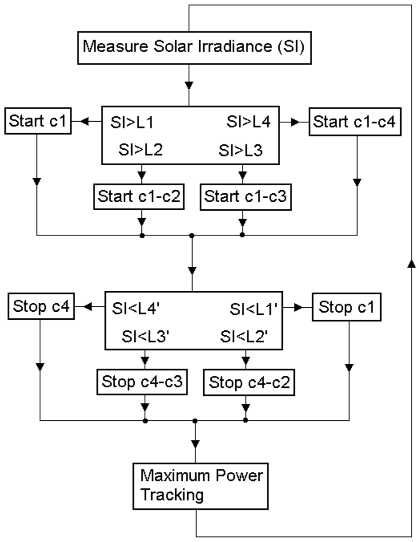


Fig.11. Main control algorithm.

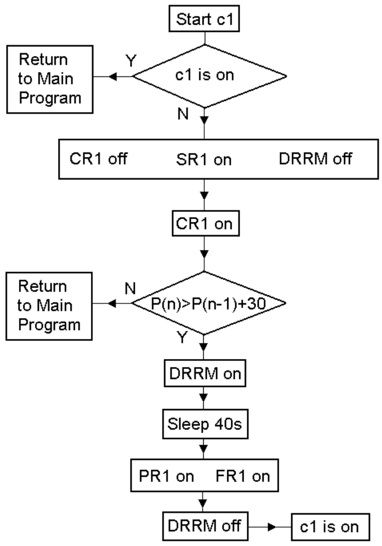


Fig.12. Startup procedure for compressor #1.

may be started at any time is determined by the level of solar irradiance. Limits on the level of solar irradiance, *L1-L4*, have been established so that the startup of the compressors is guaranteed. Four more limits, *L1'-L4'*, have been established to ensure proper compressor cutouts. It is important for the compressors to be force-stopped rather than to let them stop due to low PV power. The power transient caused by a compressor cutout is quite significant and may affect the operation of the rest of the compressors. If, for instance, three compressors are operating and suddenly the solar irradiance falls to a level that can support only two compressors, then, if one compressor stops due to the supply insufficiency it might induce such a transient on the supply line as to eventually cause all the compressors to cut out. The problem is alleviated by stopping the compressor (via its control input) before the solar irradiance reaches a critically low level. The above limits are set so as to guarantee an in-time compressor cutout.

The following stage is the maximum power tracking stage, where the speed of all four compressors is adjusted in order to draw maximum power from the PV. This function lasts for a few milliseconds and then the program loops back to the beginning.

4.3 Startup algorithm

Figure 12 shows the details of the startup algorithm for one compressor. The respective algorithms for all four compressors are identical.

A verification is made first, as to whether the compressor is already operating, so as to avoid restarting. It is then ensured that the compressor control (C1) and the duty ratio ramp-up module (DRRM) are disabled and that the speed-control relay (SR1) is set for minimum speed. Since the DRRM is off, the converter operates with its compensating loop to provide a steady 10 V output. The control relay CR1 is then enabled and the compressor starts at 2000 rpm. If the compressor does not cause a significant increase in the measured power it is judged that the startup has failed. This could happen if the solar irradiance decreased shortly after it was measured and judged to be sufficient by the main program. If the compressor starts successfully the DRRM is enabled in order to raise the converter's output voltage and then (after 40 s) the power relay PR1 connects the compressor directly to the PV. The condenser fan is also enabled via FR1. Finally, the state of the compressor is registered for future use.

5 Experiments

A prototype control system was built and connected to a 440Wp solar panel and four BD35F type compressors. The experiments were performed in Athens on 17-11-2006, with the solar panels at an optimum tilt angle and a 20° south-west orientation.

Figure 13 shows the response of the prototype system to transients. At around 10:00 the system is started (a) and the program commands the startup of two compressors, based on the level of the solar irradiance. The first compressor reaches 50 W and then follows the ramp-up of the DRRM, which lasts 40 s (b). During this period the compressor power varies lightly due to the response of the compressor imbedded power converter. At point (c) the second compressor starts and adds another 50 W to the drawn power. Both compressors are operating at 2000 rpm. At point (e) the maximum power tracking algorithm takes control and adjusts the compressors' speed (and therefore power) so as to achieve maximum power drawn from the PV. At point (g) there is a sudden increase in solar irradiance and the main algorithm commands the startup of a third compressor, which lasts another 40 s (h). Maximum power tracking resumes at (i) and the system settles to around 225 W (j). The system seems to respond as desired.

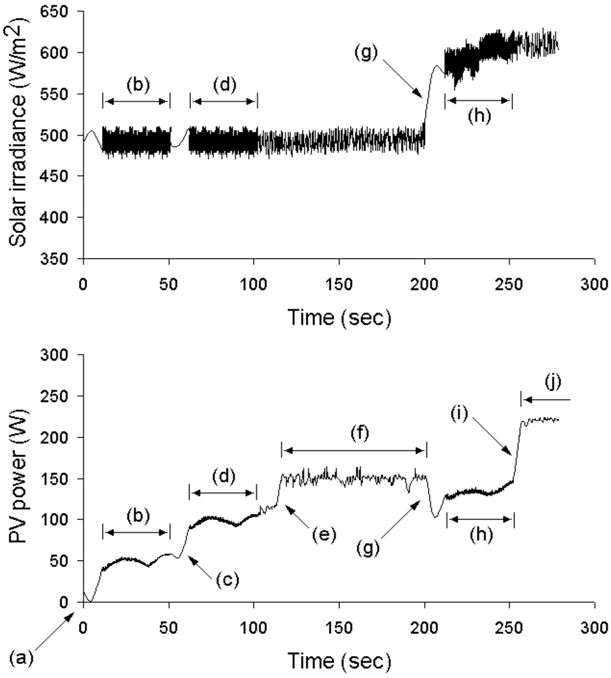


Fig.13. Transient performance of the prototype system.

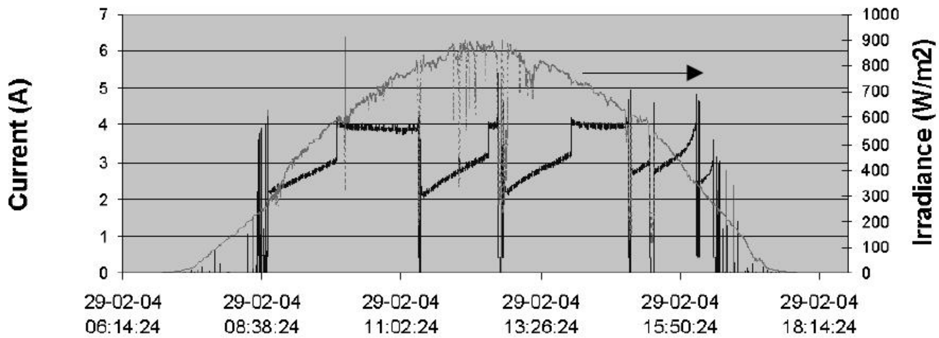


Fig.14. Experimental results from [2]. Single compressor using the manufacturer control unit.

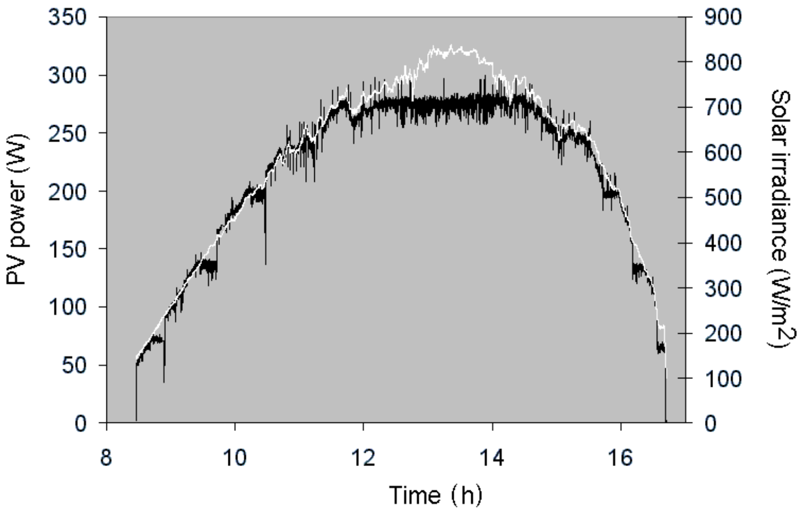


Fig.15. Experimental results from the prototype with the proposed system. White trace: solar irradiance, black trace: PV power.

The noise seen on the upper plot during periods (b), (d) and (h) is due to the converter duty ratio ramp up and the noise during periods (f) and (j) is due to the maximum power tracking control. The pyranometer amplifier handles extremely low voltages and is prone to interference. The noise was greatly reduced in the second experiment.

Figure 15 shows the system performance throughout a day's operation. The first compressor starts operating at around 8:30, quite early for a November day. The startup is significantly aided by the dedicated startup converter described above. A single high power compressor without a startup system would have required a solar irradiance of at least 400W in order to perform a startup. Right after startup the compressor enters the maximum power tracking mode. It is visible that there is a convergence of the supplied PV power and the solar irradiance curves. Since the available PV power is almost proportional to the solar irradiance one may directly reach to the conclusion that all the available PV power is being drawn from the PVs and delivered to the compressor.

After a small period of time the second compressor is started. This is visible as a short/sharp reduction in power at around 9:00. That is where the system decides to lower the speed/power of the first compressor to minimum so as to gain a power margin for the startup of the second compressor. Again, right after startup of the second compressor, the two compressors enter the maximum power tracking mode and precisely follow the available PV power. The same is done with the rest two compressors. Between 12:00 and 14:00 the system does not exceed a maximum power, which corresponds to the total rated power of the compressors. The PVs are slightly oversized, which fact gives an advantage in early startup and in the operation on cloudy days.

The same operation pattern is followed during the descent of the solar irradiance. One may notice small steps in the PV power curve at each compressor startup/cutout. These where intentionally left to show the startup points and the similarity with Figure 1(a) (that figure however assumes no speed control of the compressors). The steps in the power curve and can be reduced by changing the limits L1-L4 and L1'-L4', mentioned above.

Figure 14 shows the results from the work done in [2] (a single compressor for a solar refrigerator, controlled by its built–in unit) and is used as an example for comparison. The compressor current is shown in this case bust since the compressor operates with fixed supply voltage, the power curve would have the same shape as the current curve. It is evident that the energy utilization in this case is very much lower than that with the multiple compressor arrangement controlled by the proposed system. More details on the disadvantages of the compressor built-in unit can be found in [5].

6 Conclusions

A system architecture and a control scheme have been proposed for the operation of multiple compressors driven by PV panels. A power converter is shown to provide easy startups for the compressors and a converter overriding system in conjunction with a converter duty ratio controller are successfully used to achieve the loss-free operation of the system under steady state. The combination of a maximum power tracking loop with a smart speed-control scheme is shown to result in an advantage for the compressors' coefficient of performance. The experimental results revealed the reliability of the control system under transient situations and its advanced energy utilization performance.

7 Acknowledgements

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