Innovative design controller for PV operated compressors

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Abstract: - This paper identifies weak points in the control of commercial DC variable-speed compressors, fed by photovoltaic panels, and describes the development of an energy-efficient control method. The method can be used in any application requiring such compressors to be driven by PV's, either for heating or cooling purposes. The advantage of using the presented method is the improved utilization of the PV electric energy, achieved by modifying the compressor startup characteristics and exploiting the maximum power of the PV.

Key-Words: - compressor, PV, control-capacity, startup, maximum power tracking

1 Introduction

The new trend in solar operated or assisted thermal systems is to incorporate the use of a direct current, variable-speed compressor. It has been shown in several research works that there occur reasons why compressors with capacity control offer distinct advantages over compressors with fixed capacity, especially concerning energy management and overall system efficiency [1],[2],[3],[4]. There have, therefore, emerged commercial compressors with the above mentioned capability for use in relevant applications. While the compressor’s technology can be applied to freezers, refrigerators and air conditioners systems, initial efforts, in the past, have focused on small-scale heaters for hot water production [5],[6],[7]. A very successful series of such compressors is the solar BDxx series from Danfoss, which have found use in a wide area of applications. However, certain operational characteristics of these compressors set restrictions on the utilisation of the electric energy supplied by the PV in batteryless applications. These are namely the startup characteristics and the speed control of the compressor.

While dedicated electronics integrated with the compressor frame hold the control of the compressor, the startup problem, met with all kinds of motors, is not adequately dealt with. A typical user relies on the control electronics for the operation of the compressor and does not realize the reduced energy utilization due to startup problems. Others have noticed the demand of the compressor for excessively high startup current and have dealt with it by installing oversized energy storage capacitors and by selecting a PV with a short circuit current much higher than that required by the compressor [2]. The result is a considerable increase of the system cost and the irrational use of the available solar energy. In a similar way as above, the user of such a compressor again relies on its control electronics for the utilization of the PV energy while at steady state and under all loading or environmental conditions. It is however found that the compressor control electronics drive the compressor in a way that changing environmental conditions can dramatically degrade the total system efficiency and performance.

Since PV installations are capital-intensive, every measure must be taken to operate PV driven equipment with as much as possible available solar energy. The aim of this work is firstly to identify in detail the problems of a specific series of commercial compressors and then to propose a control method for the compressor’s electronics in order to alleviate the above-mentioned problems of performance degradation. Improved utilization of the solar energy is also achieved by varying the compressor's capacity to match the available power from the PV panels. An external to the compressor prototype system, using the proposed method, is presented and it is shown that it can be implemented by the existing dedicated electronics integrated with the compressor. Indicative measurements from the prototype justify its improved energy utilization, especially during low irradiance days or repetitive irradiance changes.

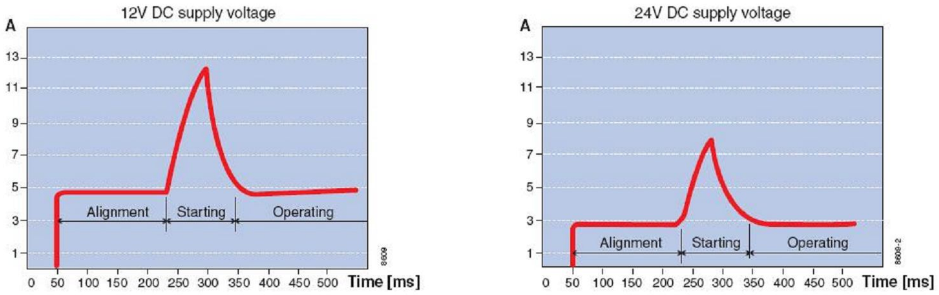

Fig.1 Compressor current profile against time for different input voltage.

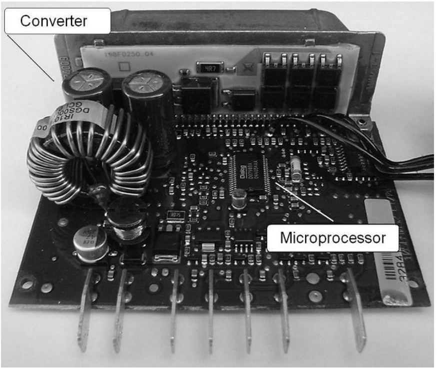

Fig.2 Controller of the compressor

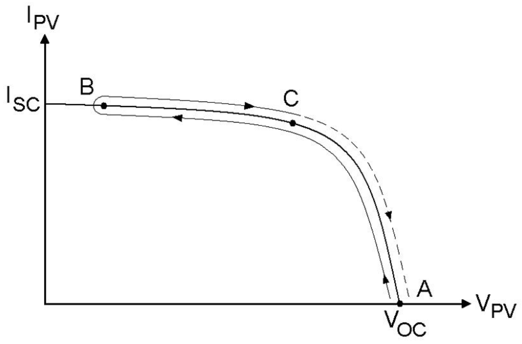

Fig.3 Compressor start up path on the PV curve

2 Identification of Compressor Characteristics

The concerned characteristics of a BD35F compressor for solar application from Danfoss are examined. These characteristics are common to a wide range of other similar compressors. The specific compressor has an input voltage range of 10-45 V DC and a maximum cooling capacity of around 170 W.

2.1 Compressor Startup

As with all motors, the compressor at startup requires a large amount of current in order to overcome its inertia and static friction. Fig.1 shows the compressor current profile against time during startup. It is evident that a current of more that twice the nominal current is required. The figure also shows that the compressor draws half the current if the input voltage is doubled. This reveals the existence of a switch-mode converter within the compressor control electronics, Fig.2, which ensures that the compressor operates at any value of input voltage without the loss of electric power.

The PV panel can only provide a constant value of current under constant irradiance and temperature, so the above requirement of the compressor cannot be satisfied by a PV that provides only the nominal value of current. The result in this case, during startup, is that the effective internal resistance of the PV panel causes a large dip in the panel output voltage. A more macroscopic explanation is that the transient impedance of the compressor is much lower than that of the PV. Fig.3 depicts the effect. Before startup the compressor is supplied with the open circuit voltage, point *A*. Right after startup, the compressor causes the drop of the PV voltage down to point *B*. If the power at that point is sufficient for startup, the compressor will operate normally and its input voltage will slowly rise to a value defined by the current it draws at steady state, point *C*. If the power at point *B* is insufficient for startup, the control circuit will abort the startup procedure and the point of operation in Fig.3 will return to *A*.

Fig.4 shows the compressor input voltage (=PV output voltage) waveform from an experiment with a prototype system to be described in section 3. Initially the voltage is around 40 V and during startup it falls down to around 5 V. The PV at the time of the experiment could provide a current of 1 A. Relating this experiment to Fig.3, one can calculate that the power at point *B* is around 5 W while the PV could provide up to 40 W at point *C*. The power at point *C* is sufficient to start the compressor but the startup transient does not allow

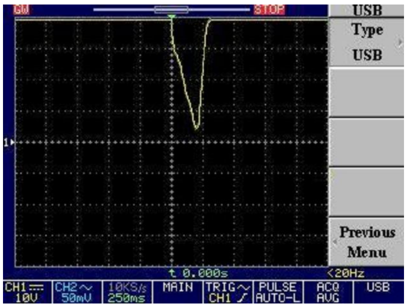

Fig.4 PV voltage waveform during startup of the compressor. Scales: 10V/div, 250ms/div.

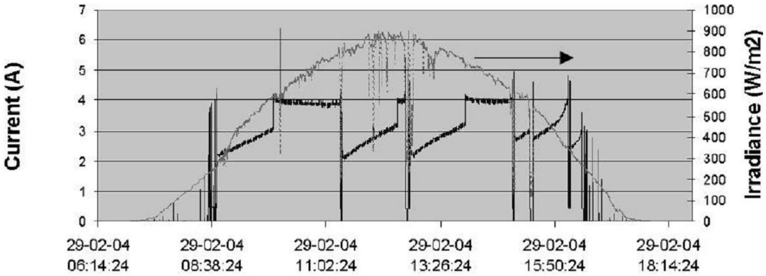

Fig.5 Experimental results from [2] using the AEO control mode

the operation at that point. The startup is eventually successful only when the irradiance reaches a relatively high level. That is the reason why a solution to the problem is the addition of large capacitors in parallel with the PV. The capacitors 'hold' the PV voltage to a high level while they provide a large transient current to the compressor. Capacitance values of over 50 mF have been used in applications [2]. Such large capacitors increase the cost of the system by a considerable percentage. Another solution is the use of oversized PV panels to provide the startup power at point *B*. This again, is an irrational use of the available solar energy and additionally an unjustifiable cost for PV panels.

It would be better if the available PV power at point *C* in Fig.3 could be used to start the compressor. The operation of a circuit/control method to aid compressor startup will be presented in section 3.

2.1 Compressor Speed Control

The compressor speed control is normally performed in two modes, either manually or automatically. A variable resistor can be used to control the compressor's speed manually. Otherwise an Adaptive Energy Optimization (AEO) algorithm can take control of the compressor speed. In this mode of operation the speed is adjusted to match the capacity needed by the thermal load. Using the compressor in any of the two modes will not result in correct use of the available electric energy from the PV. In manual mode the compressor will draw power from the PV depending on the load conditions and not the environmental conditions. The same applies to the AEO mode but with the flexibility of variable speed control to satisfy the load. One can notice from the compressor's datasheet that, even though sufficient energy may be available, the compressor, in this mode, will not reach maximum speed directly but with a speed increase rate of 12.5 rpm/min. This characteristic causes a considerable energy loss when the compressor is operated on days with wide irradiance variations. Fig.5 shows the experimental results from [2], with the compressor operating in AEO mode. It is visible that after a sudden fall of the irradiance the compressor stops and when the irradiance level is restored, shortly after, the compressor does not reach maximum speed immediately but after a long time period. The available solar energy during that period is, therefore, not fully utilized.

A maximum power tracking control system can be used, in conjunction with the manual speed control, to extract the maximum electric power from the PV. The only reason why a system such as this should not be used is load regulation, where one demands, for various reasons, to have a fixed cooling or heating capacity. However, this usually is the case in battery-based systems. In a batteryless system, where other energy storage means can be used, such as ice, the aim is to deliver as much power to the load as possible. A maximum power tracking system for the compressor is presented in section 3, simple enough to be implemented by the compressor's microprocessor, Fig.2.

3 Proposed Control Method

3.1 Proposed Method

As mentioned in section 2.1 the startup problems are caused due to impedance mismatch between the PV and the compressor during the startup transient. One could therefore design an impedance step down converter to ensure that during startup the PV impedance will not be higher than that of the compressor. A converter of this kind is shown in Fig.6. A switch, *S*, a diode, *D*, and an *LC* filter form an impedance transformation network, for which it applies that:

$$\frac{Z_o}{Z_{in}} = D^2 \tag{1}$$

Where *D* is the duty ratio of the switch, which is the *ON* time over the period time, the period being the inverse of the switching frequency.

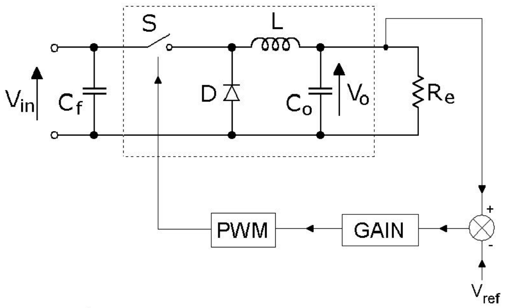

Fig.6 Impedance converter

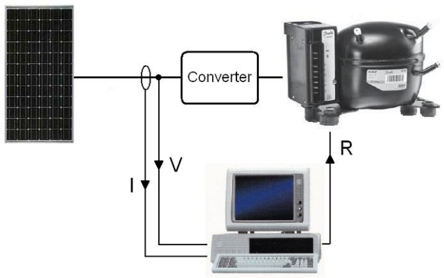

Fig.7 Maximum power tracking

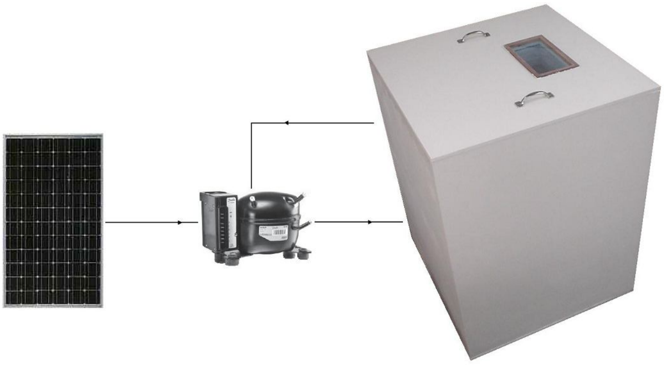

Fig.8 System of application

The filtering capacitor, C_f, is relatively small as it only has to provide high frequency current to the converter. A typical value for it would be less than a couple of milliFarads.

A circuit like the above can be found as a commercial product but unfortunately with fixed frequency response characteristics, a very important point for the required application. One needs to tune the frequency response of the circuit in order to effectively compensate for load transients, these exactly being the startups of the compressor. For the tuning to be performed one needs to know the dynamic transfer function of the compressor or to have the compressor tested. With the circuit of Fig.6 the optimum startup is achieved on-site by adjusting the gain of the compensating loop with just a few trials.

Since the compressor already includes a converter, the above process can be performed by the compressor itself. Installing an external converter would introduce extra losses, which is inevitable with all commercial models. However, one can avoid introducing these extra losses, when using an external converter, by employing a smart control procedure. As soon as the compressor starts, the impedance transformation function is not needed anymore, so the control circuit can ramp up the duty ratio of the switch up to unity. The converter inside the compressor will take control of the impedance transformation needed during steady state. Increasing the duty ratio to unity effectively means that the switch of the converter is permanently closed, which brings the switching losses down to zero. Moreover, the conduction losses, due to switch and inductor resistance, can be eliminated by the use of a relay that bridges the input of the converter to the output.

The second problematic characteristic of the compressor was dealt with by the employment of maximum power tracking. Fig.7 shows the block diagram of the process. The voltage and current of the PV are sampled and the drawn power is measured by a computer. The computer injects perturbations to the compressor by means of its speed-control resistance input. Using a special algorithm the computer manages to force the operating point of the compressor around the maximum power point of the PV.

The maximum power tracking algorithm is relatively simple and does not require high computational power. It can therefore be embedded in the PIC microcontroller already installed in the BD35F compressor. Similarly, the impedance conversion can be implemented by the compressor's internal converter. The proposed solution is thus fairly practical and can result in impressive increase of the system performance. An external to the compressor prototype system was built in order to verify the performance of the proposed control method. The following sections describe the application for which the prototype was developed and some indicative results.

3.2 Application description

The prototype was built for an ice-maker application, Fig.8, this certainly not implying that the work of this paper does not apply to any other application, heating or cooling. An SM110 photovoltaic panel and a BD35F compressor for solar applications from Danfoss where used. The application was solar chilling with ice energy storage.

3.3 Experimental Results

Fig.4 shows the voltage of the PV when connected directly to the compressor, without the use of the prototype controller. It was discussed that the startup of the compressor was impossible at low irradiance levels. The experiment was carried out with an irradiance of 415 W/m^2. At the exact same time and under the same conditions an experiment was carried out with the engagement of the prototype controller. The result is shown in Fig.9. The PV voltage falls by around 10 V for 100 ms and then rises to the steady state value. The compressor startup was smooth and the voltage transient was significantly reduced without the use of large capacitors (see Fig.4). According to this result, on a day with an irradiance level no greater than around 600 W/m^2, the proposed control method would result in a 100% use of the solar energy while the standard control system would not even allow the compressor to start. For example, Figure 10 shows comparison data that were recorded on the 7th of March of 2007, when the solar irradiance profile was such that the compressor with the manufacturer controller operated for less than 1/15th of the time that the compressor with the proposed controller operated, both compressors being connected to identical cooling circuits.

4 Conclusion

A range of commercial DC compressors has emerged for batteryless, solar applications, having the advantage of capacity control. However, it is identified in the paper that the control methods employed by the compressor electronic unit cannot operate the compressor in a way that fully utilizes the available energy from the PV. A control method has been proposed which considerably improves startup and steady state operation. The method can be implemented by the electronic unit already installed in the compressor. Early results from a prototype showed great improvement in the startup characteristics of the compressor, which effectively allows the compressor to remain operational even during days with low solar irradiance. Future work will focus on the evaluation of the total gain in efficiency throughout a long period in a year and the development of a maximum power tracking algorithm with even lower computational demand.

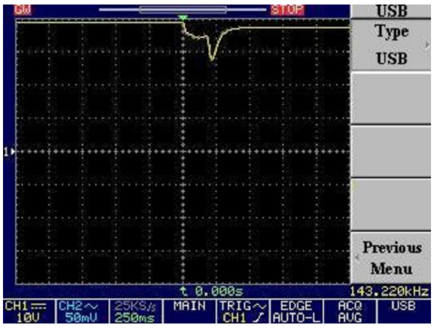

Fig.9 PV voltage waveform during startup of the compressor with the proposed controller. Scales: 10V/div, 250ms/div.

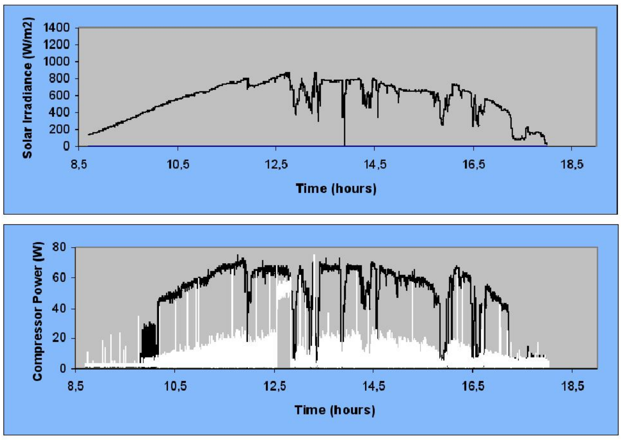

Fig.10 Daily comparison between two compressors. White trace: With manufacturer controller, black trace: with proposed controller.

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