Part 1: Gibson

Speed Control of Refrigeration Compressors with intelligent Frequency Inverters

Design considerations and experience

The control of suction pressure by varying the speed of refrigeration compressors provides many advantages.

If the installation is designed correctly then important considerations such as improved quality of stored goods, energy saving, improved performance at light refrigeration loads and increased working life can be easily achieved.

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1.1 Introduction

With speed control refrigeration compressors are operated outside the normal area of operation defined and specified by the manufacturer. It is therefore very important to take certain electrical and refrigeration technology restraints into consideration.

This article will investigate compressor packs with a "master" variable-speed compressor connected in parallel with several fixed speed compressors, see Fig. 1.1.

The following abbreviations will be used in this article:

VsC: **V**ariable-**s**peed **C**ompressor
FsC: **F**ixed **s**peed **C**ompressor
FI: **F**requency **I**nverter

In the systems which are described here,

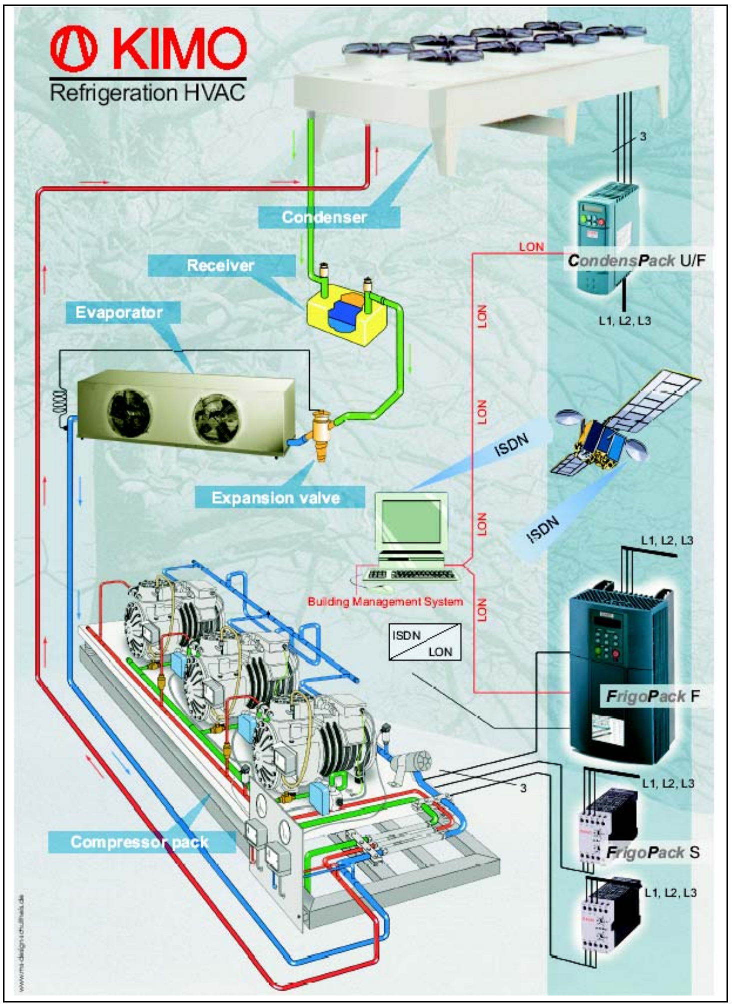

Figure 1.1: Refrigeration system with a Variable-speed Compressor (VsC) and two Fixed-speed Compressors (FsCs). Right: FrigoPack intelligent Frequency Inverter (FI)

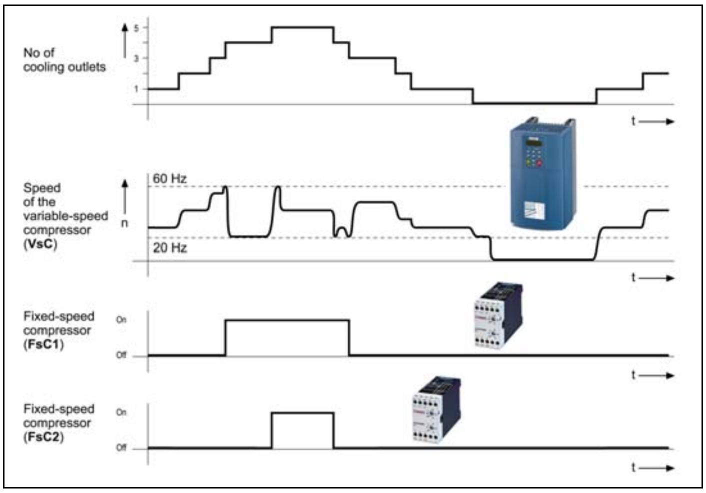

Figure 1.2: Mode of operation of a compressor bank with closed-loop speed controlled master compressor

Figure 1.3: Typical compressor bank with intelligent frequency inverter

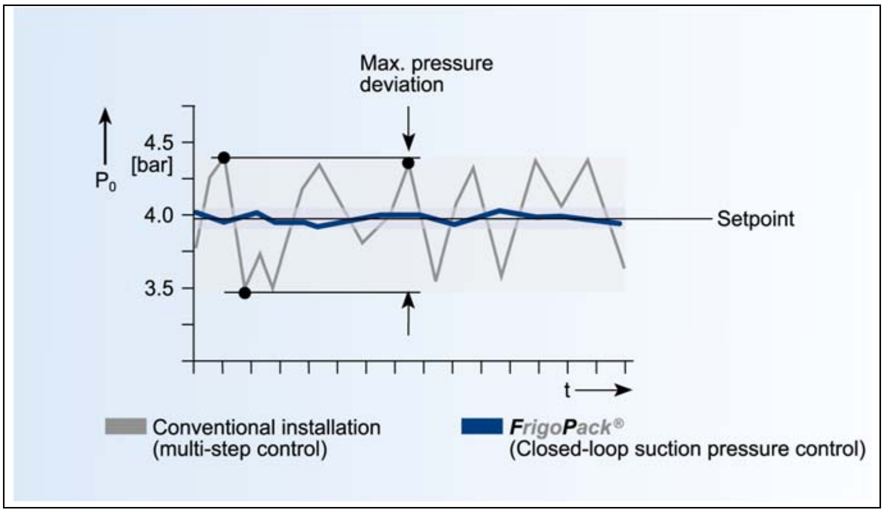

Figure 1.4: Measured characteristics in a real refrigeration system in operation with closed-loop suction pressure control using intelligent frequency inverters in comparison to operation with a conventional compressor pack with multi-stage control

speed. The mode of operation is described, for example, in [1].

This concept is based on the use of intelligent **FI**s. These **FI** types can handle the open-loop and closed-loop control tasks in the compressor pack. The main function of the intelligent **FI** is to maintain the suction pressure constant by continually adapting the speed of the **VsC**. As soon as the refrigeration power of the **VsC** is no longer sufficient, an **FsC** is switched-in, see Fig. 1.2. The system automatically adjusts itself to the refrigeration power required. A typical system utilizing this technology is shown in Fig. 1.3.

It is in principle possible to use two or more **VsC**s in a refrigeration circuit. However, in practice, such systems do not provide any significant benefits so that these systems will not be considered in this article.

1.2 Advantages

The following essential advantages are obtained by continually adapting the power of a compressor pack by controlling the speed of a **VsC**:

- Improved cooling quality by maintaining a constant suction pressure* (refer to Fig. 1.3)
- Wider range of operation of the refrigeration power+ (refer to Fig. 1.5)
- Increased power by increasing the speed of the **VsC**+ (refer to Fig. 1.7)
- Energy saving*
- Longer compressor lifetime +
- Better possibilities of providing monitoring, remote setting and diagnostics+

1.3 Closed-loop control range of the refrigeration power

The comparison of a compressor pack with the following units is shown in Fig. 1.5:

– 3 / 4 x **FsC** (conventional multi-stage control)

– **VsC** (using a master compressor regulated using an **FI**) + 2 x **FsC**s.

At almost all operating points it is possible to provide the required refrigeration power without having to frequently switch the compressors on or off. This provides the following decisive benefits:

- Fluctuation of the suction pressure, caused by switching on or off a **FsC** are minimized, refer to Fig. 1.4.
- The starting frequency of the compressors is significantly reduced, the life-

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* This will be explained in considerable detail in this article

+ This will be explained in more detail in this article

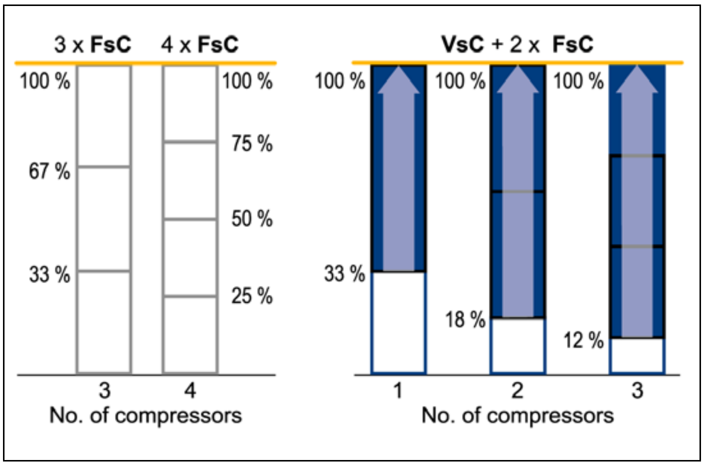

Figure 1.5: Comparison of a compressor bank with:

- **3 / 4 x FsC (conventional multi-step control)**
- **VsC + 2 x FsCs (FI controlled master compressor)**

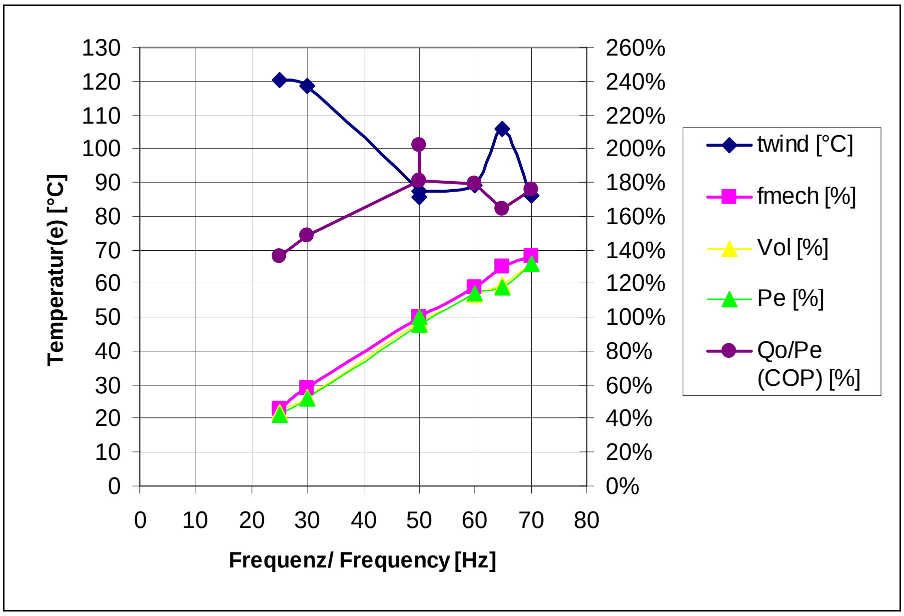

Figure 1.6: Measurements made on a typical semi-hermetic reciprocating compressor, Operating data: R404A, t_o = -10 °C, t_c = +40 °C, t_{oh} = 25 °C

time and service/maintenance intervals of the compressors is appropriately increased

- The evaporating temperature in the system can be reduced
- The similar control quality can be achieved using a lower number of larger compressors. (This minimizes the installation costs.)

A control range of 0 ... 100 % would be an optimum, but approximately 15 ... 100 % with a three compressor pack can be cost-effectively realized. In practice, the control range can be positively influenced by the following design features:

- Using three or more compressors in the compressor pack
- Using a **VsC** with a low minimum speed/frequency
- Using **VsC**s with the highest possible maximum speed/frequency.

The associated problems will be discussed in more detail in the following sections.

1.4 Minimum speed/frequency of a VsC

Several years ago it was extremely difficult to obtain technical application data at various speed/frequency points from compressor manufacturers. This is understandable as the complex measurements required to type-test a compressor are generally carried-out at 50 or 60 Hz. Data which was available for operation at other speeds were conservative general data which were applicable for all compressors in a particular range of types.

When precisely evaluating the permissible minimum speed of a certain compressor, the following questions/issues must to be taken into consideration:

- Is the lubrication system able to fulfil the required lubrication requirements ?
- Is the oil transport in the refrigeration circuit sufficient for a reduced volume flow ?
- Is the cooling of the motor winding of a semi-hermetic **VsC** adequate

In order to evaluate the winding cooling of a semi-hermetic **VsC** at reduced speed, detailed measurements were carried-out with typical compressors. The evaluation of the measurement results of a mid-range compressor is shown in Fig. 1.6.

The increase in the winding temperature (twind) due to the reduced volume flow at low speed/frequency can be clearly seen.

Measures to ensure adequate winding cooling are described in the following section.

In the meantime, important manufacturers specify the minimum speed for **VsC** operation of their reciprocating compressors in the range 20 ... 25 Hz. Very often lower speed limits can be implemented on request when the refrigeration-related operating points are known. These lower minimum speeds turn out to be extremely advantageous.

1.5 Minimum refrigeration power of a compressor pack

The minimum power of a compressor bank is of particular importance, especially for supermarkets. In winter operation with the display cases and freezers covered, the refrigeration power which is required is relatively low. If the refrigeration system is over dimensioned compared with the required refrigeration power, then, even when the **VsC** is operated at the minimum speed/frequency, the low refrigeration power required can only be achieved by frequent on/off switching of the master compressor.

This situation can be resolved by using a **VsC** combined with capacity control (cylinder-bank off loading). However this requires a close coordination with the compressor manufacturer and is not possible with all compressors. Also a very careful design of the refrigeration circuit in connection with oil transport is required.

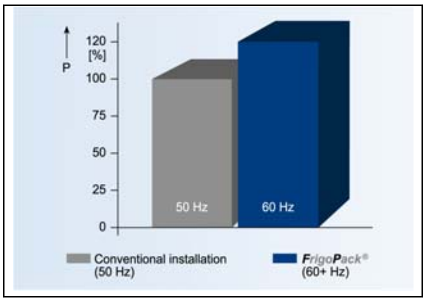

Figure 1.7: Increased refrigeration power when operating a compressor at 60 Hz using a frequency inverter

1.6 Maximum speed/frequency of a VsC (increased power)

It makes considerable sense to use an **FI** to increase the maximum speed. Almost all of the compressors are mechanically designed for operation on 60 Hz electrical supplies. The refrigeration power of a compressor can be easily increased by approx. 20% - see Fig. 1.7.

With some compressors and with some manufacturers it is often possible to increase the speed even further. The manufacturer must be contacted on a case-for-case basis, specifying the installation data. Operation up to 65 Hz (approx. 30 % increase) or even up to 70 Hz (approx. 40 % increase) is often possible. The application limits generally lie in the area of thermal and flow-related stressing in the discharge area of the compressor.

The measurement results of a semi-hermetic compressor with a 400 V, 50 Hz motor winding are shown in Fig. 1.6. The following should be noted:

- The speed (Fmech) above 50 Hz increases slightly lower than proportional with the electrical frequency due to the decreasing magnetic flux in the motor (magnetic field weakening)
- The refrigeration-related power (Qo) also increases slightly lower than proportional (approx. 30 % increased power at 70 Hz compared with operation at 50 Hz)
- The temperature of the winding (Twind) for operation at 60 Hz is lower than that for operation at 50 Hz due to the higher volume flow. However, this is a characteristic of the compressor being tested and cannot be used to make a general statement
- For the compressor being tested, the temperature at 70 Hz is insignificantly higher than at 50 Hz in spite of the magnetic field-weakening of the motor

These measurements and tests contradict the statement, which is often made that operation in magnetic field-weakening above 50 Hz can be problematical. It is incorrect to compare the thermal behaviour of a semi-hermetic compressor motor with the thermal behaviour of an industrial motor.

It is important to carefully evaluate the maximum permissible upper speed/frequency for the following reasons:

- The increased refrigeration power provides the necessary reserves in order to guarantee operation at the peak refrigeration power (especially in summer) without having to overdimension the compressors in the bank
- It is especially important to avoid overdimensioning the compressor bank, especially for operation in the partial load area (refer to the previous section).

1.7 Selecting the VsC

Positive experience has been gained using the following compressor types:

- Semi-hermetic reciprocating compressors
- Screw compressors
- Fully hermetic reciprocating compressors from several manufacturers
- Scroll compressors from several manufacturers
- Open and membrane type compressors.

The reciprocating compressor, which is well-established worldwide, will now be discussed in more detail.

Almost every manufacturer offers two motor versions for every mechanical frame size:

- Frame size with small motor (motor 2) for operation with restricted suction pressure or limited evaporation temperature
- Frame size with large motor (motor 1) - also for operation with a higher evaporation temperature

The refrigeration-related performance data of a typical semi-hermetic compressor, with different motor sizes, is schematically shown in Fig. 1.8.

When a compressor is operated with speed/frequency control, this represents an increased thermal load of the motor in the limits operating range. At a lower speed, the volume flow of refrigerant is lower and at high speed, the current is higher due to the magnetic field weakening. These potential problems can be usually completely resolved by using the compressor version with the larger motor. This can be explained as follows:

- At the critical operating points, the electric power Pe drawn by the smaller motor (M2) is significantly greater than that of the larger motor (M1), see Fig. 1.9.
- The larger motor (M1) has a larger internal surface for cooling with refrigerant (suction gas cooling).
- At the specified operating point (see Fig. 1.9), the larger motor (M1) has a lower loading which means that the winding temperature increase is significantly lower.

The starting phase of a **VsC** is of decisive significance for disturbance-free operation of the refrigeration system. This especially applies to small compressors with two cylinders which require a high starting torque. According to published information[2], torque reserves of 60 % are required for starting.

In the field, the compressors must be able to start at high evaporation pressures. This means that it is not sufficient to just consider a particular operating point. Example: If the power is interrupted for several minutes, the evaporation pressure rapidly increases, the condensation pressure is still high – and the required starting torque is now quite significant.

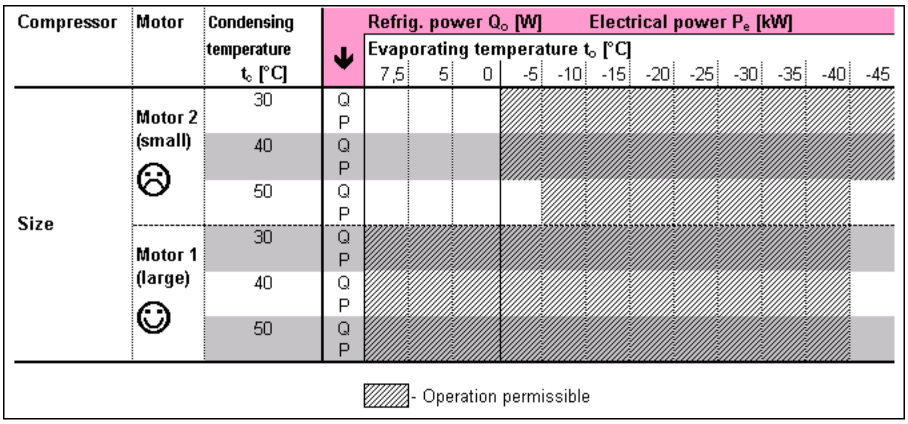

Figure 1.8: Selecting the compressor

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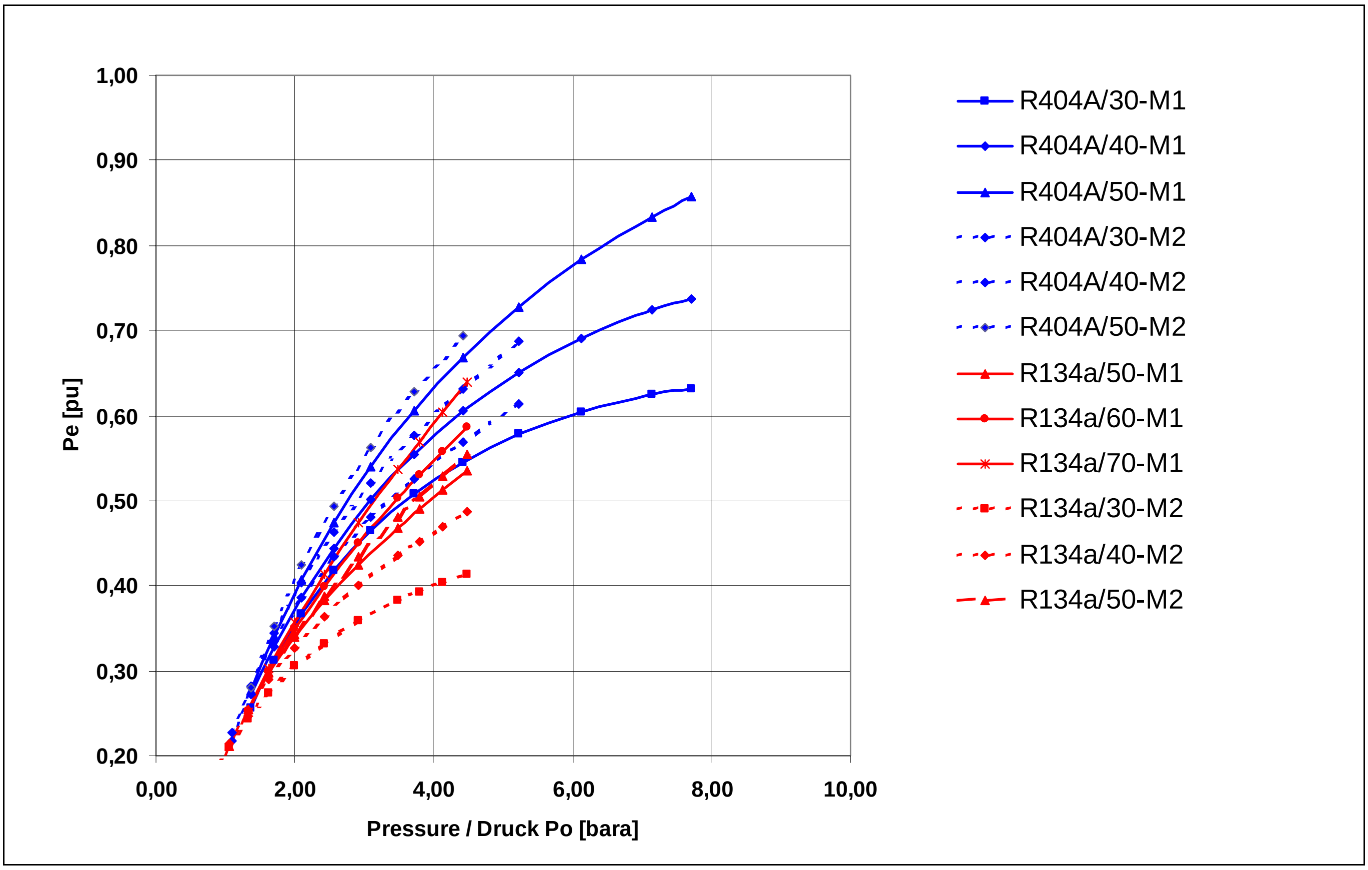

Figure 1.9: Relative electric power consumption Pe [pu] of a compressor as a function of the suction pressure Po when using motors M2 (small) and M1 (large) at a condensing temperature of 30, 40, and 50 °C

If the compressor was not able to start, then the motor winding does not have an opportunity to cool down, the winding temperature and therefore the winding resistance significantly increase at each start attempt. This generally ends in the motor being tripped by its thermal thermistor monitoring. The motor winding is significantly stressed.

The authors of this article recommend that this technology is ONLY applied for compressors with larger motors. The additional costs for the compressor compared with the aggravation associated with starting problems is negligible.

1.8 Selecting the rated power of the FIs

The following criteria should be taken into consideration:

- Required starting torque depending on the compressor design and/or the number of cylinders, refer for example to [2]
- Possible measures to reduce the starting torque, e.g.:
  - Start unloading arrangement (solenoid valve between the pressure and suction sides of the compressor opened during starting)
  - Pressure limiter in the suction gas line or at the evaporator

It is necessary to use what first appears to be an over-dimensioned **FI** in order to ensure reliable operation. This means that the FI is mainly dimensioned to achieve the correct starting torque. There is nothing worse than a compressor that cannot start. This means that it does not make sense to dimension an **FI** according to the rated operating point as is generally the case for fan and pump drives.

This new technology can only be widely used if the necessary rated power of the **FI** has been clearly defined. The authors have drawn-up so-called compressor "Cross Reference Lists" [3] for this purpose.

The required **FI**s for all common compressors summarized in the form of a data base taking into account experience gained in the field with "problematical compressors".

1.9 Closed-loop control related aspects

The integrated closed-loop suction pressure control ensures that the speed of the **VsC** is set corresponding to the actual refrigeration requirement. An FsC is only switched in if the refrigeration power of the VsC is no longer sufficient. The integrated refrigeration software of the ***FrigoPack*** system can control up to three **FsC**s. An external compressor pack step-controller is not required and is also not permissible (otherwise there would be competing with the integrated suction pressure controller). The minimum running and switch-off times, specified by the various compressor manufacturers, are taken into account in the software. A block diagram of the closed-loop control and common system control are shown in Fig. 1.10.

In order to increase the system availability, a high-pressure limiter control function is optionally available. This is extremely useful in the following cases:

- When the condensing power for high refrigeration power is not sufficient in summer
- There is dirt or obstructions in the condenser
- One or more condenser fans have failed
- The evaporator has ice build-up when used in the heat pump mode
- Noise abatement restrictions only allow the condenser, depending on the time of day, to be used at reduced speed

When a limit pressure is exceeded, the speed of the **VsC** is automatically reduced.

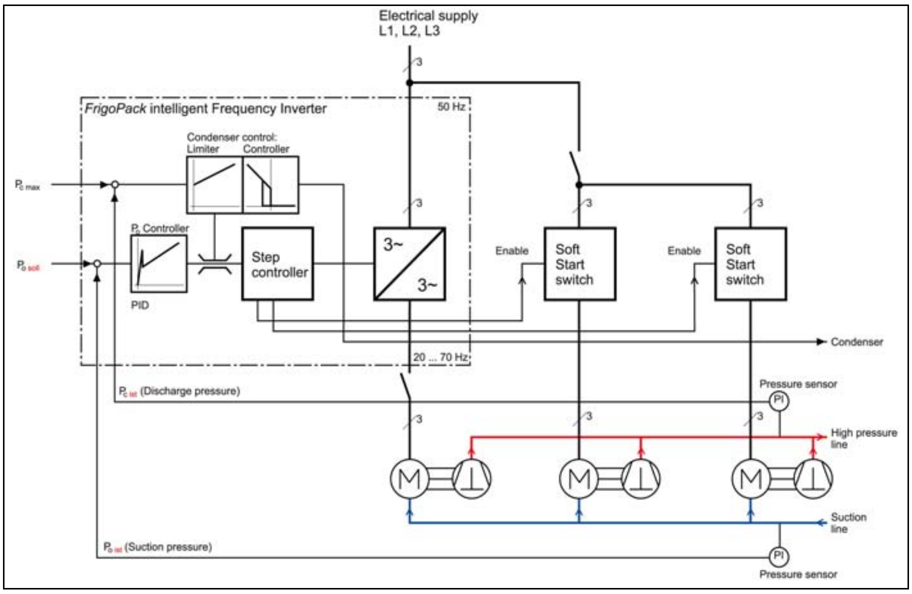

Figure 1.10: Block diagram of the closed-loop control system

1.10 Concept of the combined compressor and condenser control

It makes sense to integrate the condenser control into the closed-loop compressor control making use of the existing signal from the high-pressure sensor. This arrangement has the following advantages:

- Only one pressure sensor is required for the high pressure
- The high-pressure limit and the condenser pressure setpoint can be set together in the setup menu of the compressor control software
- The condenser monitoring can be integrated in the compressor control

1.11 Aspects of the electrical installation

The use of state-of-the-art electronic **FI**s brings with it new demands and requirements on the compressor installation. The present situation is comparable with the general introduction of variable-speed frequency inverters for driving pumps and fans approximately 8 years ago. Here are two important examples:

- The wiring of the electrical enclosure and the installation must be carefully conducted in accordance with EMC recommendations
- The best closed-loop control only functions correctly if the suction and high pressure sensor signals are available as noise-free actual values at the controller input. It is important to use only high-quality and high-reliability pressure sensors
- Special EMC measures are necessary so that the **FI**s do not disturb the signals from the pressure transducers

In summary, there are several precautions which must be given careful consideration. There is a need to train refrigeration technicians and installers in electrical engineering "knowhow", especially as far as EMC is concerned.

1.12 Remote diagnostics and remote optimization

A refrigeration system can be remotely supported when using an intelligent **FI** with its new remote diagnostics and remote optimization functionality. In this case, two technologies come to the forefront:

- The use of a fieldbus system such as LonWorks® , which allows data to be remotely transferred via a modem or through the Internet. These systems are especially suitable to integrate the refrigeration system monitoring
- The use of web-server based systems to monitor the compressor bank and, if required, the condenser.

The LonWorks® fieldbus system is especially interesting for future refrigeration systems as all leading manufacturers of refrigeration-related components and control systems operate together to define a global LonMark® standard. This work is well-progressed. The new technology of closed-loop speed control compressors has already been taken into account in this standard.

1.13 Experience

The first attempts to use this technology go back over 10 years.

Back then, the **FI**s which were available were very expensive, prone to faults and only had, to some extent, the necessary control functionality.

For approximately 5 years now, several experienced companies have increasingly used this technology with considerable success. In the meantime, there are over one thousand refrigeration and climate control systems operational in Germany and worldwide equipped with KIMO **FI**s and which operate to the complete satisfaction of their users.

There is now a very close cooperation between leading compressor manufacturers and the proponents of this technology. This means that there are common efforts to carry-out the necessary training measures to widely establish this technology.

This use of this new technology requires a lot more system philosophy than with previous conventional technologies. The advantages of this new technology can only be achieved by correctly designing and installing the refrigeration, control and electrical systems. This is the reason that system partners and distributors, with the right level of technical experience and knowhow, play an important role.

1.14 Summary and a look to the future

FI technology is an essential component of state-of-the-art refrigeration technology. Users who are both open and interested will soon get up to speed regarding the requirements placed on the system planning and implementation.

Experience and supplements to conventional refrigeration technology will be discussed in the following articles.

1.15 Literature

[1] Arndt, A. Jantsch, U.: Digitale Regelung von VRF-Multisplit. KI Luft- und Kältetechnik 38 (2002) 10, S. 468

[2] Hendriks, M, R: Leistungsregelung von Hubkolben- und Schraubenverdichtern. Kälte Klima aktuell, 21 (2002) 6, S. 36-43

[3] KIMO Refrigeration HVAC Ltd: Compressor Cross Reference Lists (available on enquiry)

1.16 Key words

Refrigeration
Compressor
Frequency Inverter
Control
Compressor Pack
Energy