STATEMENT

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ASERCOM

RECOMMENDATIONS FOR USING FREQUENCY INVERTERS WITH POSITIVE DISPLACEMENT REFRIGERANT COMPRESSORS

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1. Scope and purpose

These recommendations concern the application of externally-mounted frequency inverters for the speed variation of refrigerant compressors powered by three-phase induction motors. This paper is directed to planners and contractors designing and installing such energy-saving systems. The purpose is to reduce the risk of damage to refrigerant compressors when operated with variable-speed and to provide general design guidelines for reliable, energy-saving operation of refrigeration installations.

2. General

In classical applications without frequency inverters, the compressor operates at an approximately constant speed determined by the supply frequency and the number of motor poles.

A frequency inverter allows the stepless variation of compressor speed to the cooling capacity requirement of the installation.

Features of operation of a refrigerant compressor with a frequency inverter:

- Higher system efficiency under partial load
- Increased compressor operating life due to fewer compressor starts. With an optimum system the variable-speed compressor would operate continuously.
- Integrated soft start function:
  The starting current and torque much lower than with star/delta or part-winding starting
- Lower risk of liquid slugging due to reduced volumetric capacity during starting
- An increase in compressor capacity is often possible by operation above rated speed
- A frequency inverter controlled compressor will operate over a wide speed range. Under certain operating conditions mechanical resonances and gas resonances at critical pipe lengths can occur. In most cases these can be eliminated by good mechanical mounting and design and by making appropriate settings to the inverter control parameters (e.g. setting skip frequencies).

3. Operation

3.1 Compressors without frequency inverters for speed control

The cooling capacity of a reciprocating compressor can be adapted to the cooling demand of the installation by cylinder-bank off-loading, by hot-gas by-pass, by suction pressure control, by starting and stopping compressors in a compressor rack or by other means.

The nominal compressor speed depends on the supply frequency and on the no. of motor poles. With a 4-pole induction motor (squirrel-cage motor) the following approximate compressor speeds result:

- **4-pole: 1450 min^{-1} at 50 Hz or 1750 min^{-1} at 60 Hz**

With 2-pole motors the following corresponding compressor speeds are:

- 2-pole: 2900 min^{-1} at 50 Hz or 3500 min^{-1} at 60 Hz

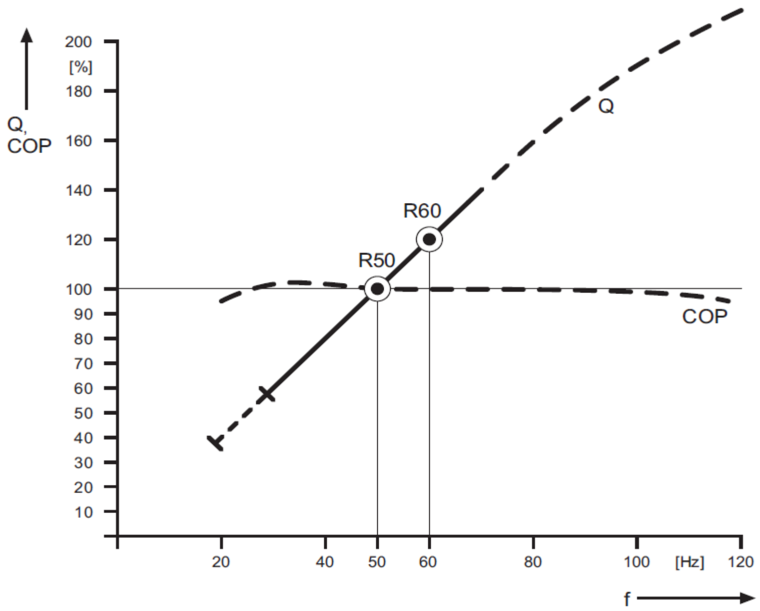
3.2 Compressors with frequency inverters for speed control

Reciprocating, screw and scroll compressors are positive displacement machines. The average load torque at the compressor shaft remains approximately constant over a wide range of speed (frequency). Cooling capacity and electrical power consumption therefore vary approximately proportional to the speed, see Fig 3.2. The cooling capacity can be adapted to the cooling requirement of the installation plant by varying the compressor speed with frequency control. Optimum stepless control is possible.

With reciprocating compressors the relative COP

(COP: Coefficient Of Performance: $\frac{\text{Refrigeration Capacity}}{\text{Electrical power input to compressor}}$)

can vary slightly with the operating frequency and speed of the compressor speed, see Fig 3.2.
At frequencies lower than rated speed a slightly higher relative COP can result.
At frequencies higher than rated speed a lower relative COP usually results.



Q: Cooling capacity
COP: Coefficient of performance
R50 Rated speed at 50 Hz
R60 Rated speed at 60 Hz

Fig 3.2: Cooling performance of a typical positive-displacement, reciprocating, refrigerant compressor over the permissible frequency range at steady-state operation

3.3 Operation below rated frequency

Since the torque of the electric motor is proportional to the product of magnetic flux and internal current, it is necessary to ensure that the magnetic flux is constant. This is achieved by selecting a control mode with a constant voltage/frequency (V/f) ratio in the inverter. Ideally the voltage of the motor reaches the rated voltage corresponding to the electrical supply voltage at the rated frequency. For compressors using standard motors this is as follows:

- 400 V at 50 Hz
- 460/480 V at 60 Hz

Operation below the rated frequency is referred to as operation in the “constant field” region, i.e. the magnetic flux in the motor remains approximately constant due to the constant V/f ratio.

The minimum permissible frequency is limited by the following considerations:

- Lubrication
- Refrigerant mass flow necessary for sufficient motor cooling
- Reciprocating compressors:
  - Inertia to ensure no significant speed droop at top-dead-center piston position
  - Suitability of compressor mounting
    (a stiffer mounting is often required at lower frequency)
- Screw compressors:
  - Adequate oil sealing
- Scroll compressors
  - Radial centrifugal forces, gas forces, adequate oil sealing.

Refer to compressor supplier for the lowest permissible frequency of operation.

3.4 Operation above rated frequency

Refer to the compressor supplier for the highest permissible frequency of operation.

The following are common connections used on standard motors for compressors:

Versorgungsspannung	Anschluß
– 400 V at 50 Hz / 480 V at 60 Hz:	Three terminals (most hermetic compressors).
– 400 V at 50 Hz / 480 V at 60 Hz: 230 V at 50 Hz:	Six terminals connected in star / Six terminals connected in delta for 230 V supplies.
– 400 V at 50 Hz / 480 V at 60 Hz:	2x three terminals each of a part winding connection connected in parallel for inverter operation.
– 690 V at 50 Hz / 828 V at 60 Hz: 400 V at 50 Hz / 480 V at 60 Hz:	Six terminals connected in star for starting/ Six terminals connected in delta for normal operation.

Operation higher than these frequencies at the above supply voltages is referred to as operation in the “field weakening” region”, i.e. the motor flux is less than the constant value up to rated speed.

Normal frequency inverters can only supply an output voltage up to the supply voltage of 400 V (or 480 V). Above the rated frequency the output voltage will remain constant at the supply voltage. The voltage/frequency ratio (V/f) will be lower resulting in a corresponding decrease in magnetic flux in the motor. However the average torque of a positive displacement compressor (such as a reciprocating compressor) is usually approximately constant under constant load conditions. The motor current will therefore increase approximately proportional to the increase in frequency.

The frequency can be increased until the maximum continuous rms (thermal) motor current is reached. In order to operate safely above rated frequency with medium temperature applications it is recommended that a compressor variant with a larger motor is used. Operation with a compressor using a smaller motor typical for low-temperature operation is not recommended due to the restricted range of frequency.

The maximum permissible frequency is limited by the following considerations:

- Power reserve of the motor at rated frequency (factor by which current is lower than the maximum current at the target operating point taking refrigerant, evaporating and condensing temperatures into consideration)
- Mechanical considerations (e.g. piston velocity)
- Gas-flow and valve plate considerations.

3.5 Operation above rated frequency with a special 87 Hz motor connection

Refer to the compressor supplier for the highest permissible frequency of operation in this standard motor connection.

The following motor connections are considered here:

- 230 V at 50 Hz / 400 V at 87 Hz with a 3 terminal motor
- 230 V at 50 Hz / 400 V at 87 Hz with a 6 terminal star/delta motor connected in delta.

The electrical rated frequency (the so-called base frequency) in these connections is 87 Hz.

Note: 87 Hz is $\sqrt{3} * 50$ Hz corresponding to the inverse of the factor of voltage when connecting a motor winding from star to delta.

Operation below 87 Hz is referred to as operation in the “constant field” region.
Operation above 87 Hz is referred to as operation in the “field weakening” region. This connection has the following advantages and disadvantages:

Advantages:

- Higher cooling capacity can be achieved with a given size of compressor
- Wide range of speed variation, i.e. high ratio (Q_{max} - $Q_{min)}$) / Q_{max}.

Disadvantages:

- Inverter and current ratings of switchgear and cables are 73 % higher which may result in a corresponding cost penalty.
- Emergency operation of compressor directly connected to the electrical supply is only possible with a 6 terminal star/delta motor connected in star which requires 4 electrical power contactors in the electrical control enclosure for activation without re-wiring.

4. Application ranges

Safe and reliable operation of a speed-controlled compressor requires a careful consideration of the permissible frequency range. In the following the limit of safe operation of the electric motor and the compressor will be considered separately for various examples of semi-hermetic reciprocating compressors.

The permissible range of frequency can be determined from the following information:

- Specific frequency range specified by the compressor manufacturer
- Maximum frequency at the design operating point based on the supply frequency multiplied by the ratio of the maximum permissible motor current divided by the prospective current at the operating point (approximate conservative design rule). This is based on standard data available from every compressor manufacturer.

4.1 Application range of the electric motor

The following information should be considered as examples of typical frequency limitations. The compressor supplier should be consulted for exact information related to each type of compressor.

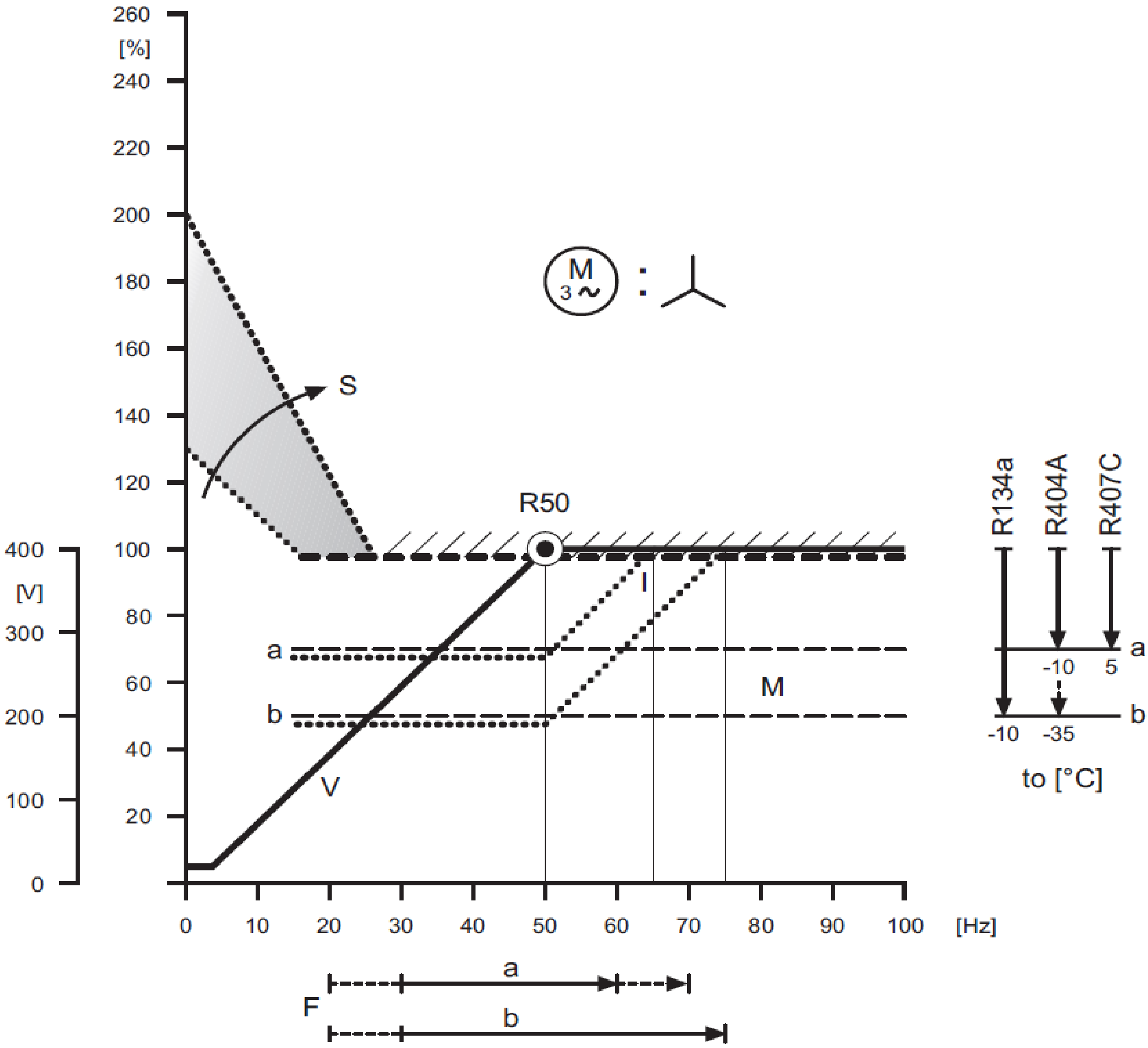


Fig 4.1a: Standard motor connection; Operation with 400 V / 50 Hz supply (Example)

Key:

a: Standard application class a (R404A: -10 / 45 °C; R407C: 5 / 50 °C)

b: Standard application class b (R404A: -35 / 40 °C; R134a: -10 / 45 °C)

M [%] Average torque after starting:
- — — — : Maximum
- – – – · : At standard application classes a or b

R50: Rated point 400 V / 50 Hz

I [%] ········ : Motor current

to: Evaporating temperature

V: ——— : Motor voltage

F: Permissible frequency range

S: Motor starting <u>current</u> required.
Shaded area indicates variation between compressors with 2 cylinders (highest) and compressors with 8 cylinders or screw compressors (lowest).

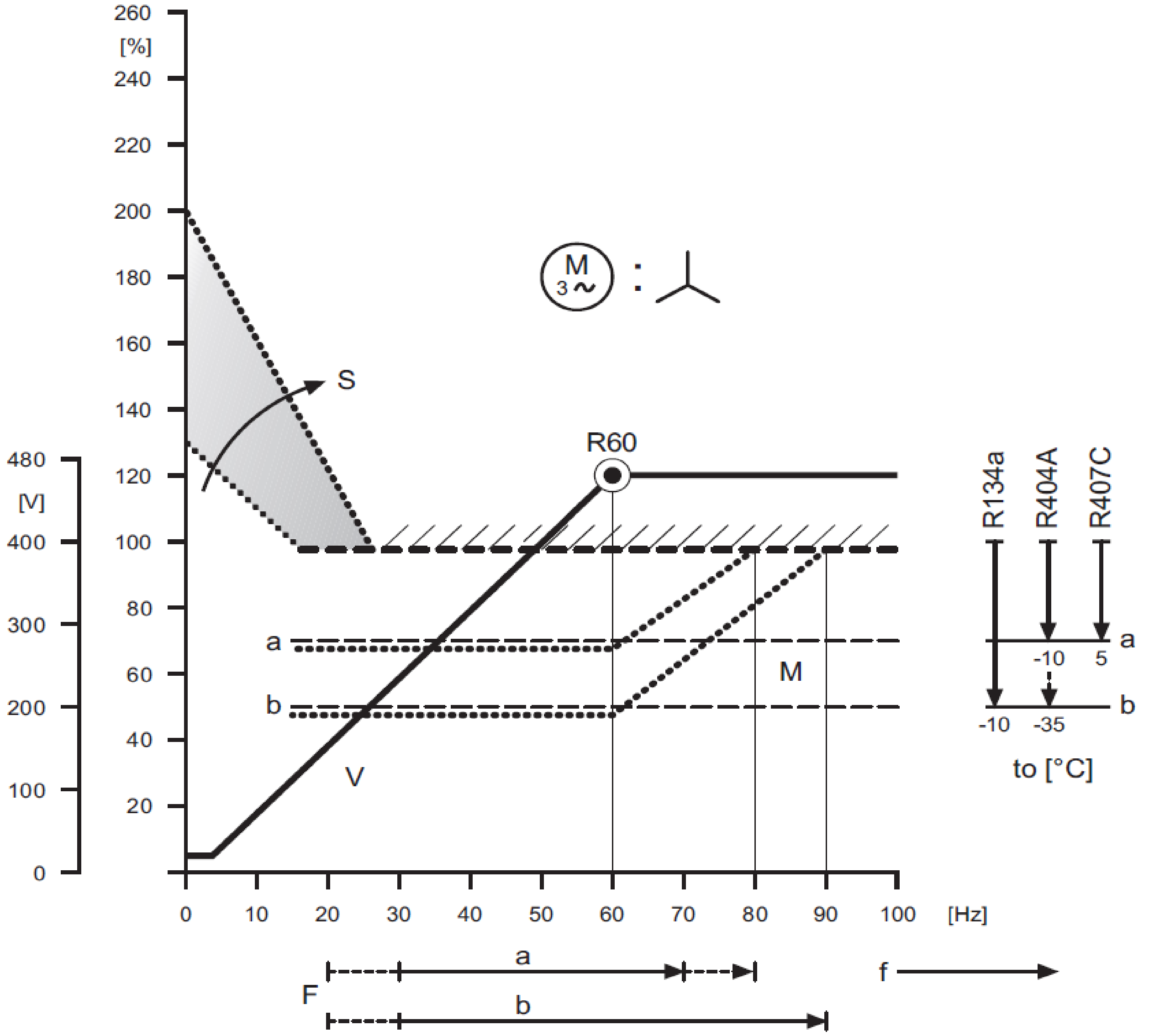


Fig 4.1b: Standard motor connection; Operation with 460 V / 60 Hz supply

Key:

a: Standard application class a (R404A: -10 / 45 °C; R407C: 5 / 50 °C)

b: Standard application class b (R404A: -35 / 40 °C; R134a: -10 / 45 °C)

M [%] Average torque after starting:
- – – – : Maximum
- – – – · : At standard application classes a or b

R60: Rated point 460 V / 60 Hz

I [%] ········ : Motor current

to: Evaporating temperature

V: ——— : Motor voltage

F: Permissible frequency range

S: Motor starting current required.
Shaded area indicates variation between compressors with 2 cylinders (highest) and compressors with 8 cylinders or screw compressors (lowest).

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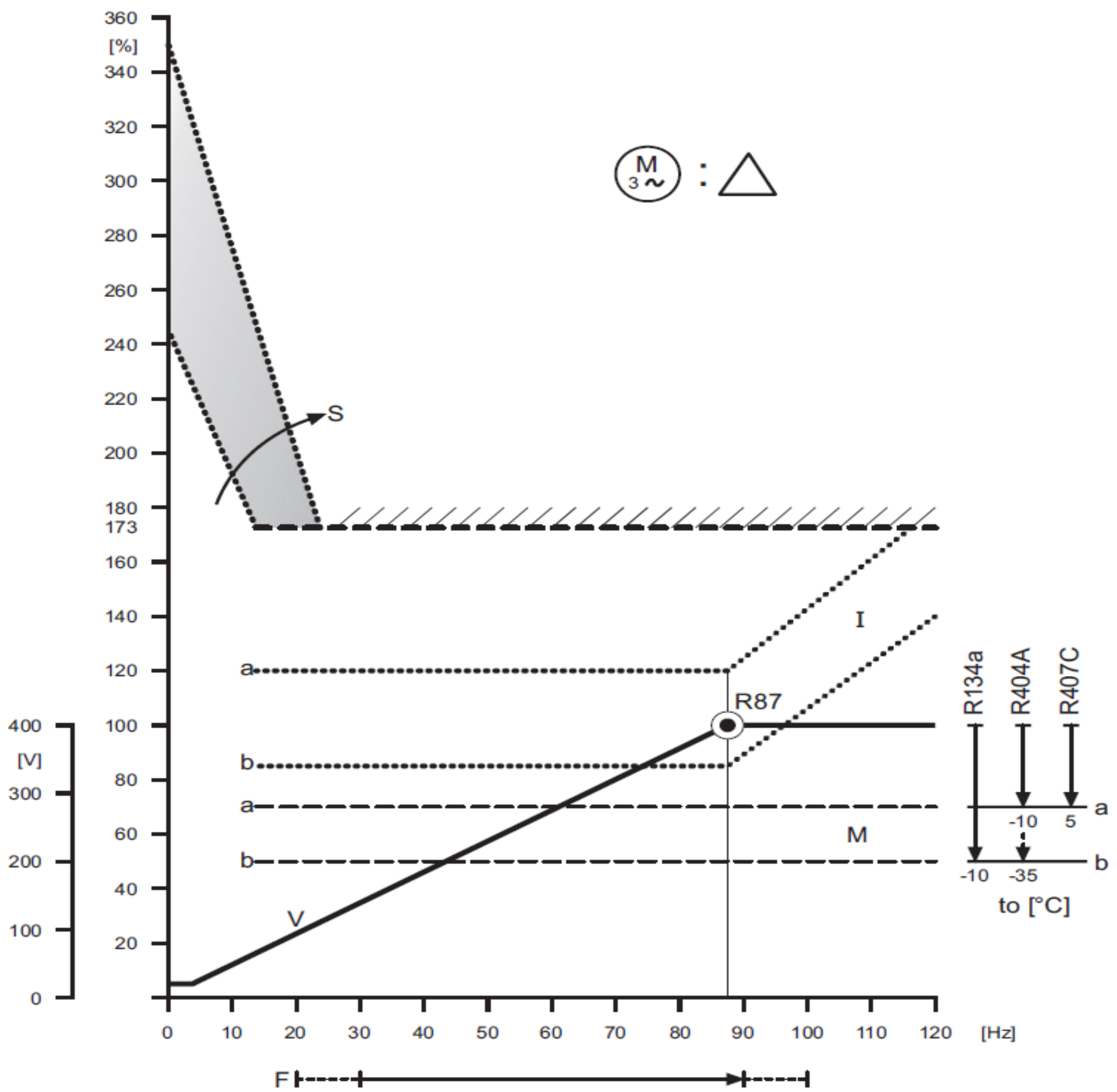

Fig 4.1c: Special 87 Hz motor connection; Operation with 400 V / 50 Hz supply

Key:

a: Standard application class a (R404A: -10 / 45 ℃; R407C: 5 / 50 ℃)

b: Standard application class b (R404A: -35 / 40 ℃; R134a: -10 / 45 ℃)

M [%] Average torque after starting:
- — — — : Maximum
- - - - - : At standard application classes a or b

R87: Rated point 400 V / 87 Hz

I [%] ········ : Motor current (compared to star 400 V / 50 Hz)

to: Evaporating temperature

V: ——— : Motor voltage

F: Permissible frequency range

S: Motor starting current required.
Shaded area indicates variation between compressors with 2 cylinders (highest) and compressors with 8 cylinders or screw compressors (lowest).

4.2 Appraisal of the permissible application range (Safe Operation Envelope)

A high potential for energy saving with single compressors and compressor racks requires the fine stepless control of cooling capacity. This can best be achieved if there is a wide range of speed or frequency control on the variable-speed compressor. The figures of the previous section indicate that there is a clear advantage of using compressors with adequately sized motors.

Examples of the permissible application ranges for adequately sized motor compressors are shown in Fig. 4.2a and Fig. 4.2b.

The following limitation boundaries for safe operation should be considered:

a: Maximum permissible discharge temperature

b: Maximum permissible discharge pressure

c: Maximum continuous (thermal) current of motor

d: Maximum evaporating temperature

e: Pressure differential to ensure correct valve operation

f: Minimum discharge pressure to ensure stable operation of the expansion valve

g: Minimum pressure which should be preferably slightly higher than atmospheric pressure.

The total boundary is referred to as the Safe Operation Envelope (SOE).

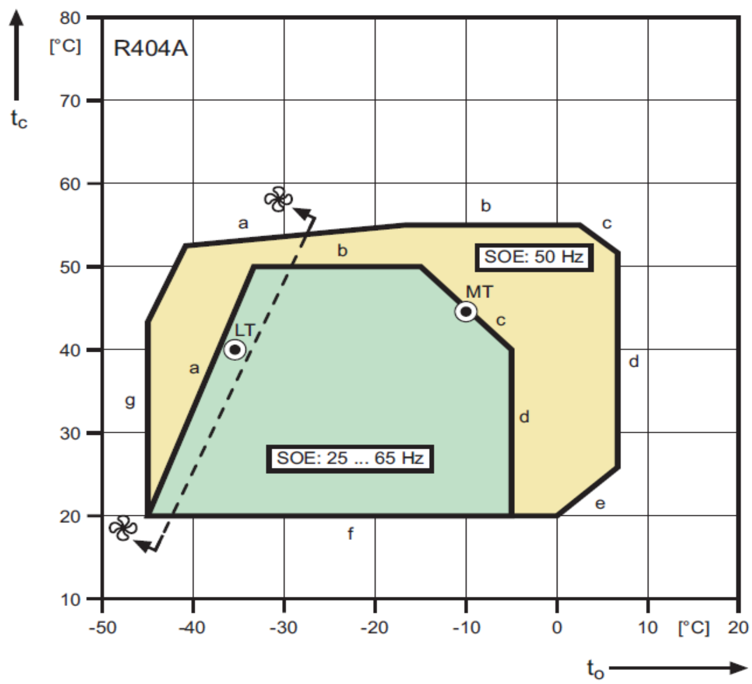

Fig 4.2a: R404A; Large motor; Standard connection; 400 V / 50 Hz supply (Example)

Key: SOE: Safe Operation Envelope **MT:** -10 / 45 ℃; **LT:** -35 / 40 ℃

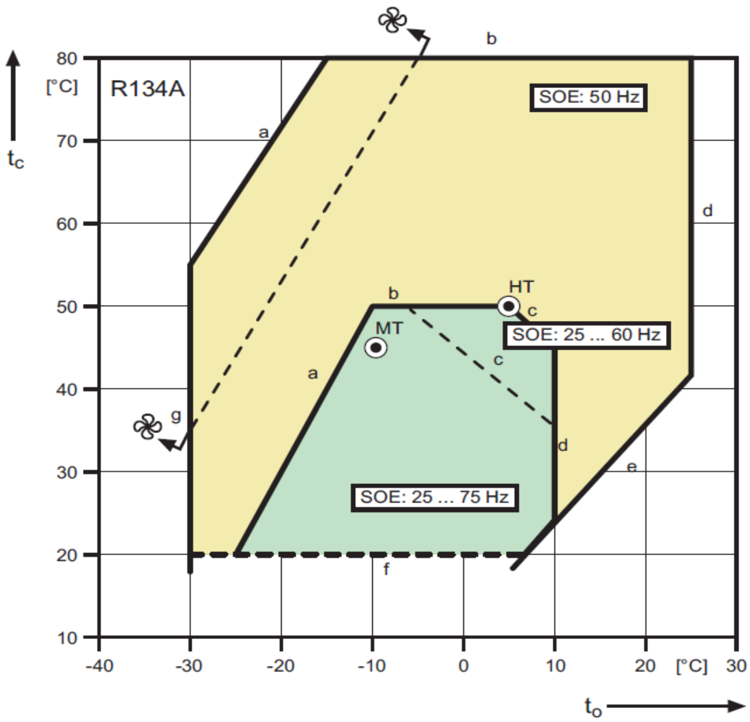

Fig 4.2b: R134a; Standard connection; Operation with 400 V / 50 Hz supply (Example)

Key: SOE: Safe Operation Envelope **HT:** +5 / 50 ℃; M **T:** -10 / 45 ℃

5. Design criteria

5.1 Permissible frequency of operation

Fig 5.1 shows the typical range of permissible frequency for different types of compressors.

Limiting factors of maximum and minimum frequency have been already described in Sections 3.3 … 3.4. Here are some further considerations relevant to each type of compressor:

- Vertical hermetic compressors: Due to centrifugal lubrication there is a minimum speed required to transport oil to the moving mechanical parts
- Semi-hermetic screw compressors: Careful coordination of the oil injection delay and, if appropriate, the slider position while starting is required
- Hermetic and semi-hermetic screw compressors with integrated oil separator: Careful consideration of the maximum speed (frequency) to avoid excessive oil carry-over is required

The compressor supplier must be consulted for permissible limits of frequency valid for each compressor used at the intended point of operation. Points of operation under transient and fault conditions must also be considered.

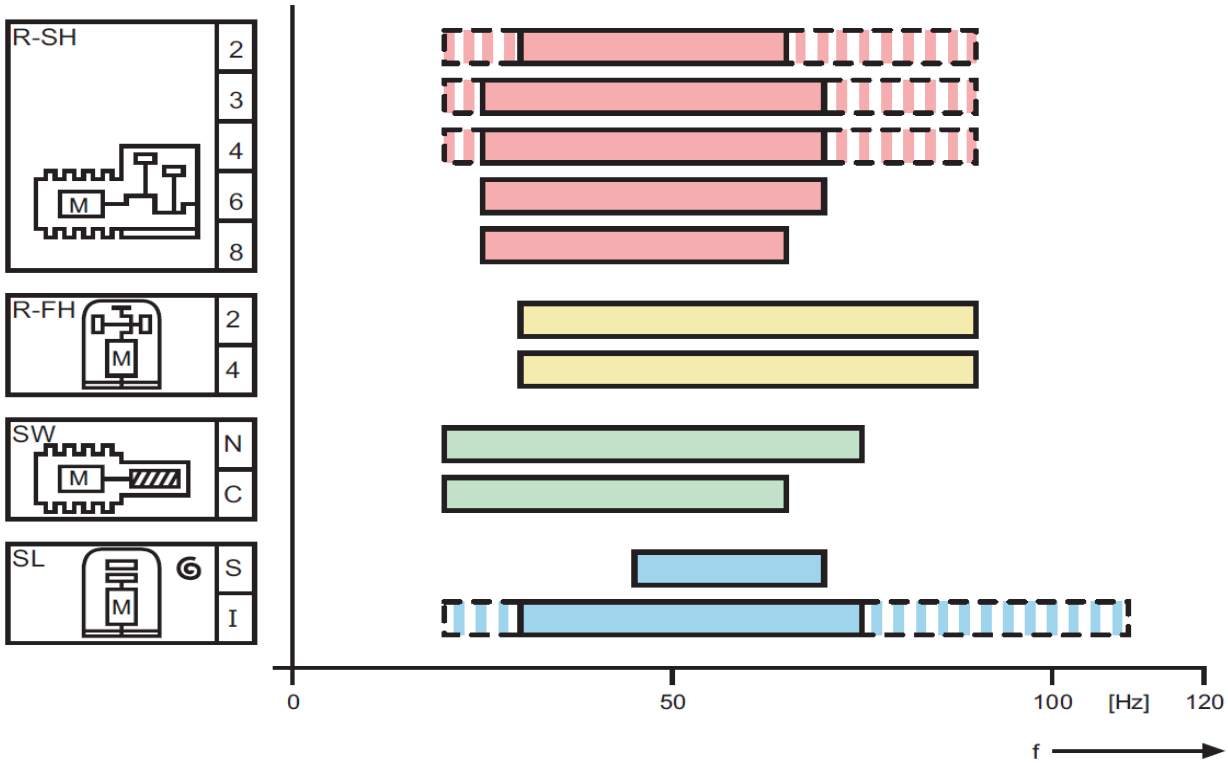

Fig 5.1: Typical permissible ranges of frequency for different types of compressor

Key:

R-SH:	Reciprocating, semi-hermetic	2 … 8:	Number of cylinders
R-FH:	Reciprocating, hermetic	N:	Semi hermetic
SW:	Screw	C:	Hermetic with integrated oil separator
SL:	Scroll	S:	Standard
		I:	Designed for inverter operation.

5.2 Considerations with open drive compressors

- Cooling:
  The motor is normally cooled by an integral fan which may be main-shaft mounted or make use of fan driven by a separate motor. The following must be considered with a main-shaft mounted fan:
  - Reduced cooling at lower speeds
  - Increased fan loading at higher speeds.
- Motor protection
  The use of thermistor thermal motor winding protection is recommended to protect the motor over the entire speed range.
- Shaft coupling:
  With reciprocating compressors the selection of the shaft coupling requires careful consideration. For low speed (frequency) operation a shaft coupling with sufficient inertia must be selected.
- Selection of size of motor and frequency inverter:
  The compressor supplier should be consulted for the selection of a suitable motor and frequency inverter.

5.3 Other considerations

- Capacity control:
  The operation of compressors with frequency inverters in combination with conventional capacity control by blocked suction to cylinder banks is not usually permitted. It cannot be guaranteed that the motor will be cooled adequately because the refrigeration mass flow is greatly reduced. Also there can be severe vibration problems due to the relatively high torque pulsation.
- Oil equalization with tandem compressors:
  When tandem compressors are operated with a frequency inverter, then the oil level between both compressor sides may differ. An oil-level control system or oil and gas equalization is often required.
- Liquid injection valve for 2-stage compressors:
  Sufficient superheat at the liquid injection valve must be ensured over the entire speed range. This requires a careful selection of the liquid-injection valve. The use of electronic expansion valves is recommended.
- Phase sequence / Direction of rotation:

  Reciprocating:
  - Usually not critical

  Screw and Scroll:
  - Very critical. An incorrect direction of rotation will damage the compressor. At first-time starting always verify that the suction pressure decreases and the discharge pressure increases.
  - Once verified an inverter selected for use with compressors will prevent reverse direction of rotation.

Phase sequence protection relays:

- Most are not suitable for sensing the output voltage of an inverter
- Consult compressor manufacturer

- Piping:
  - Mount as parallel and as close as possible to the crankshaft of the compressor to avoid pipe breakages due to metal fatigue.

- Mounting of reciprocating compressors:
  The rubber vibration absorbers bushes supplied with most compressors are designed for operation at
  50 or 60 Hz. During low frequency operation severe compressor vibration can occur. This usually requires one of the following measures:
  - Rigid mounting to a rack subframe using plastic or metal bushes
  - Rigid mounting to a compressor subframe with vibration absorbers which are at least 2x the distance between the compressor mounting lugs.

  Fig 5.3 indicates some mounting alternatives.

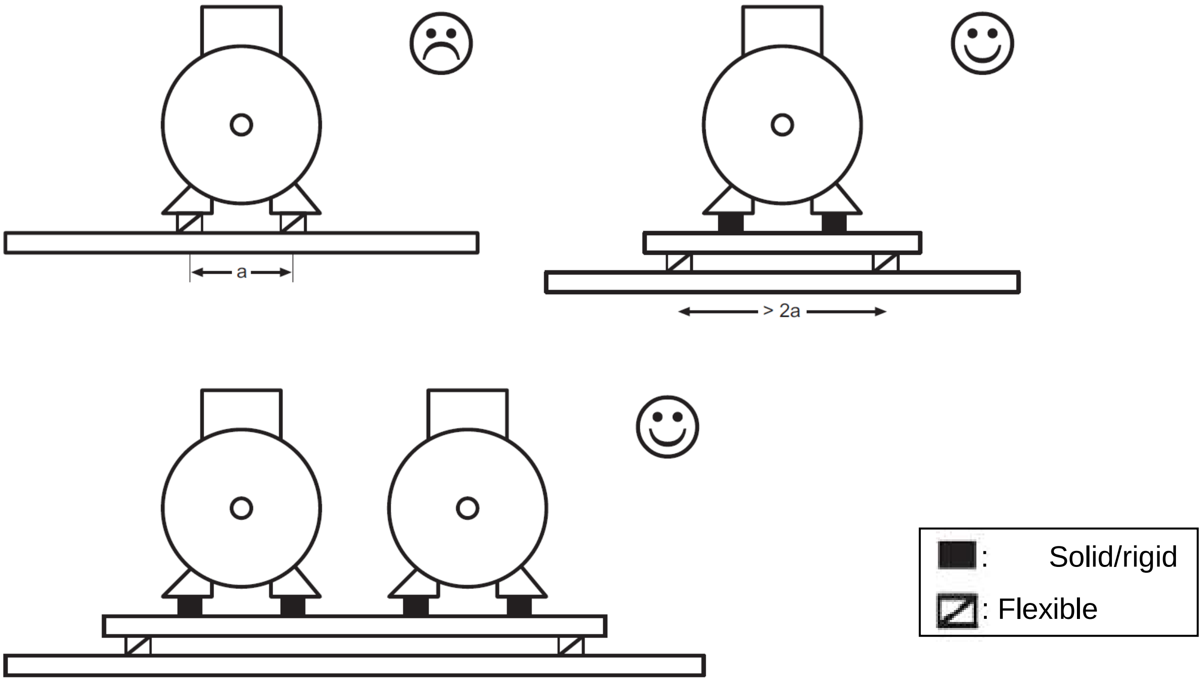

Fig 5.3: Mounting of reciprocating compressors for variable-speed operation (Example with 2-cylinder reciprocating compressors)

6. Selection of Frequency Inverters and electrical design considerations

6.1 Basic current rating

The frequency inverter must be able to continuously supply the maximum continuous (thermal) current (at maximum evaporating and condensing temperatures) to the compressor motor. 10 % Reserve should be planned additionally.

6.2 Starting Torque

The torque of reciprocating compressors varies with the angle of rotation of the crankshaft: the higher the number of cylinders, the more constant the torque. A higher starting torque is required with a smaller number of cylinders.

To achieve reliable starting under all operating conditions a short-term starting torque of a few seconds duration is required. A recommendation of the starting overcurrent requirement should be requested from the compressor supplier and be used for the selection of the frequency inverter.

The attempted use of a frequency inverter without sufficient starting current can cause serious damage to the compressor. Reliable starting must be guaranteed under worst possible starting parameters such as following a power failure at high ambient conditions.

The use of inverters rated for fan operation with practically no overload is not recommended unless they are adequately rated to provide the required short-term starting current. Also such inverters must be set for constant torque operation with a linear V/f ratio.

The use of inverters has the following beneficial effects on starting:

- Lower mechanical stress on the motor and moving mechanical parts
- Considerable reduction in the electrical supply current during starting. The maximum compressor input current is usually not exceeded even though the actual compressor current will exceed this value for a short duration on starting.

6.3 Electrical installation

The official European regulations on Safety and EMC appropriate to the place of installation (hospital, commercial, industrial) and the conformity required (CE mark) must be given careful consideration. Special EMC filters and supply chokes may be required.

The installation recommendations and instructions of the manufacturer of the frequency inverter should be observed in detail and with great care. In particular the following should be verified:

- Cable between the compressor motor and the frequency inverter should have a copper screen or other suitable EMC shielding which is connected to both the mounting plate of the electrical enclosure and to the body of the motor with large contact-area bonding of the screen without any “pigtail” connections. The motor should also be earthed using the earth core of this cable.
- In addition the compressor mounting frame should be separately earthed with cable of suitable cross-sectional area.
- The recommendations of the manufacturer of the frequency inverter concerning motor cable should be observed. In particular:
  - The length must not exceed the maximum specified length
  - The spacing to other cables must confirm to recommendations.

– The temperature of the cooling air around the inverter must also be considered. Operation at a high temperature will result in a significant reduction of the working life of the inverter. A 10 K increase of temperature can half the working life of typical inverters, the critical components being the bearings of the fans and the DC link capacitors.

6.4 Safety circuit

Safety relevant trips such as the activation a high-pressure trip must result in an immediate stop of the inverter without relying on any electronic control circuitry. Suitable means of achieving a “safe stop” in an emergency (such as a high–pressure trip) must be provided for. This could be by using a contactor between the inverter and the compressor motor or by using an inverter with an integrated and qualified electronic safe stop circuit in accordance with EN61800-5-2
(Adjustable speed electrical power drive systems – Part 5-2:Safety requirements – Functional).

6.5 Ramp-up time to minimum speed

Experience has shown a ramp-up time between 1 .. 4 s to minimum speed to be a good compromise. This enables a soft start and at the same time adequate lubrication.

Some special scroll compressors require ramp-up times considerable longer.

Refer to the compressor supplier for recommended ramp-up times for specific compressors.

6.6 Start boost

To ensure a successful compressor start it is recommended that the starting torque is increased momentarily (so-called boost). To achieve this, the motor voltage should be increased at low frequency during starting to exceed the linear V/f characteristic or other equivalent method be used. Refer to the inverter manufacturer’s documentation on how to adjust parameters for an increased torque during starting.

Start boost should only affect the start phase and must never lead to a deviation from the normal V/f characteristic or other equivalent continuous control method during normal operation.

The amount of inverter short-term overload current reserve to ensure reliable starting depends on the number of cylinders with reciprocating compressors and on various other factors with other compressor types. Fig. 4.1a…d indicate typical values. The compressor manufacturer should be consulted for suitable recommendations.

6.7 Modulation frequency

The modulation frequency (or switching frequency) is the frequency at which the voltage of the power output stage of the inverter switches between the positive and negative voltages of the DC link in the inverter. The output voltage is the fundamental component normally in the range of 25 … 60 Hz. The modulation can produce acoustic noise. Every voltage transition is a stress for the motor winding and insulation. Therefore the modulation frequency should therefore be set to the lowest possible frequency. Typical values are 2 … 6 kHz to ensure a long working life of the compressor motor.

6.8 Cable between the Frequency Inverter and the Compressor Motor

The following general recommendations ensure good reliability and a long working life of the compressor motor and the frequency inverter (see also section 6.3 for similar requirements for EMC conformance):

- Use copper screened multi-core cable with large contact-area bonding of the screen to the mounting plate of the electrical enclosure and to the frame of the compressor.
- Verify that the cable length is within the recommendations of the Frequency Inverter

6.9 Inverter output voltage switching

The output of modern frequency inverters using modern IGBT power-electronic technology switch at a high rate of change of voltage (typically 5 kV/µs) often referred to as dV/dt. This high dV/dt at the inverter output is a potential hazard to the insulation of the copper winding due to the risk of so-called “partial discharge” effect.
Experience from a large number of compressors fed by inverters has shown that this is a negligible problem at normal operating voltages of 3AC 400 V. However it is recommended that the electrical installation is conducted in accordance with the recommendations in Section 6.3 because this will provide additional attenuation of voltage dV/dt at the motor winding. Particular reference is made to the using screened motor cable with large contact-area bonding at both the mounting plate of the inverter and also at the motor.
It is also recommended that the recommendations in the standard IEC/TS 60034-25 are adhered to.

7. Recommendations for commissioning

7.1 Vibration

The following sources of vibration can occur with the variable-speed operation of compressors:

- Gas pulsations in the discharge line
- Torque vibration acting on the compressor mountings
- Torque vibration acting on the flanges for pipe connections
- Resonances with the economizer pipe of screw compressors

The frequency of these vibrations is related to the compressor operating frequency which can vary over a wide range. There is a potential danger that mechanical resonances in the compressor rack can be excited. This can result in pipe breakages due to metal fatigue or other resonance problems.

It is therefore recommended that the entire installation is carefully checked for abnormal vibrations or resonances at all possible frequencies of operation.

Frequencies at which resonances occur must be blended out by making appropriate settings of parameters of the inverter.