Control System for a Multiple Compressor Ice-maker Driven by Photovoltaic Panels

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Abstract: - The present paper describes the architecture of a control system that may be used for the efficient operation of multiple compressors driven by photovoltaic panels, without batteries. The compressors under control are direct-current, variable-speed ones. In this work are presented circuit arrangements and control schemes that can be followed so that the system exploits the maximum possible solar energy and exhibits reliable operation under transient conditions.

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. For example, a single compressor has a minimum power of operation of 50% of the 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 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, as shown in Figure 1. 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 1 shows the block diagram of the entire system. Four compressors make up the refrigeration system (see Figure 2 for details) and are being driven by a control system, which in turn is fed by the solar panels.

2 The Refrigeration System

Figure 2 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.

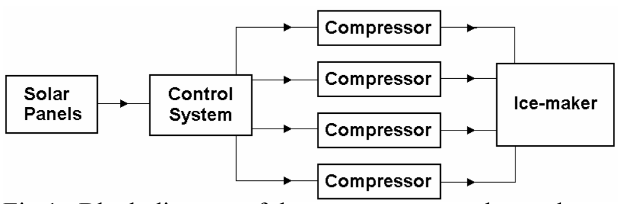

Fig.1. Block diagram of the arrangement under study.

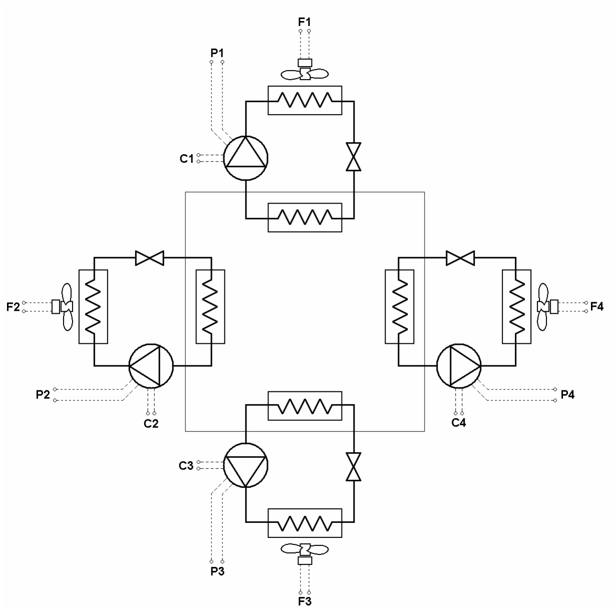

Fig.2. Schematic representation of the refrigeration system.

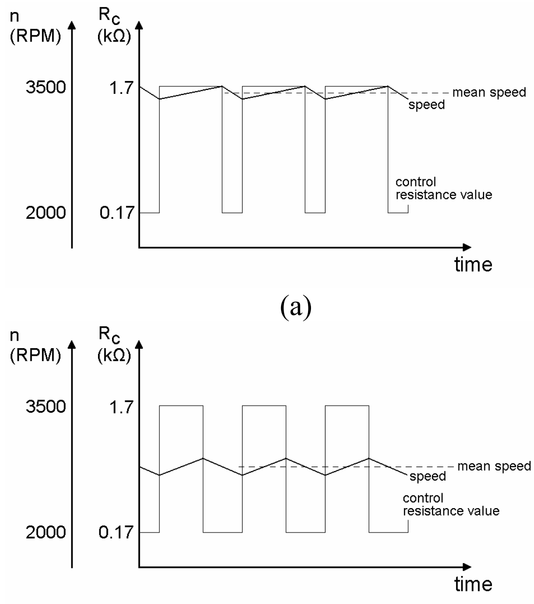

Fig.3. Hysteretic control of the compressor speed.

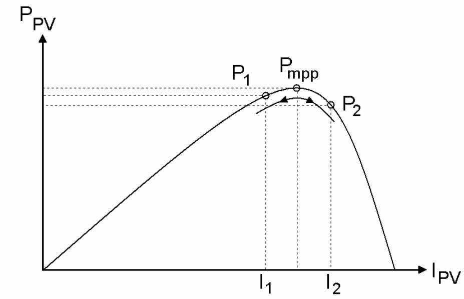

Fig.4. Maximum power traking.

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 2). This compressor has a speed control input (ports C1-C4 in Figure 2). 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 3 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.

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 4 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 5) 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 5 shows the schematic of the control system. At the left side of Figure 5 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.

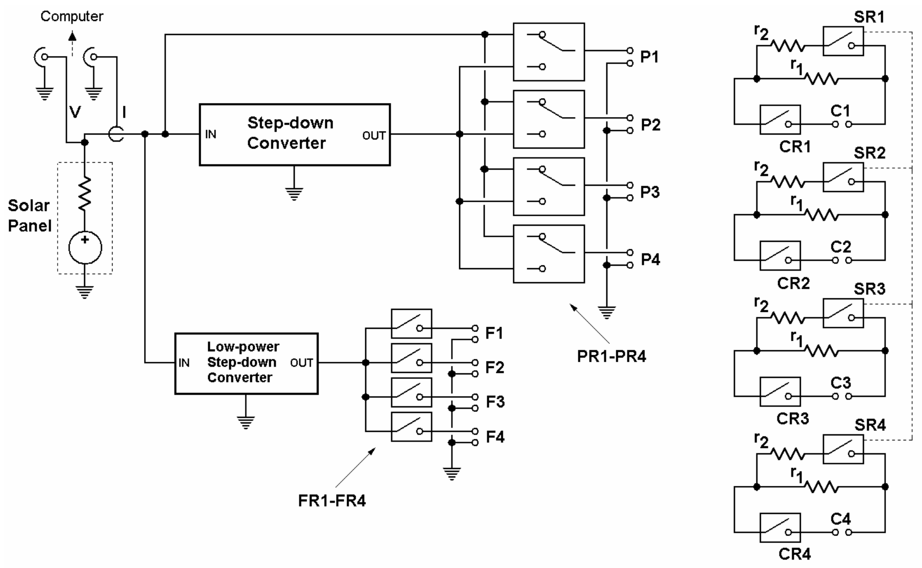

Fig.5. Schematic representation of the control system.

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 2). 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.3). 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.

3.2 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 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 6 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 5) 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 6, 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.7)

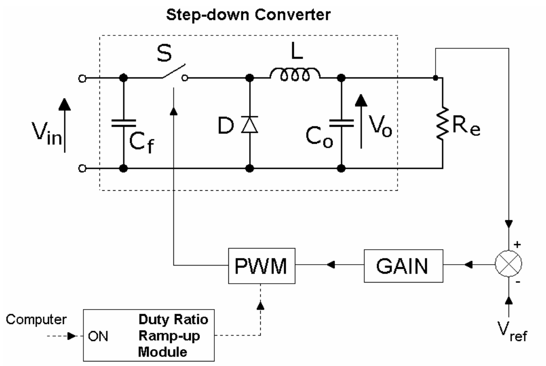

Fig.6. Step-down converter

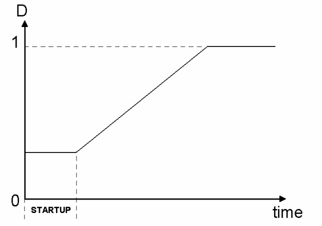

Fig.7. Duty ratio ramp-up.

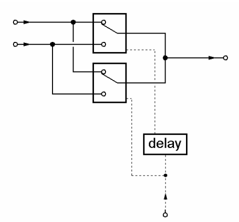

Fig.8. Detailed schematic of a power relay.

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 5, are used to perform the overriding of the main Step-down converter. The symbol for the relays in Figure 5 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 8 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 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 5) 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 9 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.9). If excess power is available, both compressors will speed up to their maximum speed and the previous procedure will be repeated with the

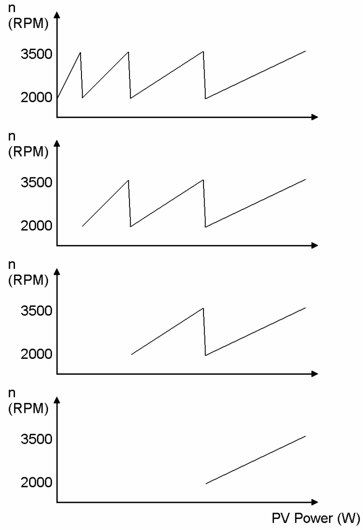

Fig.9. Compressor speed control pattern.

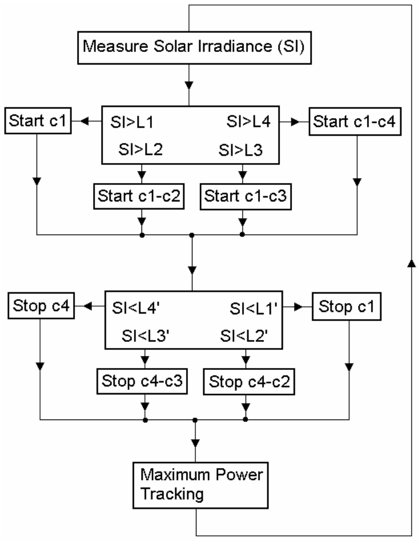

Fig.10. Main control algorithm.

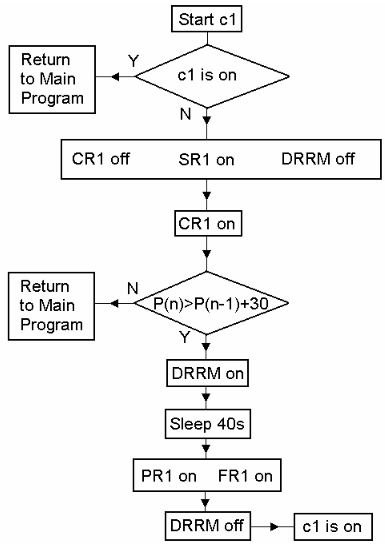

Fig.11. Startup procedure for compressor #1.

third compressor. Figure 9 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. It is therefore 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 10 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 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 11 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.

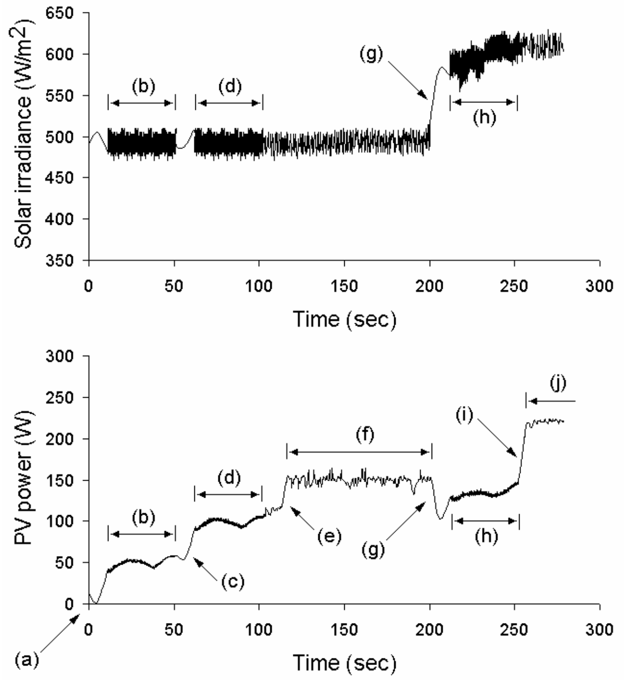

Fig.12. Experimental system operation.

5 Experiment

Figure 12 shows the operation of the prototype system and its response upon a number of situations. The prototype is connected to a 440Wp solar panel and four BD35F type compressors.

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.

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.

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 guaranteed 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. A maximum power tracking loop along with a smart speed-control scheme are shown to enhance the system performance. Finally, the developed software was found to reliably operate the compressors at steady state and under environmental transients. More results are expected from the long run of the system.

7 Acknowledgements

This work is co-funded by 75% from the European Union and 25% from the Greek Government under the framework of the Education and Initial Vocational Training Program – Archimides.

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