Capacity control of screw compressors: speed or slider control – a comparative study

Abridged version

There are different technologies to adapt the compressor’s cooling capacity to the changing requirements of the A/C and refrigerant systems when operating with screw compressors.

- Distribution of the requirements to several compressors (parallel operation)
- Evaporation pressure control with hot gas bypass
- Internal bypass in the compressor
- Reduction of the compressor displacement by a control slider
- Variable compressor speed

The difference between the methods lies in the quality of the control – stepped or infinite – and in the achievable part-load efficiencies. The following comparison shows results from extensive measurements of two “modern” methods of capacity control of a semi-hermetic compact-screw compressor, slider control, and speed control by frequency inverter.

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1 Introduction

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The difference between the methods lies in the quality of the control – stepped or infinite – and in the achievable part-load efficiencies. The following comparison shows results from extensive measurements of two modern methods for capacity control of a semi-hermetic compact-screw compressor, slider control, and speed control by frequency inverter.

2 System description

Slider control

The slider control allows an adaptation of the compressor displacement to the power requirement by shifting the start of the compression process through an axial slide of the control slider. At the same time the outlet window is adapted to the newly developing displacement in this series.

Speed control

To regulate the speed, a frequency inverter was added to the same compressor. The speed had been selected in such a way that the same performance as for the slider control was achieved in each measuring point.

3 Test setup, components, refrigerants, application range

The measurements were conducted on a test stand with gas circuit without refrigerant condensation. The heat equivalent of the required electric power is led out via a liquid cooled heat exchanger. The operating points can be adjusted by a control valve (by the temperature of the coolant) and by the refrigerant charge of the measuring circuit. The suction gas flow is measured in order to get the cooling capacity. The electric current consumption is calculated from the effective value of the current consumption and the tension. All relevant data, pressures and temperatures are recorded electronically and are also analysed electronically. The measuring values shown are mean values of a measuring time of 5 minutes.

For the measuring a semi-hermetic compact screw compressor type CSH6561-60Y was used. The theoretical displacement is 170 m³/h at 50 Hz, max. operating current 105 A. Slider position 100%, 75%, 50%, and 25%.

The frequency inverter, type 75FEP, used to regulate the speed control, was set on a proportional tension frequency line. The max. operating current is 145 A, the nominal capacity is 75 kW.

The frequency variable operation was done by a standard motor for 400 Volts at 50 Hz. This means that when rising over 50 Hz operating frequencies, the compressor is operated with increasing sub tension and proportionally increasing operating current. The max. possible compressor speed is in this case limited by the motor voltage rate.

The application range of the compressor in connection with the refrigerant R407C is shown in figure 1. An evaporation temperature range of +10°C to -10°C is examined, which covers the application in A/C systems with direct evaporator, water- and brine chillers. The condensing temperature is 30, 40 and 50°C. The condensing and evaporation temperatures are referring to the respective dew point temp. of the mix-refrigerant R407C.

Fig. 1 Application range
4 Control ranges

The slider of the compressor, starting from the full load position 100% had been positioned to nominal 75%, 50% and 25%. The cooling capacity which results thereof can – dependent on the pressure ratio – deviate from the nominal values.

For the measurements with frequency inverter the operating frequency of the compressor had been selected in such a way that in each measured operating point the cooling capacity adjusted to a value that was identical with the slider position.

In addition to the directly comparable measurements the operating frequency at the max. tension of 400 Volts was increased so far over 50 Hz that the voltage limit of the motor was achieved.

5 Volume ratio

The volume ratio of the compressor is defined by the position of the suction contour and the size of the discharge port. The outlet window consists of an opening, which is axially aligned in the discharge flange and a discharge port, which is radially integrated in the control slider.

The partial integration of the discharge port into the slider leads to an automatic adaptation of the outlet window at part load operation. The volume ratio stays at a constant level up to 70% load. When further reducing the load (to 25%), an independent Vc-control results, by which the volume ratio is adapted to the lower condensing pressure, which is to be expected in part load operation.

When operating in frequency variable ranges, the control slider stays at the 100% position. An adaptation of the volume ratio to the lower conditions at part load operation does not happen in this case.

6 Results

Fig. 2 shows the power consumption with frequency inverter in comparison to direct net operation.

The higher power consumption at FI operation is based on the efficiency ratio of the FI, and by a smaller part, which cannot be defined by measuring technique, on the reduced efficiency ratio of the electric motor, when supplied with the pulsed tension by the FI.

The further examinations are made for each single measured condensing temperature of 30°C, 40°C, and 50°C. At 30°C condensing temperature the relative power consumption shows a continuous curve for FI operation. The relative power consumption at the slider control lies partly above, partly below the power consumption for FI operation. This unsteady behaviour is caused by a volume ratio, defined in various slider positions. The results show that this compressor is not optimised for the relatively low condensing temperature of 30°C. This is quite common as air cooled A/C systems do not work with such low condensing temperatu-
res. (For water cooled systems compressors with accordingly adapted volume ratio are available).

At 40°C condensing temperature the power consumption in all operating points \( (t_0 = -10°C, 0°C \text{ and } +10°C) \) lies below the one at FI operation.

At 50°C condensing temperature (fig. 5) the ratio of the power consumption of the compressors regulated by a slider is a little more favourable than at 40°C \( t_c \). At this operating point the advantages of the slider control are obvious. Moreover, the reduced peripheral velocity of the dental tops has a negative effect on the performance – as well as on the volumetric and isentropic efficiency of the compressor when operated at low speed.

7 Comparison of application limits

The full-load application limits for slider operation with frequency inverter are shown in fig. 6. The upper limit line is based on the max. admissible motor temperature. For operation with frequency inverter there is a restriction of the max. possible condensing temperature in comparison to net operation. Reason is the stronger heating of the motor at FI operation.

Operation of the compressor at frequencies above 50 Hz

The data shown for the operation of the screw compressor were evaluated by the standard motor (400 V, 50 Hz) at a proportional characteristic curve of the frequency inverter. Operating frequencies above 50 Hz are possible at a constant supply tension. In this range, the so called weakening of the field, the current consumption increases proportionally to the speed. The motor is therefore operated at an increasing frequency with rising sub-tension. This operation is possible up to the max. current consumption of the compressor. The current resources of the motor result from the relation of the max. possible current consumption to the operating current for FI operation at the selected operating point.

Experiences show that the operating current must not exceed 90% of the max. admissible operating current for direct drive. The table shows some examples.

<table>
<thead>
<tr>
<th>Oper. point</th>
<th>current cons.</th>
<th>( I_{\text{max}} )</th>
<th>max. freq. for ( I_{\text{max}} = 94,5 \text{ A} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-10°C/40°C)</td>
<td>69,1 A</td>
<td>105 A</td>
<td>78 Hz</td>
</tr>
<tr>
<td>(-10°C/50°C)</td>
<td>71,4 A</td>
<td>105 A</td>
<td>66 Hz</td>
</tr>
<tr>
<td>(0°C/40°C)</td>
<td>62,9 A</td>
<td>105 A</td>
<td>75 Hz</td>
</tr>
<tr>
<td>(0°C/50°C)</td>
<td>74,5 A</td>
<td>105 A</td>
<td>63 Hz</td>
</tr>
</tbody>
</table>

For the operating point \( t_0 = 0°C, t_c = 45°C \) the operating behaviour of the compressor has been recorded for operation with FI. The maximum frequency resulted in 74 Hz.

Fig. 7 shows the FI increase of the cooling capacity and the COP above the speed. Both values do not behave proportionally to the speed increase.

Abb. 5 Curve of the power consumption at 50°C condensing temperature

Abb. 6 Application limits

Abb. 7 Relative curve of capacity and COP at frequencies above 50Hz
The relative cooling capacity related to frequency is still approx. 92% for 40 Hz. Reasons are an enlarged slip of the motor caused by sub-tension when operating above 50 Hz, and the increasing throttling losses in the compressor caused by the increasing refrigerant mass flow. When the speed increases due to higher peripheral speed of the rotors, the backflow losses are reduced and cannot compensate this effect.

The COP shows a similar behaviour. The sub-tension, rising proportionally to the frequency, causes a lower magnetization of the motor and thus a reduction of the efficiency ratio. At the max. possible frequency of 74 Hz the performance drops 14%.

Provided that the max. frequency is only needed to cover the peak loads – for a few days a year – the reduction of the COP value becomes less important. Especially important is the capacity increase at higher compressor frequencies – for this operating point – 36% from 117 to 159 kW.

Alternatively to the selected motor voltage of 400 V, 50 Hz the compressor can also be equipped with a motor of 230 V, 50 Hz. In this case the frequency inverter is able to provide a tension which is proportional to the frequency over the entire speed range. Thus, the performance and COP losses for operation with sub-tension mentioned before can be avoided. The respective operating data had been measured with the available motor at an intensified voltage, proportionally to the frequency (50 Hz, 390 V to 60 Hz, 460 V). With respect to motor efficiency and speed the results are comparable to those of the motor 230V, 50Hz. The operating point $t_o = 0^\circ$C, $t_c = 45^\circ$C was selected.

The cooling capacity increases sub-proportionally to 99% relative value. The power consumption also increases sub-proportionally to 98% relative value. This leads to a 1,4% increase of the COP.

Due to the higher flow losses at increasing mass flow in the compressor, the cooling capacity increases sub-proportionally to the speed increase. The relative reduction of the power consumption results from the lower back flow losses of the compressor at higher frequencies. The COP increases to 1.4%. With the 400 V motor the COP dropped to 97% at this operating point, as already mentioned. This result shows that systems, which are primarily operated at frequencies above 50 Hz should be equipped with a motor, which allows a proportional increase of voltage and frequency in this range as well. This is a motor selected for 230 V, 3 PH, 50 Hz. In this case it must be paid attention to the fact that the frequency inverter has to be selected for higher currents when using 230 V motors.

Performance curve with frequency inverter (27 to 74 Hz)

The diagram shows the part load behaviour with frequency inverter for 0°C / 45°C with R407 C. The red curve represents the part load behaviour for proportional change of tension and frequency. For frequencies above 50 Hz the curve comes close to the curve of the proportional line. The distance to the proportional line, which is still obvious, is due to the efficiency ratio of the frequency inverter. The measurements had been conducted up to 60 Hz. For higher frequencies the efficiency of the inverter is almost compensated by the better isentropic efficiency of the compressor developing at higher speed. This positive effect is partly neutralized by the increasing throttling losses of the compressor.

<table>
<thead>
<tr>
<th></th>
<th>50 Hz</th>
<th>60 Hz</th>
<th>Relative values for 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling capacity [kW]</td>
<td>116,9</td>
<td>139,4</td>
<td>99%</td>
</tr>
<tr>
<td>Power consumption [kW]</td>
<td>41,9</td>
<td>49,3</td>
<td>98%</td>
</tr>
<tr>
<td>COP</td>
<td>2,79</td>
<td>2,83</td>
<td>1,014</td>
</tr>
</tbody>
</table>

Fig. 8  Curve of the cooling capacity at over-synchronous operation

Fig. 9  Curve of the cooling capacity with FI
The blue curve shows the part load behaviour for compressor operation from 50 Hz with increasing sub-tension. It is obvious that the power consumption increases superproportionally to the increasing frequency. This characteristic, which is achieved by the 400 Volts standard motor, should be used only when this high performance is needed temporarily.

7 Summary

- Due to the efficiency of the frequency inverter, the COP achieved by this system in the respective control range is always lower than it is for direct net operation.

- The application range of the compressor is reduced when operating with a frequency inverter. This leads to a slight reduction of the maximal possible condensing temperature. A very suitable alternative for applications with higher condensing temperatures is provided by the refrigerant R134a.

- The possibility to increase the compressor’s performance by operating over 50 Hz and then using smaller compressors, increases the efficiency of such systems.

- For systems, which are primarily operated above 50 Hz, one should check, if the application of a motor with 230 V would be an economically efficient solution.

- If there are requirements of the power companies concerning restrictions of the starting currents, these might also be met by using frequency inverters. Separate soft starters are not necessary.

- Both systems, slider control and variable frequency operation are suitable to adapt the compressor capacity to the required performance. The decision, which system to use, can be made only after a calculation of the system configuration, taking into account the performance, capacity ratio and the investment costs.

- Net impedance, sinus filter and the load on the frequency inverter can significantly reduce the blind current at frequency inverter operation. The priority of each measurement has to be specified more precisely by further tests.