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(71) Applicant *(for all designated States except US)*: **CARRIER CORPORATION** [US/US]; One Carrier Place, P.O. Box 4015, Farmington, CT 06034-4015 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **WILSON, Francis, P.** [US/US]; 101 Cedar Lane, Jamesville, NY 13078 (US). **ROUSEAU, William, H.** [US/US]; 5 Myrtlewood Drive, Savannah, GA 31405 (US). **WILSON, James, C.** [US/US]; 3918 Stone Quarry Road, Cazenovia, NY 13035 (US). **YANNASCOLI, Donald** [US/US]; 8543 Lamp Post Circle, Manlius, NY 13104 (US).

(74) Agent: **SLATE, William, B.**; Suite 1201, 900 Chapel Street, New Haven, CT 06510-2802 (US).

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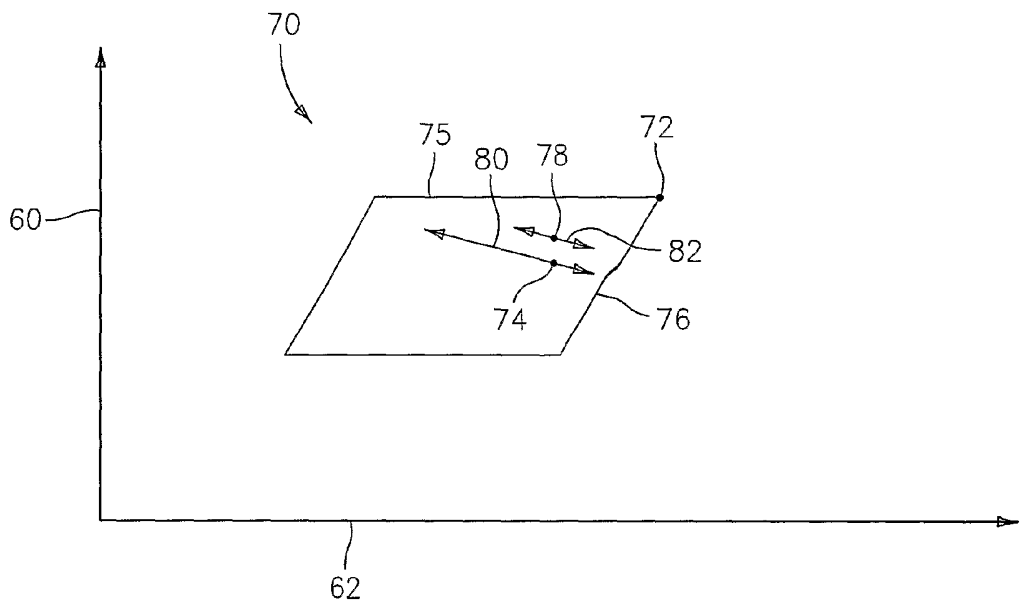
(54) **Title:** VSD CONTROL



(57) **Abstract:** A compressor is powered by a motor which is, in turn, powered by a variable speed drive (VSD). The voltage/frequency relationship of the VSD may be adjusted dynamically to maximize efficiency or permit performance within a compressor performance envelope otherwise unavailable in view of the VSD and motor.

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VSD CONTROL

CROSS-REFERENCE TO RELATED APPLICATION

[0001] Benefit is claimed of U.S. Patent Application Ser. No. 60/623,355, filed October 29, 2004, and entitled "VSC Control", the disclosure of which is incorporated by reference herein as if set forth at length.

BACKGROUND OF THE INVENTION

[0002] This invention relates to motor control. More particularly, the invention relates to control of variable speed drives for compressor motors.

[0003] In refrigeration applications, a compressor is used to compress a working fluid (the refrigerant) from initial (suction) conditions to compressed (discharge) conditions. The initial conditions are characterized by a saturated suction temperature (SST) and the discharge conditions are characterized by a saturated discharge temperature (SDT). For a given refrigerant, the compressor (exclusive of the motor powering it) will have a performance envelope dictated by a variety of considerations including efficiency and longevity. This envelope may be approximated by a three dimensional space whose dimensions are SST, SDT, and a third dimension (e.g., a compressor speed or a power parameter) indicative of an output in view of the other two dimensions. Considerations involving the motor and other components will further restrict the system operating envelope within the compressor operating envelope.

[0004] An exemplary compressor is powered by a hermetic motor which is, in turn, powered by a variable speed drive (VSD). The VSD supplies an alternating current output voltage at an output frequency. The VSD receives power from a power supply (e.g., 460 VAC, 60 Hz). In a basic VSD, the relationship between output voltage and output frequency is substantially fixed and approximately linear. With such a basic VSD and hermetic motor, the motor speed is a substantially fixed and approximately linear function of drive frequency. In the absence of a variable ratio transmission, the ratio of motor speed to compressor speed will be fixed and may be a simple 1:1 ratio.

[0005] The torque required by the compressor (and thus supplied by the motor) will essentially be a function of SDT and SST and will essentially be independent of the third compressor performance envelope parameter. In the basic operation, at given SST and SDT, the motor and compressor speed will be determined by the load (e.g., the air conditioning load). A given motor speed is associated with a proportional frequency position on the drive's fixed voltage/frequency curve (line). At a given point on the voltage/frequency curve, however, the current draw of the drive will accordingly be determined by the SST and SDT values. For example, at a given voltage and frequency, if the SDT were to increase suddenly, the torque would increase at a given speed thus necessitating a power increase from the VSD and, accordingly, a current increase.

[0006] Certain VSD's permit selection of the voltage/frequency relationship. These are typically preset when the drive is associated with its motor for a given application.

BRIEF SUMMARY OF THE INVENTION

[0007] One aspect of the invention is to dynamically change the voltage/frequency characteristic curve (line) with the intent to allow the compressor/motor/VSD system to operate over a broader portion of the SST/SDT/speed operating spectrum.

[0008] Accordingly, implementations of the invention may involve a method for controlling a VSD supplying electric power to a motor to drive a compressor. Within a portion of a compressor performance envelope, the VSD is operated with a dynamically changing relationship of voltage to frequency. The relationship in this portion may be essentially current-limited by a maximum current of the drive. The operating may involve operating at a first condition with a first torque and a ratio of voltage to frequency having a first value and with a first current draw that is a maximum target current draw. Operation transitions from the first condition to a second condition with a second torque, greater than the first torque, and with the voltage to frequency ratio having a second value, greater than the first value. In the second condition, a second current draw may be essentially no greater than the first current draw. The second voltage may be greater than the first voltage and/or the second frequency may be smaller than the first frequency.

[0009] Various implementations of the invention may involve a compressor system having a compressor, a motor coupled to the compressor to drive the compressor and a VSD coupled to the motor to supply the motor with electric power. A control system is coupled to the VSD and is programmed to operate the VSD to supply the power.

[0010] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a graph of compressor operating parameters.

[0012] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0013] In a refrigeration system, if the compressor physical and operating parameters are given, control of motor and VSD operating parameters may be utilized to provide an expanded envelope of operation. For example, the compressor physical parameters would include the configuration and size of the compressor and the nature of its working fluid. The operating parameters would include the saturated suction temperature (SST) and saturated discharge temperature (SDT) for a target or other operating environment. These values may serve as proxies for suction and discharge pressures.

[0014] For a given compressor, the required motor torque will be a function of the SST and SDT. If these values are fixed, torque will be essentially fixed. If motor torque is fixed then the motor power output is proportional to the motor (rotational) speed. In a typical system, there is a fixed linear normal or default voltage/frequency curve (shaft speed and frequency being essentially related by a constant factor).

[0015] Possibilities arise when different torques are considered. FIG. 1 shows exemplary compressor operating conditions characterized by the saturated discharge temperature 60 and saturated suction temperature 62 of refrigerant being compressed. The closed curve 70 contains the operating points practical for a given compressor/fluid. Different drive and motor combinations may be selected to permit operation in some or all of this envelope. Where such combinations serve overlapping portions of that envelope, they may have different efficiency, cost, or other attributes. By way of example, FIG. 1 shows a maximum point 72 which corresponds to the highest torque requirement. Point 74 identifies a desired normal operating condition. For example, in a building air conditioning system the normal condition may be associated with interior and exterior temperatures, each associated with a respective SST and SDT. The operating envelope may include, as an additional dimension, a compressor speed range.

[0016] The power input to the motor is given by the equation:

$$\dot{W}_{in} = V \cdot I \cdot PF\sqrt{3}$$

where V is voltage, I is current, and PF is the power factor. If the power factor is constant, then, at fixed power, the product of voltage and current is constant.

[0017] The power output is:

$$\dot{W}_{out} = \eta_m \dot{W}_{in}$$

where η_m is the motor efficiency.

[0018] Combining these yields:

$$\dot{W}_{out} = \eta_m V \cdot I \cdot PF\sqrt{3}$$

[0019] If the motor is idealized as having a fixed resistance R, the current I is simply V/R so that:

$$\dot{W}_{out} = \eta_m \frac{V^2}{R} PF\sqrt{3} = T\omega$$

where T is the motor torque and ω is the shaft speed.

[0020] Solving for R, this yields:

$$R = \eta_m \frac{V^2}{T\omega} PF\sqrt{3}$$

[0021] As an approximation, R is treated as a constant even though it will vary somewhat based upon operating conditions (especially upon the temperature of the motor windings. Thus at first and second operating conditions:

$$\eta_{m1}\frac{V_1^2}{T_1\omega_1}PF_1\sqrt{3}=\eta_{m2}\frac{V_2^2}{T_2\omega_2}PF_2\sqrt{3}$$

[0022] If the power factor and efficiency are also treated as constant (which may be a valid approximation for small changes), then:

$$\frac{V_1^2}{T_1\omega_1}=\frac{V_2^2}{T_2\omega_2}$$

[0023] Consistent with the approximations used, at a fixed motor speed, there is a small change in required torque:

$$\frac{T_2}{T_1}=\left(\frac{V_2}{V_1}\right)^2$$

[0024] At a fixed input power, the torque output by the motor will vary as the inverse of the motor speed. Thus for first and second operating conditions:

$$\frac{T_2}{T_1}=\frac{\omega_1}{\omega_2}$$

[0025] Typically, for a given supply voltage (e.g., 230-3-60 or 460-3-60 VAC) VSD's are rated by maximum current output and priced accordingly. The maximum output voltage will be limited by the supply voltage. The VSD may be selected to have the capacity to operate at the highest torque and power of the compressor or at another extreme condition along an SDT-limited portion 75 of the curve 70 or an SST-limited portion 76 of the curve 70. For example, if this max. design point is the point 72, the VSD may be selected to provide a desired power at such point. If the volts/frequency ratio of the drive is fixed, the drive will provide enough power to operate the motor at any other point in the operating envelope at the same or lower speed.

[0026] Alternatively, however, a smaller VSD may be selected. In such a situation, the VSD may be operated normally until the maximum current condition is detected (e.g., from a point 78 which is closer to the origin to and perhaps somewhat beyond the normal point 74 but not to the curve 70). For example, FIG. 5 shows constant torque curves 80 and 82 through the aforementioned normal point 74 and an increased SDT point 78, respectively. Attempting to service beyond this point 78 (e.g., toward the point 72) by moving along the normal V/f curve would involve a current overload. However, the increased torque may be achieved through increasing the voltage and decreasing the drive frequency. If the required torque is increased by the factor of 1.5, the voltage would have to increase by the square root of that factor and the speed would change by the inverse of that factor (decrease). Drive and/or motor efficiency may decrease which might require further speed reduction to maintain current below overload conditions. Accordingly, in portions of the envelope above the line 82, operation will be at reduced power output. The V/f curve may be dynamically controlled in this portion of the envelope so as to provide maximum power without overloading the drive or motor. Below this curve, operation may be along the normal V/f curve or along yet alternative V/f curves.

EXAMPLE

[0027] A particular job application specifies that a variable speed chiller will operate at 42/100 (SST=42F or 51.7psia suction pressure and SDT=100F or 140psia discharge pressure) 90% of the time, but must also be able to operate at 42/122 (SDT=122F or 191psia discharge pressure) some of the time. This part-time condition may be achieved at reduced capacity. For these operating conditions, typical compressor performance values are as follows. At 42/100, W_1=61kW, I_1=93A and T_1=112ft-lbf at ω_1 (speed at full capacity). At 42/122, W_2=80kW, I_2=122A and T_2=146.9ft-lbf at ω_2 (speed at full capacity). Rather than choosing the VSD (variable speed drive) based on the larger 122-ampere current condition, one could choose the VSD based on the 93-ampere current condition since the chiller is not actually required to operate at 42/122 at ω_1. In doing this, money could be saved since VSD costs are proportional to the current output of the drive. For example, if the nominal fixed volts/frequency proportion of the drive is 460V/60Hz this ratio can be dynamically changed to meet higher torque demand conditions at reduced speed. Table 1 shows how this is accomplished.

Table 1

Power (kW)		Voltage	Current	ω	Torque		$3^{0.5}$ x PF	V/ω
T x ω	V x I x 3 x PF	(V)	(A)	(Hz)	(ft•lb_f)	(kW•s)	(-)	ratio
61.0	61.0	460.0	93.0	60.00	112.0	1.017	1.426	460/60
80.0	80.0	460.0	122.0	60.00	146.9	1.333	1.426	460/60
80.0	80.0	526.8	106.5	60.00	146.9	1.333	1.426	526.8/60
69.9	69.9	460.0	106.5	52.39	146.9	1.333	1.426	460/52.39
61.0	61.0	401.7	106.5	45.75	146.9	1.333	1.426	460/52.39
61.0	61.0	460.0	93.0	45.75	146.9	1.333	1.426	460/45.75
80.0	80.0	460.0	122.0	45.75	192.6	1.749	1.426	460/45.75

[0028] The first row indicates the initial low torque 42/100 condition: 112 ft•lbf is the maximum torque that the motor can deliver at a voltage/frequency ratio of 460/60. The second row indicates the 42/122 high torque condition: the motor needs to deliver 146.9ft•lbf. However, the current requirement may exceed that of an economically selected drive. The third row condition shows the result of an increased voltage at constant ω to determine the new V/ω ratio (526.8/60 which is the same as 460/52.39) required to deliver the required 146.9 ft•lbf. The current is accordingly reduced to 106.5V. The fourth row condition shows the VSD voltage set to 460V with 460/52.39 ratio. The fifth row shows the maintenance of the low torque power level (61kW) at the 460V/52.39Hz ratio (multiply 60 by the ratio of torques (i.e., 60*112/146.9) to get the 45.75Hz frequency). However, to maintain 93-ampere current and knowing that at a given speed, voltage is inversely proportional to current, the new voltage is 401.7 (460*93/106.5). The maximum torque that the motor can deliver is actually 192.6 ft•lbf (((60/45.75)*460/460)2*112). The sixth row shows the maximum torque that the motor could otherwise actually deliver at 122-amperes current.

[0029] One or more embodiments of the present invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, the drive/motor control may take into account additional factors beyond those discussed and, thereby, further balance the results achieved. Accordingly, other embodiments are within the scope of the following claims.

CLAIMS

What is claimed is:

1. A method for controlling a variable speed drive supplying electric power of a voltage and frequency to a motor to drive a compressor operating within a compressor performance envelope, the method comprising:

within a portion of the envelope, operating the drive with a dynamically changing relationship of said voltage to said frequency so as to operate the compressor over a range of relative suction and discharge conditions unavailable at a fixed default voltage to frequency relationship.

2. The method of claim 1 wherein said relationship in said portion being essentially current limited by a maximum current of the drive.

3. The method of claim 1 wherein the operating comprises:

operating at a first condition with a first torque and with a ratio of said voltage to said frequency having a first value and with a first current draw that is a maximum target current draw; and

transitioning from the first condition to a second condition with a second torque, greater than the first torque, and with a ratio of said voltage to said frequency having a second value, greater than the first value.

4. The method of claim 3 wherein:

in the second condition, a second current draw is essentially no greater than the first current draw.

5. The method of claim 3 wherein at least one of:

the second voltage is greater than the first voltage; and

the second frequency is smaller than the first frequency.

6. A system for controlling a variable speed drive (VSD) supplying electric power to a motor to drive a load within a performance envelope, the system comprising an electronic controller programmed to operate the VSD to supply the electric power:

in a first portion of the envelope, operating the VSD below a limit on a current draw of the drive; and

in a second portion of the envelope, operating the VSD essentially at the limit on current draw and with varying voltage to frequency ratio.

7. The system of claim 6 wherein:

in the first portion, the operating is with a voltage to frequency ratio of an essentially fixed first value; and

in the second portion, the operating is at least partially at motor torque conditions where the drive would not be effective to drive the motor at the ratio first value.

8. The system of claim 6 wherein:

in the first portion, the operating is with a voltage to frequency ratio of an essentially fixed first value; and

in the second portion, the operating is at a voltage to frequency ratio greater than the first value..

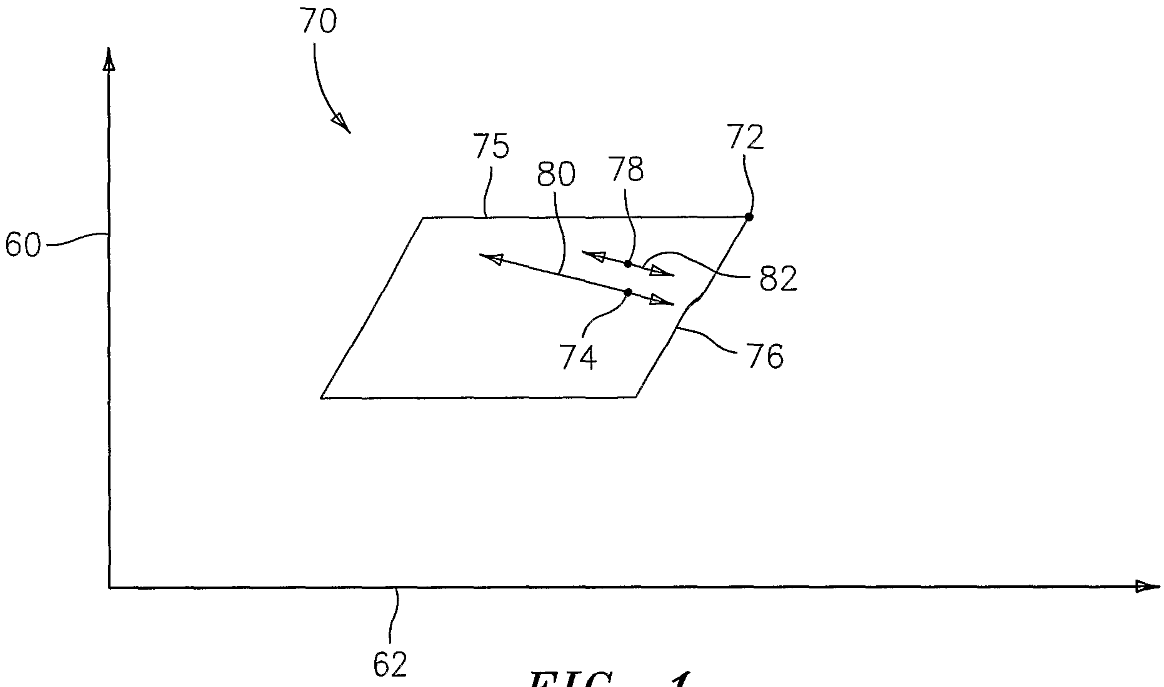

FIG. 1

INTERNATIONAL SEARCH REPORT	International application No. PCT/US05/39287

A. CLASSIFICATION OF SUBJECT MATTER
IPC: F25B 1/00(2006.01)

USPC: 62/115,228.4,230
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 62/115, 228.4, 230; 62/228.3, 228.5

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,370,888 b1 (GRABON) 16 April 2002 (16.04.2002), see Fig. 1 and column 3, lines 36-55.	1-8
A	US 4,282,719 A (KOUNTZ et al) 11 August 1981 (11.08.1981), see the entire document.	1-8
A	US 5,036,676 A (DUDLEY) 06 August 1991 (06.08.1991), see the entire document.	1-8
A	US 6,772,607 B2 (TSUBOE et al) 10 August 2004 (10.08.2004), see the entire document.	1-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US05/39287

Continuation of B. FIELDS SEARCHED Item 3:
EAST Search Tool;
Searched terms: variable speed or VSD, current, voltage, motor, compressor, maximum, limited, suction, discharge, pressure, temperature, frequency.