GUIDELINE

Last update: January 2016

ASERCOM guidelines for the design of multiple compressor racks using frequency inverters

Contents

1 SCOPE AND PURPOSE

This document provides a guideline for the design of compressor racks containing inverter driven and fixed speed compressors.

The scope is limited to refrigeration application using semi-hermetic or hermetic compressors, based on scroll, reciprocating and screw compression technology.

For a guideline of the application of inverter technology on single compressor, please refer to the *ASERCOM* document:

"**RECOMMENDATIONS FOR USING FREQUENCY INVERTERS WITH POSITIVE DISPLACEMENT REFRIGERANT COMPRESSORS**"

Most common compressor rack configurations are the following:

- **Two or more compressors: one of the two is equipped with inverter**
  - The variable speed compressor is in continuous operation.
  - The fixed speed compressors are controlled in sequence.

- **Two compressors: both are equipped with inverter**
  - The displacement of the two compressors is equal.
  - The full scale frequency ramp of the first VS compressor is controlled by the first half scale of the control signal (e.g. 0-5 V)

- The full scale frequency ramp of the second VS compressor is controlled by the second half scale of the control signal (e.g. 5-10 V)

2 SELECTION OF COMPRESSORS

The compressor rack design should include an accurate evaluation of the required capacity range. The necessary input information is:

- Capacity at lowest load (maintenance, night running, lower condensing temperature, …)
- Capacity at highest load (depending on the application, could be during cold room loading or after-defrosting events)
- Quantity of active users, and activation algorithm if any.

If activation algorithm is not available, it could be important to include a factor to correct the maximum load for simultaneous operating refrigerating loads, such as the example below:

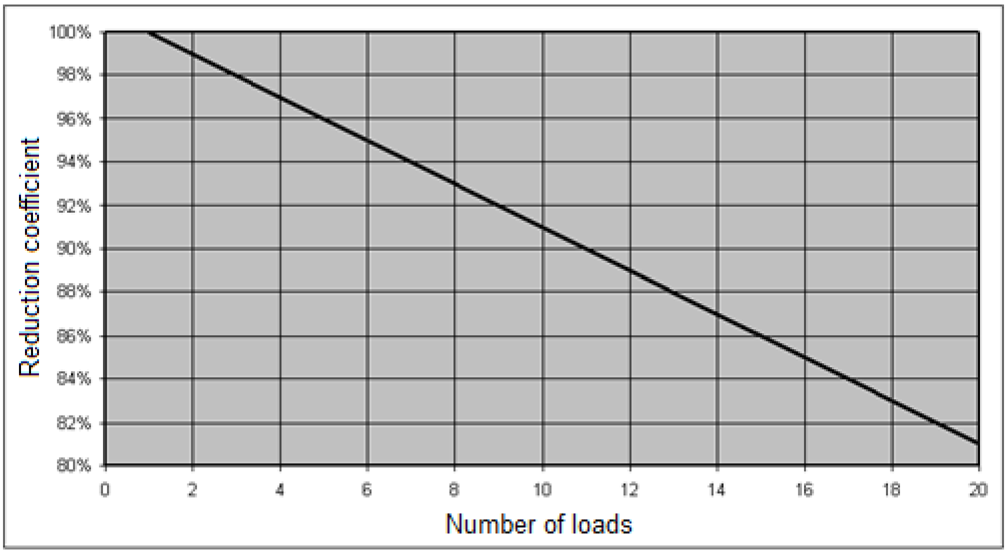


Fig. 1 – Reduction coefficient based on number of utilities

Since each utility (or user or evaporator) may contribute differently to the total load, it could be necessary to weight the single outlets on how they contribute for the duration.

The best dimensioning result is achieved when the compressor rack can fulfil the load requirement varying the refrigerating capacity from the minimum value to the maximum, with a damping effect on the inevitable steps that occurs when loads or source changes their state (ON-OFF).

Steps normally occur in multiple compressors/users systems when:

- Compressors are turned ON or OFF
- Solenoid valves on liquid line open or close
- Defrosting cycles are activated or deactivated
- Large thermal loads are connected or disconnected from the system

Steps have a negative impact on the stability of suction gas pressure and efficiency of the system.

NOTE: The use of variable-speed compressors in rack design offers a valid solution for a stable process control provided the speed and capacity variations cover the gaps created by the other compressors of the rack, when they are turned ON/OFF.

The compressor sizing process for compressor racks application having a single variable speed compressor shall at least include following steps:

I. **Select compressors size, from the manufacturer selection tools, considering the following information:**
   - Total number of compressors in rack
   - Constraints from environment (energy net, dimension, noise level, …)
   - Safety margin
   - Design working condition and allowed ranges (evaporating and condensing temperature)
   - Inverter size and compressor motor wirings (star/delta, …)

II. **Calculate the capacity gap when compressors are turned ON/OFF. A reduction coefficient to the single compressor capacity could be possibly applied, for the pressure loss in the rack suction line.**

III. **On the manufacturer selection tool check the frequency limit of the variable speed compressor at the design working condition and the allowed ranges:**

   - Higher and lower frequency limit at design working condition and based on selected refrigerant

IV. **Eventually change the size of the variable speed compressor or select a different motor wiring to extend the maximum frequency limit.**

V. **Consider mutual influences between other modulating devices, and select appropriate control devices:**

   - Condenser with fan speed control
   - EEV
   - Mechanical capacity control (CC head, …)
   - Feature of the control device

IMPORTANT NOTE

In order to achieve a continuous step-less capacity modulation, it is important to select those sizes of the compressors which comply with the following equation:

$$Qvsmax - Qvsmin \geq Qfs$$

Where

- Qvs_{MAX} = Capacity of Variable Speed compressor at maximum frequency
- Qvs_{MIN} = Capacity of Variable Speed compressor at minimum frequency
- Qfs = Capacity of Fixed Speed compressor

The relationship and the control factor coefficient (CF) defined below could be of help in the selection of compressors size:

$$CF = \frac{(QVsCmax - QVsCmin)}{QFsC} 100\,\%$$

Where,

QVsCmax	Refrigerating capacity of VsC at maximum speed
QVsCmin	Refrigerating capacity of VsC at minimum speed
QFsC	Minimum refrigerating capacity of FsC (taking capacity control into consideration if fitted)
VsC	Variable speed compressor
FsC	Fixed speed compressor

The control performance can be assessed for the following values of CF:

≥ 100%	Excellent, few fluctuations in suction pressure
≥ 80%	Good, some fluctuations in suction pressure
≥ 70%	Acceptable but several fluctuations in suction pressure
≤ 69%	Unacceptable, several fluctuations in suction pressure with instability of control

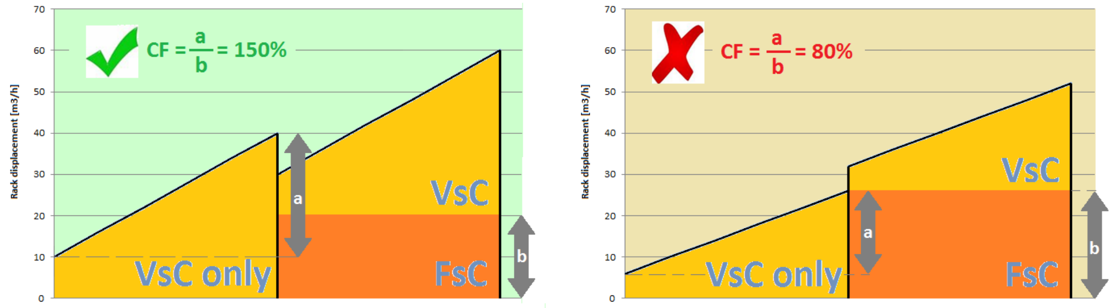
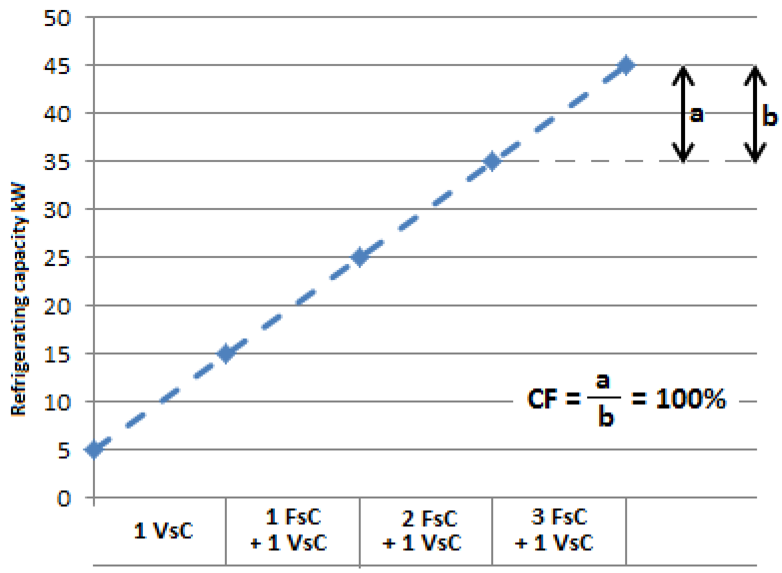


Fig. 2 – Displacement difference between optimum and non-optimum design

NOTE:

The frequency limits shall be provided by the compressor manufacturer. If no information is available then ASERCOM Guidelines “**RECOMMENDATIONS FOR USING FREQUENCY INVERTERS WITH POSITIVE DISPLACEMENT REFRIGERANT COMPRESSORS**” could be used for guidance.



Rack with four compressors
1 VsC, Qmin = 5kW,
Qmax = 15kW
3 FsC, Qrated = 10kW each
Qtot = 45kW at full speed

Fig. 3 – Refrigerating capacity in a compressor rack − optimum design

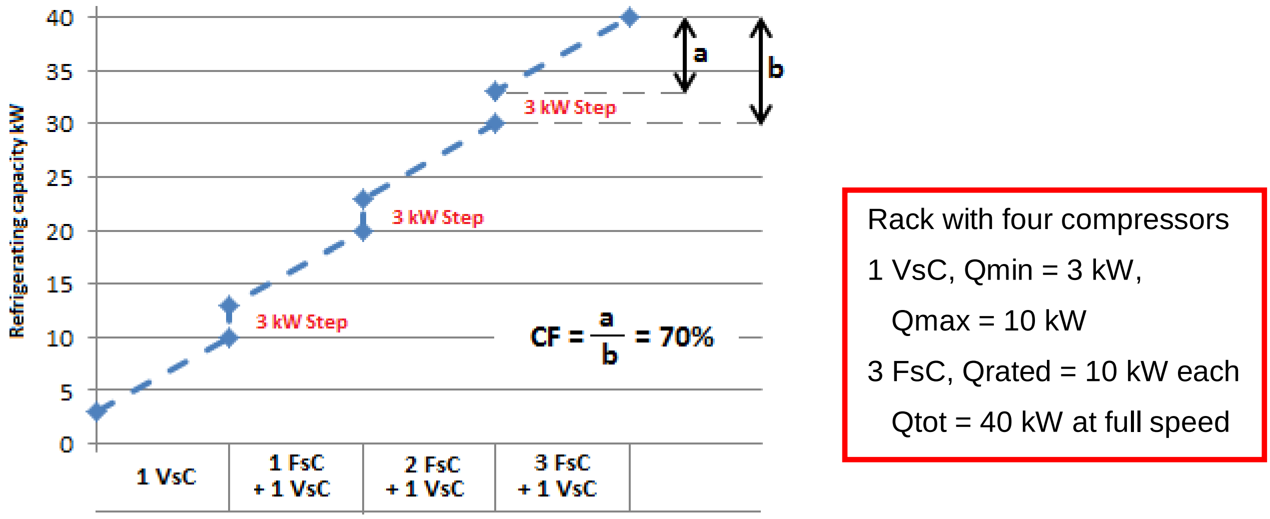


Fig. 4 – Refrigerating capacity in a compressor rack − non-optimum design

Notice how the second selection (Fig. 4) leads to discontinuities in the regulation of the refrigerating capacity. If the steps are significant, they can lead to instable operating temperatures.

3 DESIGN FEATURES

The common design criteria applicable to compressor racks are widely recognised and applied for the last many years by different rack manufacturers.

This guideline refers to those design concerns that are likely to be influenced by the variable speed capacity control, such as:

- Oil separation, oil level control and distribution between compressors
- Suction and discharge line sizing, layout and mountings
- Measuring points for pressure and temperature feedbacks
- Vibration damping − noise mitigation
- Interaction with mechanical capacity control
- Safety devices

The control design criteria are treated in more detail in the next chapter 4.

Important note: In this chapter, general design guidelines are described and represented. Proposed design criteria shall be evaluated for each specific application.

3.1 Oil separation, level control and distribution

The oil management in a system with variable speed compressors requires special attention.

In widely branched systems with large load variation, oil return is a possible challenge and requires special attention to system design and the selection of oil separator(s).

In a tandem compressor arrangement having one of the two motors varied in speed by inverter, the oil level may differ between the compressors. In this case it might be necessary to use a specially designed oil and gas equalizing arrangement or an active oil level control system (according to manufacturer's specification).

In a multi compressor system, the dimensioning of pipelines, oil separator, oil reservoir etc. could turn out to be oversized at low frequency operation of a single compressor. This may impact oil return to the compressors.

The control of oil level inside the variable-speed compressor becomes critical and simple equalizing arrangements may not be sufficient. To effectively manage oil return it is recommended to use oil level control on each of the compressors.

A very common solution is to choose a system with a single oil separator and oil reservoir – connected to the suction header with a differential pressure valve in between for maintaining a higher pressure in the reservoir of approx. 1.4 bar. The reservoir can also be integrated in the oil separator which then is under high pressure. Both solutions allow for adequate oil distribution to each compressor by oil level regulators which, however, must be designed accordingly for low or high pressure operation:

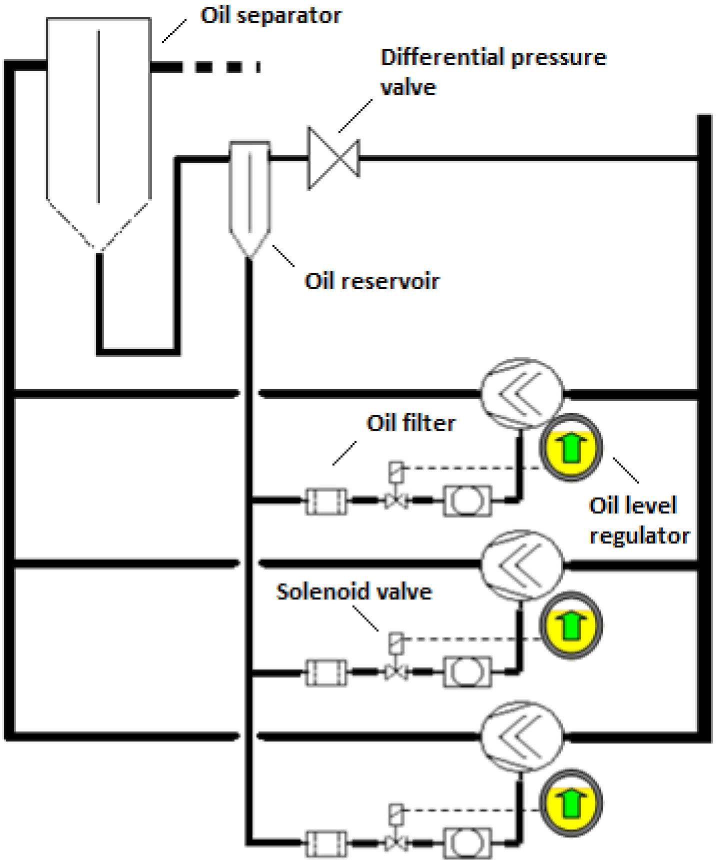


Fig. 5 − Scheme of oil distribution in a compressor rack − optimal design

3.2 Suction and discharge line sizing

Select appropriate sizes of pipes considering the displacement of the Variable Speed Compressor, when running at full speed. Proper sizing avoids excessive pressure losses at high frequencies but reduces the gas and liquid velocities in the pipeline at lower frequencies.

Vibration isolators on the discharge and suction lines of the compressors may be used to mitigate stronger vibrations. This can occur when the variable speed compressor runs through the resonance frequencies of the pipes. This reduces noise and avoids abnormal vibrations.

Vibration isolator mountings should follow manufacturer's instructions. In general best practice is to install them at positions where their axes are parallel to the compressor crankshaft and as close as possible to the compressor body in order to avoid pipe fractures due to metal fatigue.

With variable speed compressors discharge gas pulsations cover a wide frequency range that may result in resonance issues in the discharge line. One of the criteria for the layout of discharge lines is to avoid so-called “critical pipe lengths” as far as possible. The critical pipe length is equal to the length of the pulsation sine wave (or its harmonic fraction). In turn this wave is dependent on the oscillating frequency (discharge pulses per second) and the sonic speed of the refrigerant at discharge pressure and temperature conditions.

Due to the wide frequency range and constraints in the pipe work it is often difficult to find an ideal dimension. Therefore, it might be appropriate to install a discharge gas muffler in order to smoothen the amplitude of pulsation. This in particular with compressors which may operate at relatively low speed (pulsation frequency) and high pressure ratio.
In critical cases it is also possible to skip defined resonance frequencies by inverter configuration (see also chapter 3.5).

3.3 Relative position of fixed speed and variable speed compressors

The simplest and one of the common arrangements to use the suction-gas piping diagram as shown in Fig. 6.
However there is a danger that the sharp redirection of the gas flow can lead to a centrifugal effects of oil separation if the VsC compressor is located at the first position. The higher density oil will be separated at the dead end of the pipe. This can lead to severe oil slugging after the start of the single compressor.
However this system is only recommended in conjunction with an oil regulation system on each compressor.

A preferable arrangement is to design the piping in order to have an equal redirection of gas and oil (see Fig. 7). The variable-speed compressor can be mounted at any position. With good design this system may sometimes be operated without an oil regulation system.

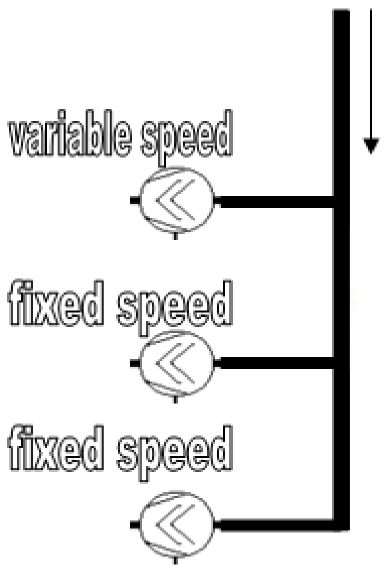


Fig. 6 − Pipe distribution at the suction side of compressors in a rack system

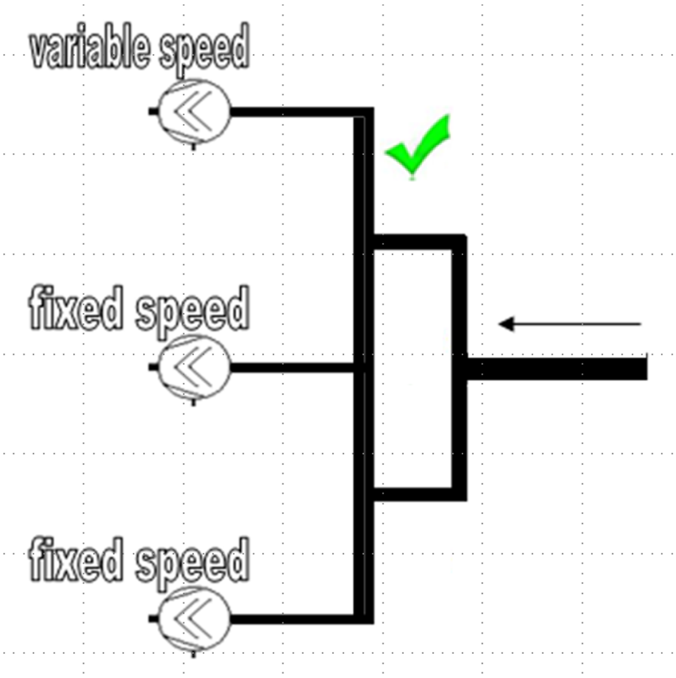


Fig 7. − Alternative system of good design which may allow to operate without an oil-level control

3.4 Measuring point of suction pressure

In case of suction pressure control the measuring position of pressure in the suction line is important for good regulation. In order to minimize pressure pulsations it is recommended the pressure transmitter is mounted on the suction header.

Increasing distance of the measuring point from fixed speed compressors suction port also helps damping pressure fluctuations when fixed speed compressors are turned ON/OFF.

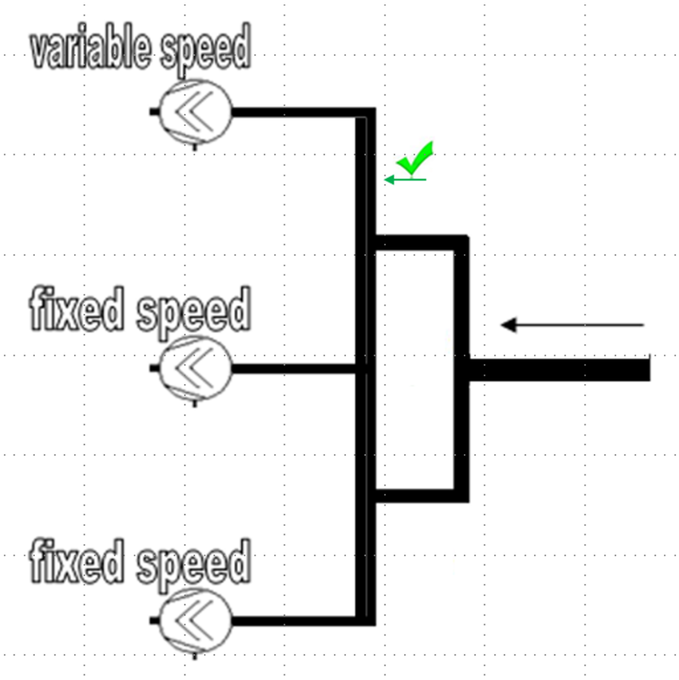


Fig. 8 – Preferred measuring point of suction pressure

3.5 Vibration damping

The rubber vibration absorber bushes supplied with most compressors are designed for operation at 50 and 60 Hz. During low frequency operation severe compressor vibrations can occur. This usually requires alternative solutions such as the use of solid mounting elements between compressors and frame.

In particular, it could be advantageous to follow guidelines stated below:

1. Use rigid mountings made of plastic or metal bushes beneath the compressor mounting feet.
2. Use flexible mountings beneath the compressor or rack sub-frame with vibration absorbers which are apart at least 2 times the distance between the compressor mounting legs.

The following figures show some mounting alternatives:

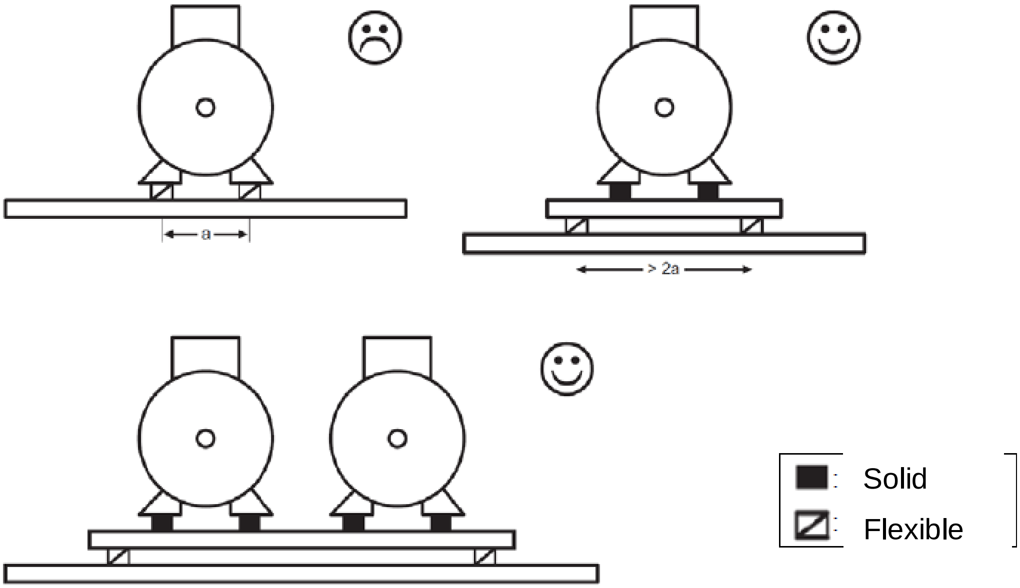


Fig. 9 – Example of vibration damping mounting

If stronger vibrations occur at certain frequencies, only it is possible to reduce the problem with the use of inverter control features (if available). In many cases, it is possible to skip defined resonance frequencies without creating relevant problems of discontinuity in the cooling capacity control.

It is recommended to carefully check the whole installation and take measures to mitigate and prevent abnormal vibrations or resonance within the operating frequency range in order to avoid pipe fractures and other associated issues (noise, …).

On a refrigeration compressor rack it is always recommended to electrically connect the compressors such as their direction of rotation is the same.

3.6 Interaction with Mechanical Capacity Control, EEV and Fan Speed Regulator

As explained in chapter 2, in rack applications it is advisable to minimize the step size of the discontinuities produced when fixed speed compressors are turned on or off. This in order to improve the stable operating behaviour of the system.

This target could be achieved by incorporating mechanical capacity control in fixed speed compressors that increases the number of steps and reduces the amplitude thus enhancing process stability and reducing the size of variable speed compressor.

However, the use of mechanical capacity control on a variable-speed compressor depends on the technology used and is normally not recommended (see also "*ASERCOM* Inverter Guideline Book").

As for standard compressor racks, the use of Electronic Expansion Valves (EEV) and Fan Speed Regulator (on the condenser) is recommended to achieve stable and efficient control especially under the consideration of a very wide range of refrigerating capacity and varying seasonal ambient temperature conditions.

3.7 Interaction with other devices

Compressors released by the manufacturer for variable-speed drive are usually equipped with adequate motor protection which also features thermal monitoring. In case the compressor is equipped with a protection device for monitoring of direction of rotation (e.g. screw, scroll or rotary type) specific measures may be required – consultation of manufacturer is recommended.
If compressors with fixed direction of rotation are applied without protection modules for phase sequence control the setting of the inverter must ensure the correct phase sequence. Furthermore the correctness of wiring connections between inverter and motor terminals must be verified before start-up.

If the inverter is used to interrupt the power to the compressor (safe torque off) in order to prevent an unexpected start or when an alarm from an electrical safety device occurs, it must fulfill the new European Machinery Directive requirements. In this case the stop must be safe and quick and should not be handled by any intermediate electronic control circuit. Alternatively, the safety devices can be connected to a contactor placed between the inverter and the compressor motor. For further information see chapter 7.

If the inverter driven compressor has an oil pump, check the minimum safe speed in the manufacturer's manual to avoid a trip from the differential pressure protection device. Check also that no pressure limiter trips occur on the whole range of frequency variation or when fixed speed compressors are turned ON/OFF.

If possible connect an oil level alarm for the variable speed compressor in the safety circuit.

NOTE: Each safety device should have the right level of EMI immunity to ensure complete protection (mainly low voltage devices).

4 CONTROL FEATURES

There are various alternative methods of controlling the variable-speed Compressor (VsC) which may be used such as:

- Using an external controller with an analogue output (usually 0…10 V) to vary the inverter frequency of the compressor
- Using control functions integrated in the inverter for controlling the suction pressure or evaporation temperature. These are usually based on PI (Proportional+ Integral) control.

An advanced controller may also control the suction pressure (or evaporating temperature) in a floating mode to operate at as high a value as permissible to minimize energy consumption.
In addition, there can be features to optimize oil return and to ensure the compressor is operated within the permissible operating boundaries and electrical limitations.

There are several important limitations for ensuring reliable VsC operation with a long working life including:

- Number of starts per hour (with inverter?)
- Minimum running time
- Minimum time between starts.

The control of the variable-speed Compressor (VsC) in a multiple compressor rack system is usually combined with the control of the fixed-speed compressors (FsC) where the above limitations also apply. Here there are two predominant methods of control used:

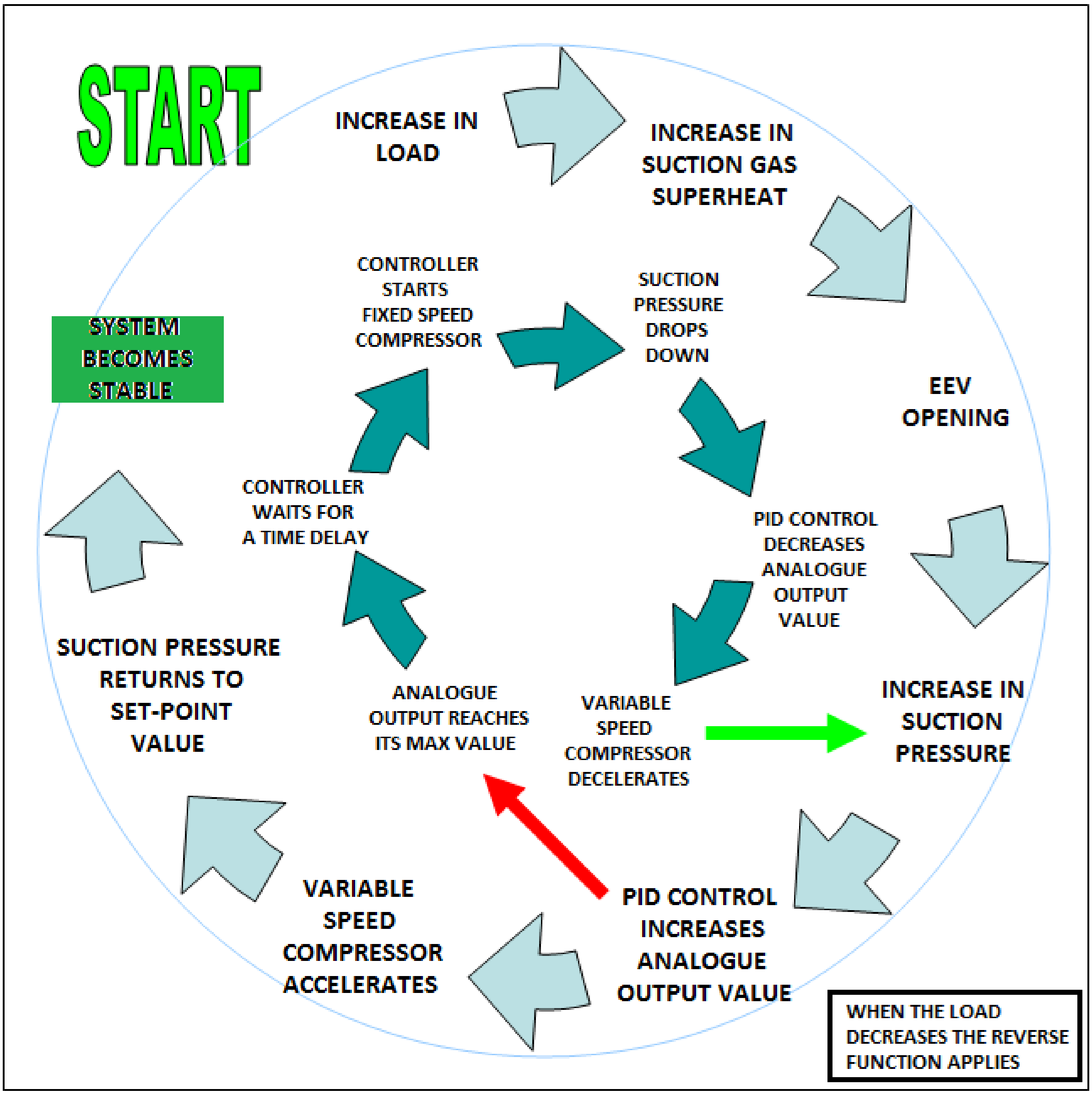
- "Neutral Zone" method of compressor rack capacity control that allows VsC to ramp up/ down in accordance with load variations as the suction pressure goes above / below the defined neutral zone. When the VsC reaches maximum / minimum speed and there is further increase / decrease of suction pressure, the FsC cuts-in / out after a defined time delay.
- Activation of a further FsC when the VsC is operated at maximum frequency longer that a defined length of time (time delay). Similarly one FsC less when the VsC is operated at minimum frequency longer that a defined length of time.

The Control Factor (CF) referred to in Section 2 is very important to achieve stable energy-saving operation.

With above methods of control the VsC compensates for variations in capacity during normal operation. Only when there is a large variation in capacity is it necessary to bring in or drop off one FsC in a compressor-rack situation. This results in an increase in the working life of the compressors as the number of starts and stops is considerably reduced.

This method of control is illustrated in Fig. 10, whereby:

- The external loop shows the operation of the VsC compensating for normal variations in refrigerating capacity
- The inner loop shows the action when a further FsC is required to meet the capacity requirement.



OUTER LOOP: CONTRIBUTE BY Vs COMPRESSORS
INNER LOOP: CONTRIBUTE BY Fs AND Vs COMPRESSORS

Fig. 10 − Illustration for method of control in variable speed compressor racks

5 STABILITY OF WORKING CONDITION & ENERGY SAVING

Compressor installations based on single or multiple fixed-speed compressor racks always have an inherent deviation in evaporating temperature (capacity too high or too low). The actual deviation depends on the design of the system.

When using a correctly-designed variable-speed compressor (VsC) system this deviation can be reduced by a factor of typically 5 (often higher), see Fig. 5. An analysis of the compressor data indicates that this results in an important reduction in energy consumption.
In addition the expansion-valve control (with a relatively slow response time) is better able to ensure that evaporator filling is an optimum which is also important for minimizing energy consumption.

Since heat exchangers are always designed for full load operating conditions. The capability of operating stably at part load with inverter control enables operation at higher evaporating and lower condensing temperatures for the same cooling requirement. The coefficient of performance (COP) of the compressors is higher with a resulting lower energy consumption. This is particularly relevant as the time at part-load operating conditions is usually dominant.

The more stable operating conditions of inverter-based compressor systems with reduced deviation also lead to the following benefits:

- In Chiller systems, the possibility of downsizing the capacity of the associated water-storage tank often used to minimize temperature variations.
- Better temperature control for critical applications such as in food processing, plastic injection moulding machines. The process wastage and thermal shock is considerably reduced.

Figures 5.1 and 5.2 illustrate the reduction in power consumption and the improvement in COP under part-load conditions.

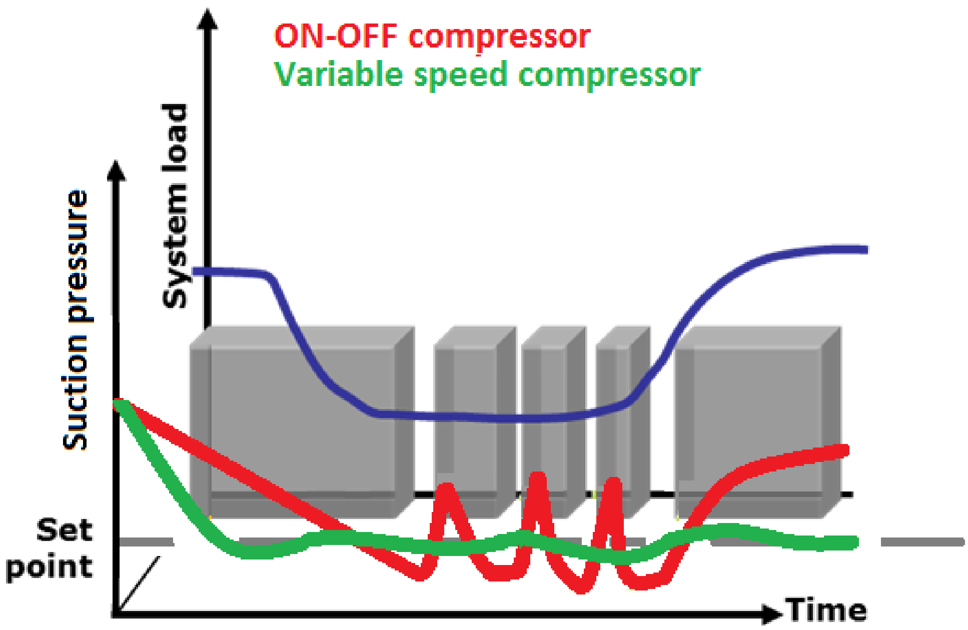


Fig. 11 − Illustration of suction pressure control – variable speed compared with ON/OFF control

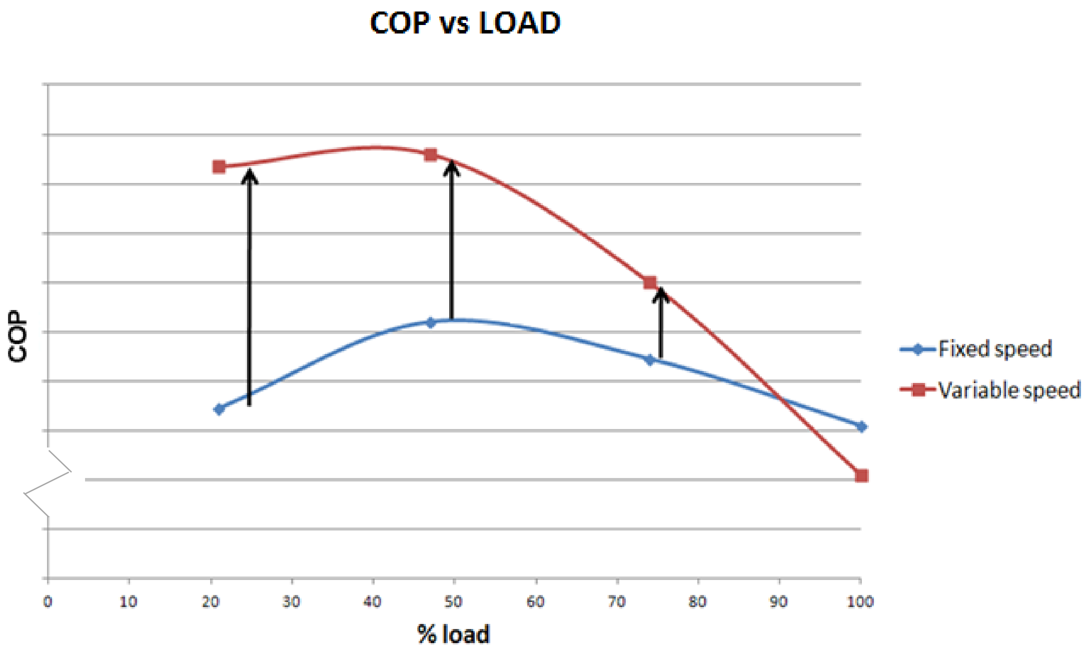


Fig. 12 − Example of COP characteristics of a variable speed compressor compared to a single fixed speed compressor with mechanical capacity control

6 LIFETIME EXTENSION - RELIABILITY

6.1 Compressor reliability

- Start /stop sequence
  Most of the mechanical wear in a compressor occurs during transient phase and especially during start and stop sequence.

  The variable-speed compressor will operate most of the time thus having very low ON/OFF cycles . This is also valid for the fixed compressors in a multiple compressor rack as they will also cycle less. This means:

  - less electrical stress on the motor winding.
  - less mechanical stress on all moving parts of the compressors.

- Smooth start up (soft start)
  With the inverter parameters being properly set up, the controlled speed ramp-up will reduce stress on the compressor mechanical parts. The inrush current being also reduced by the drive leads to lower stress on the motor winding as well.

- Drive protections
  Most of the inverters will also provide current monitoring and will reduce the compressor speed in case of overload.
  Protections against short cycling, phase loss and reverse rotation are common features in drives.

All above features provided by the inverters will extend the lifetime of the compressors.

6.2 Reliability of a multiple-compressor rack:

- Vibration
  The main constraint on the multiple compressor rack is vibration generated by the variable speed compressor. The large speed range can potentially increase the risk of rack operation near its natural frequency. This has to be carefully checked during qualification. Some inverters are capable to skip certain frequency ranges to avoid strong resonances with the consequence of pipe or frame element fractures. The frequencies to be skipped are manually entered in the inverter parameters.
  This feature can be also used in the field when the rack is installed in the refrigeration system. The rack natural frequency can shift when the piping is connected and when the rack is fixed on the unit frame.

- Piping fatigue
  Reduced number of start /stop on the compressors will also limit the fatigue on the rack piping.

7 CONFORMITY TO SAFETY STANDARDS

The regulations for refrigeration equipment reference the safety standard EN 60204-1 (Safety of machinery - Electrical equipment of machines - Part 1 General requirements)

It is established and proven practice that safety circuits (including pressure-limiting devices) are processed by electromechanical devices such as relays or contactors.

It is not permissible to use standard software-based automation controls (such as PLCs) as these are not functionally fail-safe or a software error can result in dangerous operating conditions.

In an emergency (such as a pressure-limit reached) the Stop Category 0 (immediate removal of power) is appropriate

Contactor interruption in the energy supply to the compressor is a proven circuit technique for the immediate and safe stopping of compressor motors in an emergency condition.

The integrated Safe Torque-Off (STO) function of a Frequency Inverter may be used as an alternative method provided that a bypass contactor is not used. With correct installation a Safety Integrity Level of SIL3 can be achieved.

A typical safety circuit would normally consist of the following:
- Essential safety-relevant devices such as approved over-pressure switches
- Optional devices such as low-pressure switches, oil pressure or level monitoring controls
- Sensible devices such as motor over-temperature relays

The previously described standards and recommendations are general guidelines for the safety-relevant design of the installation.

However it is the installer or contractor's responsibility to assess the risk of each installation and to ensure that all safety measures are appropriate and functional.