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(54) **SYSTEM AND METHOD FOR CAPACITY CONTROL IN A MULTIPLE COMPRESSOR CHILLER SYSTEM**

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See application file for complete search history.

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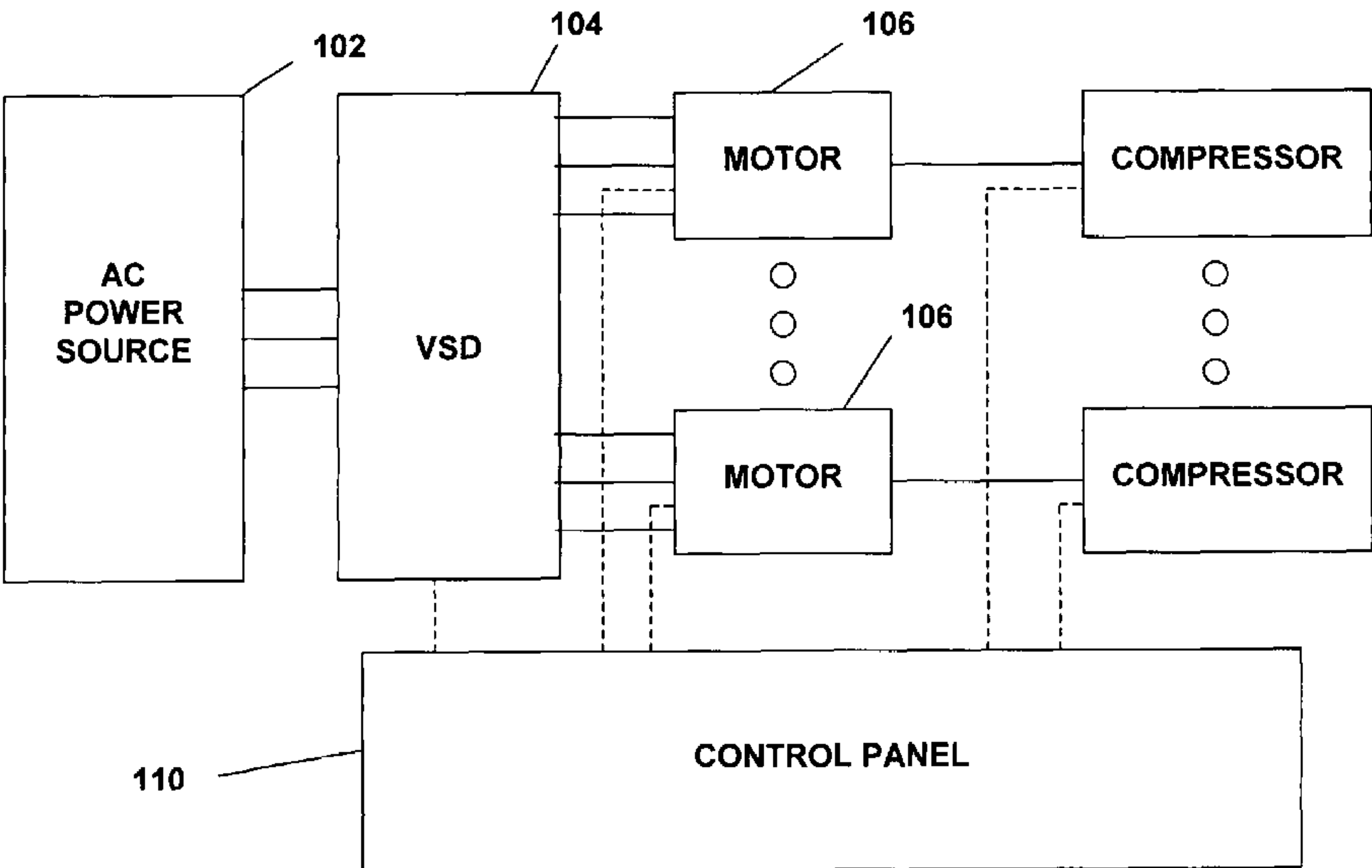
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(57) **ABSTRACT**

A capacity control algorithm for a multiple compressor liquid chiller system is provided wherein the speed and number of compressors in operation are controlled in order to obtain a leaving liquid temperature setpoint. In response to an increase in the load in the chiller system, the algorithm determines if a compressor should be started and adjusts the operating speed of all operating compressors when an additional compressor is started. In response to a decrease in the load in the chiller system with multiple compressors operating, the algorithm determines if a compressor should be de-energized and adjusts the operating speed of all remaining operating compressors when a compressor is de-energized.

42 Claims, 7 Drawing Sheets



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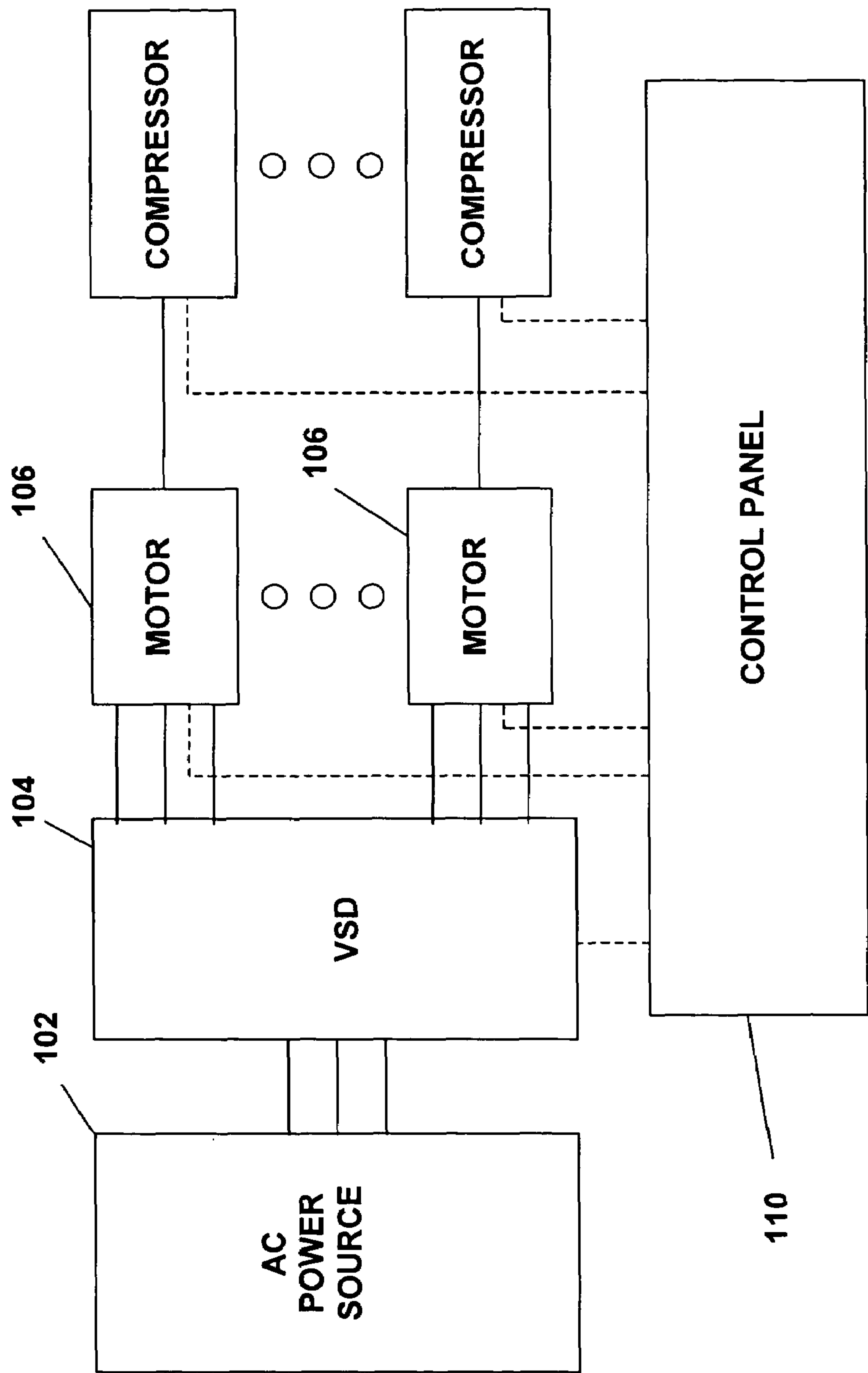


Figure 1

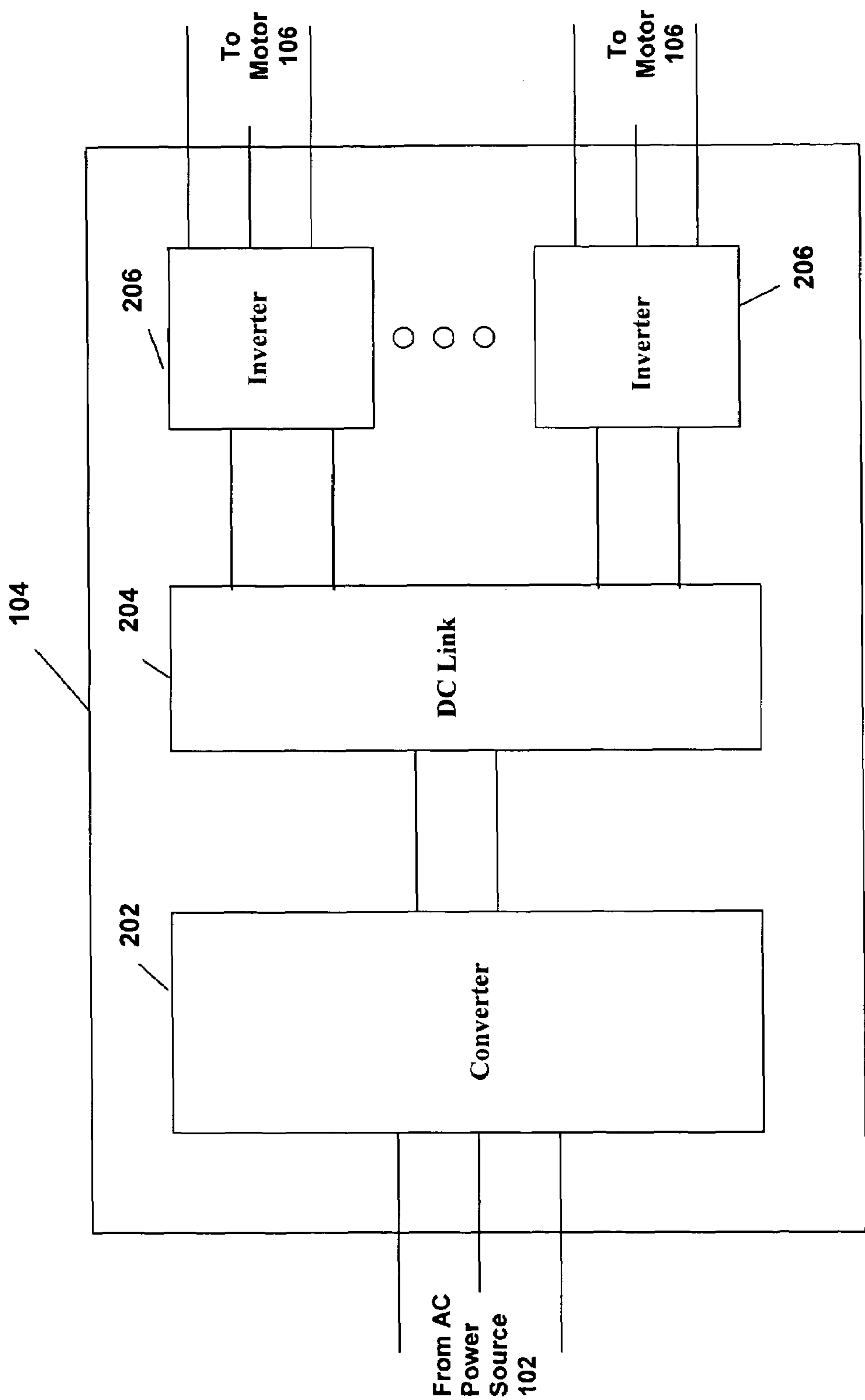


Figure 2

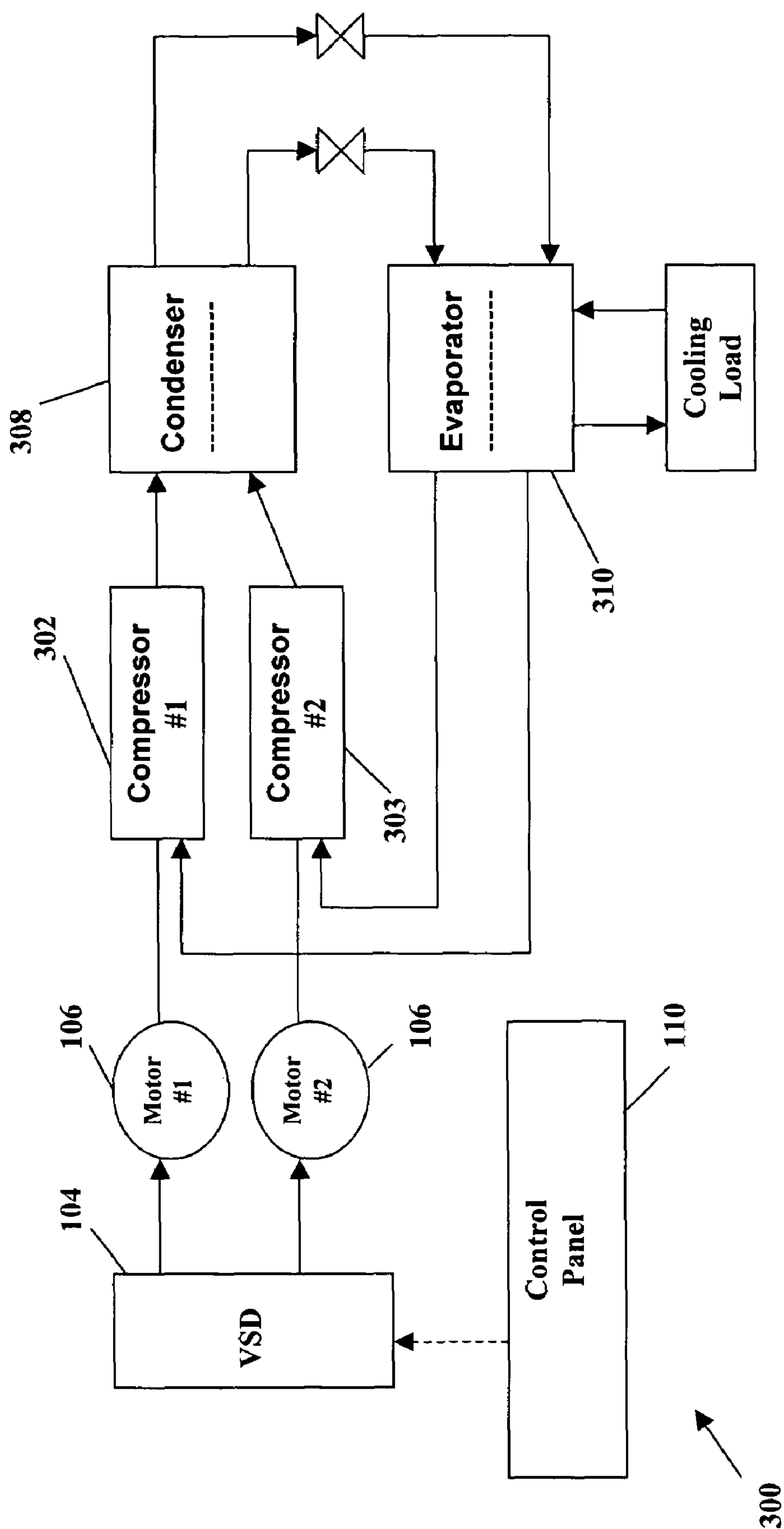


Figure 3

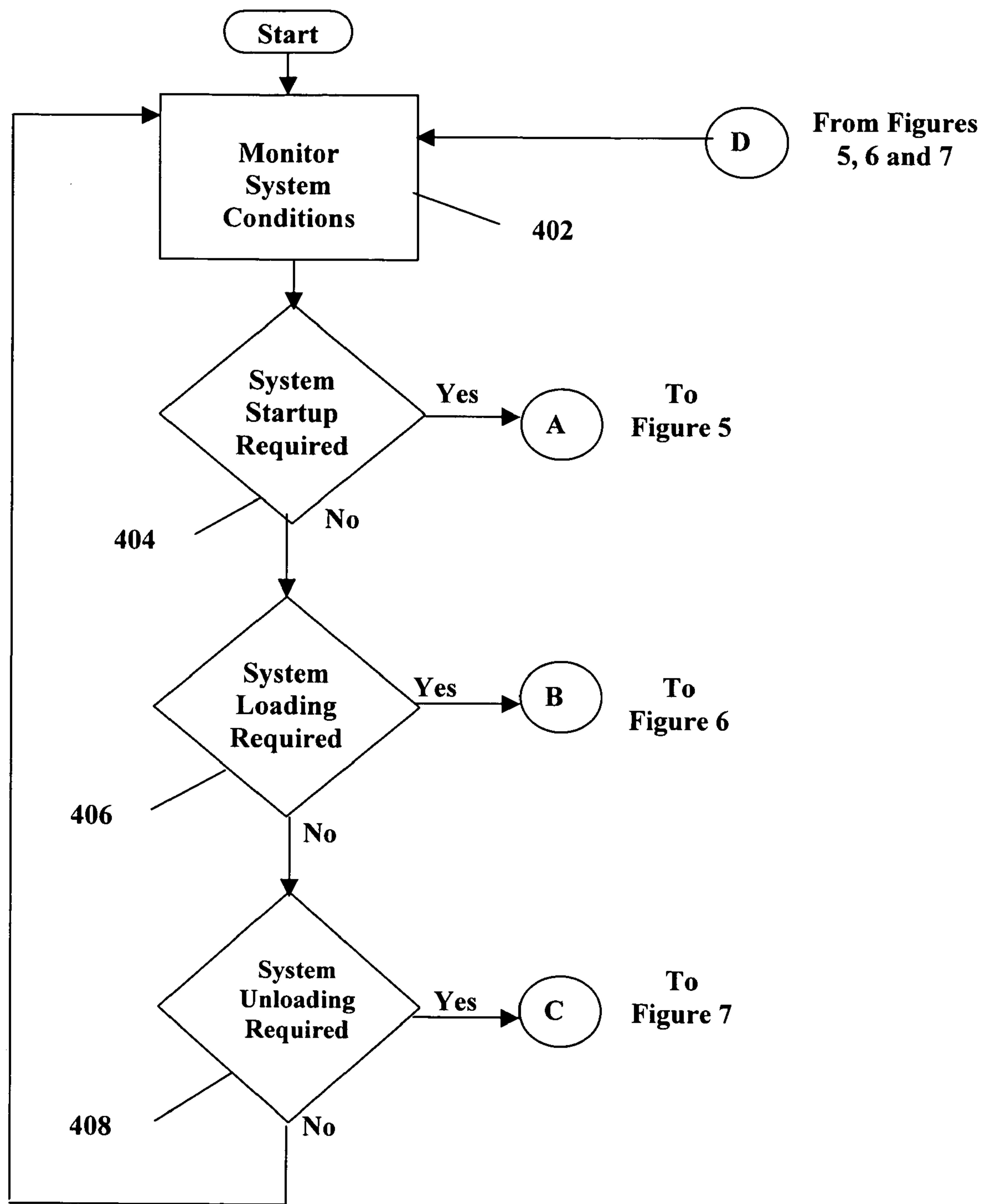
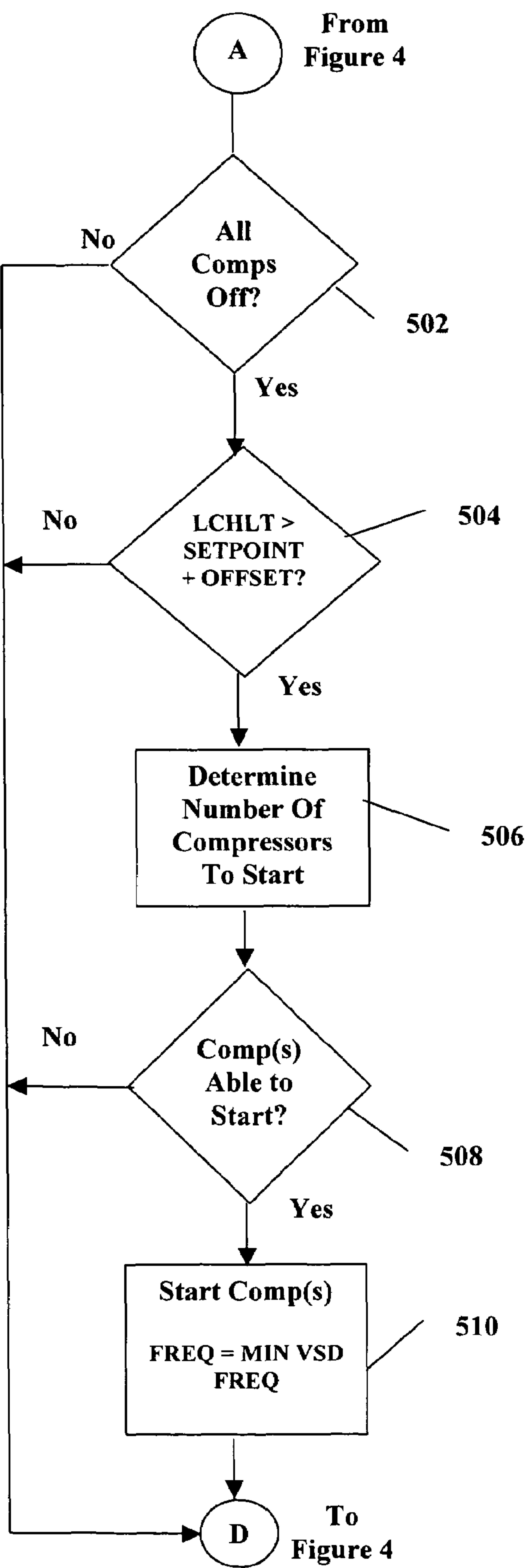
**Figure 4**

Figure 5



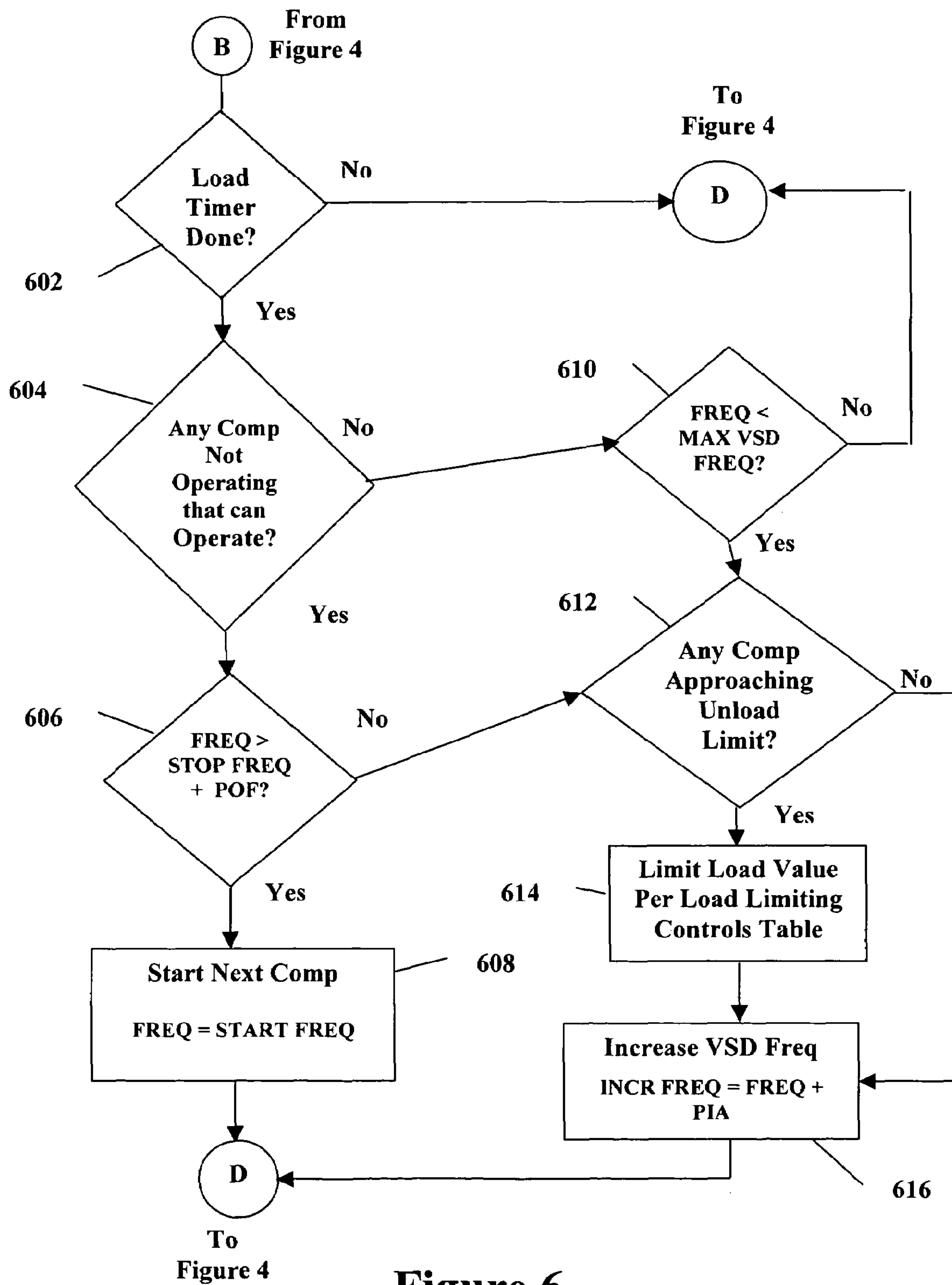
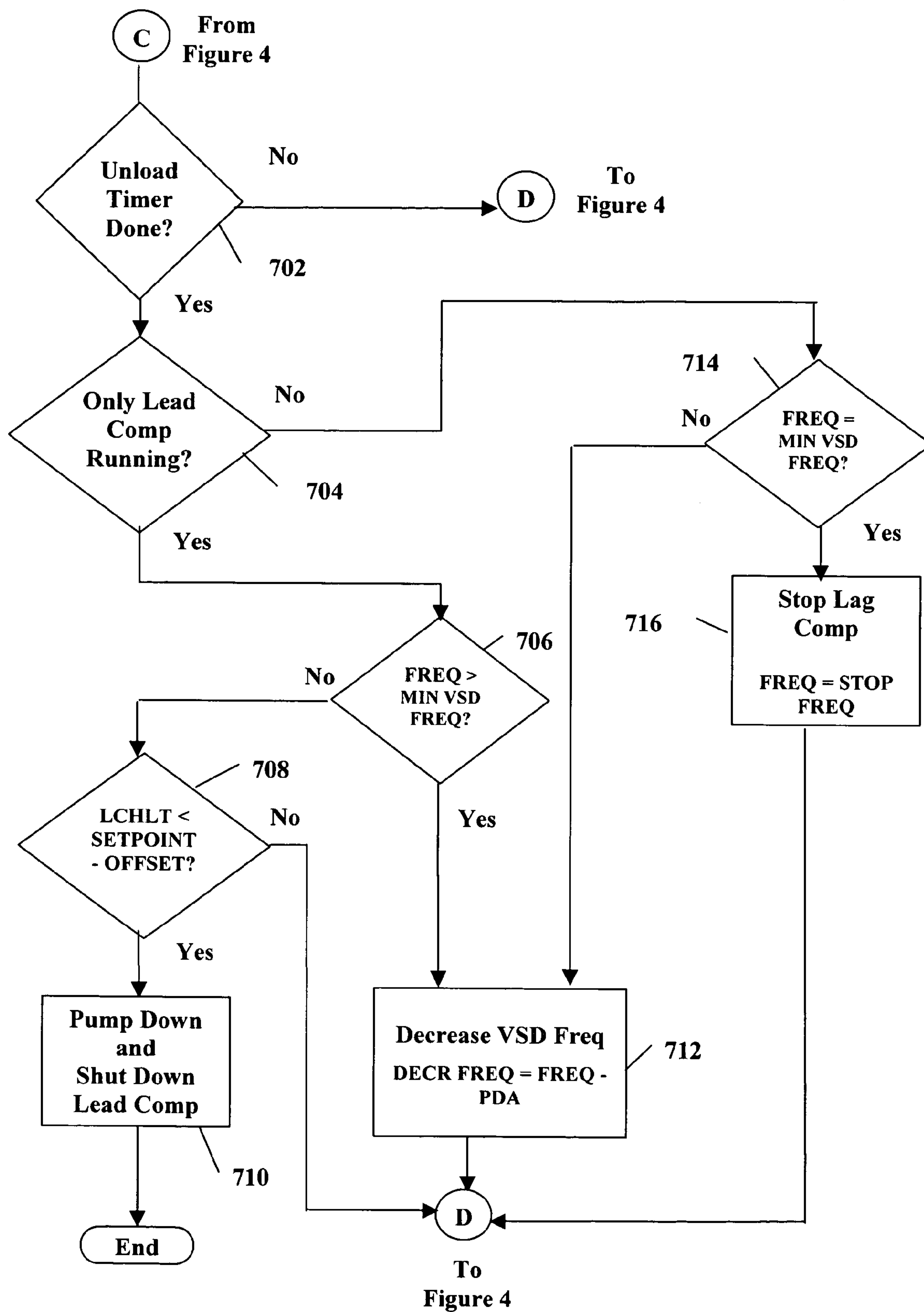


Figure 6

**Figure 7**

SYSTEM AND METHOD FOR CAPACITY CONTROL IN A MULTIPLE COMPRESSOR CHILLER SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates generally to controlling the capacity of a chiller system. More specifically, the present invention relates to controlling the capacity of a multiple compressor chiller system having a single variable speed drive to power the compressors of the chiller system.

Many liquid chiller or refrigeration applications use multiple compressors, i.e., two or more compressors, in one or more corresponding refrigerant circuits. One purpose for the use of multiple compressors is to obtain an increased capacity from the chiller system, which increased capacity could not be obtained by operating a single compressor. In addition, the use of multiple compressors can provide for improved reliability of the overall system by having one or more compressors remain operational to provide a reduced level of cooling capacity in the event that a compressor fails and can no longer provide cooling capacity.

The compressor motors of the chiller system can be powered directly from the AC power grid at the system location, which would result in the compressor being operated at only a single speed. Alternatively, the compressor motors can use a variable speed drive inserted between the system power grid and the motor to provide the motor with power at a variable frequency and variable voltage, which then results in the compressor being capable of operation at several different speeds. Variable speed operation of the motors can be obtained by providing a corresponding variable speed drive for each compressor motor or by connecting all of the compressor motors in parallel to the inverter output of a variable speed drive. One drawback of using a variable speed drive for each compressor is that the overall chiller system becomes more expensive because multiple drives with a given cumulative power rating are more expensive than a single drive of the same output power rating. One drawback to connecting the compressor motors in parallel to the single inverter output of the variable speed drive is that a fault or failure of one of the motors may disable the variable speed drive and thus prevent the other motors connected to the variable speed drive from operating the remaining compressors on the chiller system. This disabling of the other motors connected to the variable speed drive defeats the function of the redundant compressors because all the compressors are disabled as a result of the disabling of the motors and the variable speed drive.

The corresponding control for the compressor motor powered by the AC power grid is relatively simple involving mainly the starting and stopping of the motor. While the corresponding control for the variable speed drive powered compressor motor is much more complicated and involves determining an appropriate speed for each compressor motor (and compressor) based on system conditions.

One type of control for multiple compressors involves the sequential engaging and disengaging of compressors to obtain a desired system load. This control process usually involves the starting of one compressor to meet an increasing system demand and subsequently adding additional compressors until the system demand is satisfied. The compressors are then shutdown or unloaded in a similar manner in response to a decreasing system demand. One example of this type of control is found in U.S. Pat. No. 6,499,504 (the '504 Patent). The '504 Patent is directed to a compressor control system that operates in response to both the system

pressure and the volumetric flow rate capacity of the system. Specifically, a compressor is loaded or unloaded from the compressor system after sensing the actual pressure and volumetric flow rate capacity of the compressor system.

Another type of control process for multiple compressors involves determining an operating configuration for a lead compressor based on system conditions and then controlling one or more lag compressors using additional control instructions to match the output of the lead compressor. One example of this type of control is found in U.S. Pat. No. 5,343,384 (the '384 Patent). The '384 Patent is directed to a control system and method that operates a plurality of compressors at similar operating points. A microcontroller continually compares the system pressure with the desired pressure and causes corresponding adjustments, either up or down, in first, the position of the inlet valve of a lead compressor, and subsequently, in the position of the bypass valve of a lead compressor, so that these changes can be passed to the remaining compressors in the system by way of the CEM program.

Therefore, what is needed is a system and method for controlling the capacity of a multiple compressors chiller system by controlling both the operating speed of the compressors and the number of compressors in operation to maintain a leaving chilled liquid temperature setpoint in the chiller system.

SUMMARY OF THE INVENTION

One embodiment of the present invention is directed to a method for controlling the capacity of a multiple compressor chiller system. The method includes the step of providing a variable speed drive having a plurality of inverters. Each inverter is configured to power a corresponding compressor motor of a multiple compressor chiller system. The method also includes the steps of monitoring at least one operating condition of a multiple compressor chiller system, determining whether to increase output capacity of a multiple compressor chiller system in response to the at least one monitored operating condition, and adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system in response to a determination to increase output capacity. The method further includes the steps of determining whether to decrease output capacity of a multiple compressor chiller system in response to the at least one monitored operating condition and adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system in response to a determination to decrease output capacity.

Another embodiment of the present invention is directed to a multiple compressor chiller system having a plurality of compressors. Each compressor of the plurality of compressors being driven by a corresponding motor and the plurality of compressors are incorporated into at least one refrigerant circuit. Each refrigerant circuit includes at least one compressor of the plurality of compressors, a condenser arrangement and an evaporator arrangement connected in a closed refrigerant loop. The multiple compressor chiller system also has a variable speed drive to power the corresponding motors of the plurality of compressors. The variable speed drive includes a converter stage, a DC link stage and an inverter stage. The inverter stage having a plurality of inverters each electrically connected in parallel to the DC link stage and each powering a corresponding motor of the plurality of compressors. The multiple compressor chiller system further has a control panel to control the variable

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speed drive to generate a preselected system capacity from the plurality of compressors. The control panel is configured to determine a number of inverters of the plurality of inverters to operate in the variable speed drive and is configured to determine an operating frequency for the number of operating inverters of the plurality of inverters in the variable speed drive to generate the preselected system capacity from the plurality of compressors.

A further embodiment of the present invention is directed to a capacity control method for a multiple compressor chiller system. The method includes the step of providing a variable speed drive having a plurality of inverters. Each inverter is configured to power a corresponding compressor motor of a multiple compressor chiller system at a preselected output frequency. The method also includes the steps of monitoring at least one operating condition of a multiple compressor chiller system, determining whether to increase capacity in the multiple compressor chiller system in response to the at least one monitored operating condition, and configuring the plurality of inverters to generate increased capacity in the multiple compressor chiller system in response to a determination to increase capacity. The step of configuring the plurality of inverters to generate increased capacity includes determining whether to enable an additional inverter of the plurality of inverters in order to start an additional compressor motor of the multiple compressor chiller system, enabling an additional inverter of the plurality of inverters in response to a determination to enable an additional inverter, and adjusting the preselected output frequency of each operating inverter of the plurality of inverters. The method further includes the steps of determining whether to decrease capacity in the multiple compressor chiller system in response to the at least one monitored operating condition and configuring the plurality of inverters to generate decreased capacity in the multiple compressor chiller system in response to a determination to decrease capacity. The step of configuring the plurality of inverters to generate decreased capacity includes determining whether to disable an operating inverter of the plurality of inverters in order to stop a compressor motor of the multiple compressor chiller system, disabling an operating inverter of the plurality of inverters in response to a determination to disable an operating inverter, and decreasing the preselected output frequency of each operating inverter of the plurality of inverters.

One advantage of the present invention is that compressor cycling is reduced, while providing optimum control of the compressors.

Another advantage of the present invention is that system efficiency is improved by operating as many compressors as possible to satisfy a given load condition.

Other features and advantages of the present invention will be apparent from the following more detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings which illustrate, by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a general application that can be used with the present invention.

FIG. 2 illustrates schematically a variable speed drive that can be used with the present invention.

FIG. 3 illustrates an embodiment of a refrigeration or chiller system used with the present invention.

FIG. 4 is a flowchart showing the basic capacity control process of the present invention.

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FIG. 5 is a flowchart showing a compressor starting control process of the present invention.

FIG. 6 is a flowchart showing a system loading control process of the present invention.

FIG. 7 is a flowchart showing a system unloading control process of the present invention.

Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates generally an application that can be used with the present invention. An AC power source 102 supplies a variable speed drive (VSD) 104, which powers a plurality of motors 106. The motors 106 are preferably used to drive corresponding compressors that can be used in a refrigeration or chiller system. A control panel 110 can be used to control operation of the VSD 104 and can monitor and/or control operation of the motors 106 and compressors.

The AC power source 102 provides single phase or multi-phase (e.g., three phase), fixed voltage, and fixed frequency AC power to the VSD 104 from an AC power grid or distribution system that is present at a site. The AC power source 102 preferably can supply an AC voltage or line voltage of 200 V, 230 V, 380 V, 460 V, or 600 V at a line frequency of 50 Hz or 60 Hz, to the VSD 104 depending on the corresponding AC power grid.

The VSD 104 receives AC power having a particular fixed line voltage and fixed line frequency from the AC power source 102 and provides AC power to each of the motors 106 at desired voltages and desired frequencies, both of which can be varied to satisfy particular requirements. Preferably, the VSD 104 can provide AC power to each of the motors 106 that may have higher voltages and frequencies and lower voltages and frequencies than the rated voltage and frequency of each motor 106. In another embodiment, the VSD 104 may again provide higher and lower frequencies but only the same or lower voltages than the rated voltage and frequency of each motor 106.

The motors 106 are preferably induction motors that are capable of being operated at variable speeds. The induction motors can have any suitable pole arrangement including two poles, four poles or six poles. However, any suitable motor that can be operated at variable speeds can be used with the present invention.

FIG. 2 illustrates schematically some of the components in one embodiment of the VSD 104. The VSD 104 can have three stages: a converter or rectifier stage 202, a DC link stage 204 and an output stage having a plurality of inverters 206. The converter 202 converts the fixed line frequency, fixed line voltage AC power from the AC power source 102 into DC power. The converter 202 can be in a rectifier arrangement composed of electronic switches that can only be turned on either by gating, when using silicon controlled rectifiers, or by being forward biased, when using diodes. Alternatively, the converter 202 can be in a converter arrangement composed of electronic switches that can be gated both on and off, to generate a controlled DC voltage and to shape the input current signal to appear sinusoidal, if so desired. The converter arrangement of converter 202 has an additional level of flexibility over the rectifier arrangement, in that the AC power cannot only be rectified to DC power, but that the DC power level can also be controlled to a specific value. In one embodiment of the present invention, the diodes and silicon controlled rectifiers (SCRs) can

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provide the converter **202** with a large current surge capability and a low failure rate. In another embodiment, the converter **202** can utilize a diode or thyristor rectifier coupled to a boost DC/DC converter or a pulse width modulated boost rectifier to provide a boosted DC voltage to the DC link **204** in order to obtain an output voltage from the VSD **104** greater than the input voltage of the VSD **104**.

The DC link **204** filters the DC power from the converter **202** and provides energy storage components. The DC link **204** can be composed of capacitors and inductors, which are passive devices that exhibit high reliability rates and very low failure rates. Finally, the inverters **206** are connected in parallel on the DC link **204** and each inverter **206** converts the DC power from the DC link **204** into a variable frequency, variable voltage AC power for a corresponding motor **106**. The inverters **206** are power modules that can include power transistors or integrated bipolar power transistor (IGBT) power switches with diodes connected in parallel. Furthermore, it is to be understood that the VSD **104** can incorporate different components from those discussed above and shown in FIG. 2 so long as the inverters **206** of the VSD **104** can provide the motors **106** with appropriate output voltages and frequencies.

For each motor **106** to be powered by the VSD **104**, there is a corresponding inverter **206** in the output stage of the VSD **104**. The number of motors **106** that can be powered by the VSD **104** is dependent upon the number of inverters **206** that are incorporated into the VSD **104**. In a preferred embodiment, there can be either 2 or 3 inverters **206** incorporated in the VSD **104** that are connected in parallel to the DC link **204** and used for powering a corresponding motor **106**. While it is preferred for the VSD **104** to have between 2 and 3 inverters **206**, it is to be understood that more than 3 inverters **206** can be used so long as the DC link **204** can provide and maintain the appropriate DC voltage to each of the inverters **206**.

In a preferred embodiment, the inverters **206** are jointly controlled by a control system, as discussed in greater detail below, such that each inverter **206** provides AC power at the same desired voltage and frequency to corresponding motors based on a common control signal or control instruction provided to the inverters **206**. The control of the inverters **206** can be by the control panel **110** or other suitable control device that incorporates the control system.

The VSD **104** can prevent large inrush currents from reaching the motors **106** during the startup of the motors **106**. In addition, the inverters **206** of the VSD **104** can provide the AC power source **102** with power having about a unity power factor. Finally, the ability of the VSD **104** to adjust both the input voltage and input frequency received by the motor **106** permits a system equipped with VSD **104** to be operated on a variety of foreign and domestic power grids without having to alter the motors **106** for different power sources.

FIG. 3 illustrates generally one embodiment of the present invention incorporated in a refrigeration system. As shown in FIG. 3, the HVAC, refrigeration or liquid chiller system **300** has two compressors incorporated in corresponding refrigerant circuits, but it is to be understood that the system **300** can have one refrigerant circuit or more than two refrigerant circuits for providing the desired system load and can have more than a one compressor for a corresponding refrigerant circuit. The system **300** includes a first compressor **302**, a second compressor **303**, a condenser arrangement **308**, expansion devices, a water chiller or evaporator arrangement **310** and the control panel **110**. The control panel **110** can include an analog to digital (A/D) converter,

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a microprocessor, a non-volatile memory, and an interface board to control operation of the refrigeration system **300**. The control panel **110** can also be used to control the operation of the VSD **104**, the motors **106** and the compressors **302** and **303**. A conventional HVAC, refrigeration or liquid chiller system **300** includes many other features that are not shown in FIG. 3. These features have been purposely omitted to simplify the drawing for ease of illustration.

The compressors **302** and **303** compress a refrigerant vapor and deliver it to the condenser **308**. The compressors **302** and **303** are preferably connected in separate refrigeration circuits, i.e., the refrigerant output by the compressors **302** and **303** are not mixed and travel in separate circuits through the system **300** before reentering the compressors **302** and **303** to begin another cycle. The separate refrigeration circuits preferably use a single condenser housing **308** and a single evaporator housing **310** for the corresponding heat exchanges. The condenser housing **308** and evaporator housing **310** maintain the separate refrigerant circuits either through a partition or other dividing means with the corresponding housing or with separate coil arrangements. In another embodiment of the present invention, the refrigerant output by the compressors **302** and **303** can be combined into a single refrigerant circuit to travel through the system **300** before being separated to reenter the compressors **302** and **303**.

The compressors **302** and **303** are preferably screw compressors or centrifugal compressors, however the compressors can be any suitable type of compressor including reciprocating compressors, scroll compressors, rotary compressors or other type of compressor. The output capacity of the compressors **302** and **303** can be based on the operating speed of the compressors **302** and **303**, which operating speed is dependent on the output speed of the motors **106** driven by the inverters **206** of the VSD **104**. The refrigerant vapor delivered to the condenser **308** enters into a heat exchange relationship with a fluid, e.g., air or water, and undergoes a phase change to a refrigerant liquid as a result of the heat exchange relationship with the fluid. The condensed liquid refrigerant from condenser **308** flows through corresponding expansion devices to an evaporator **310**.

The evaporator **310** can include connections for a supply line and a return line of a cooling load. A secondary liquid, which is preferably water, but can be any other suitable secondary liquid, e.g. ethylene, calcium chloride brine or sodium chloride brine, travels into the evaporator **310** via return line and exits the evaporator **310** via supply line. The liquid refrigerant in the evaporator **310** enters into a heat exchange relationship with the secondary liquid to chill the temperature of the secondary liquid. The refrigerant liquid in the evaporator **310** undergoes a phase change to a refrigerant vapor as a result of the heat exchange relationship with the secondary liquid. The vapor refrigerant in the evaporator **310** then returns to the compressors **302** and **303** to complete the cycle. It is to be understood that any suitable configuration of condenser **308** and evaporator **310** can be used in the system **300**, provided that the appropriate phase change of the refrigerant in the condenser **308** and evaporator **310** is obtained.

Preferably, the control panel, microprocessor or controller **110** can provide control signals to the VSD **104** to control the operation of the VSD **104**, and particularly the operation of inverters **206**, to provide the optimal operational setting for the VSD **104**. The control panel **110** can increase or decrease the output voltage and/or frequency of the inverters **206** of the VSD **104**, as discussed in detail below, in response to increasing or decreasing load conditions on the

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compressors **302** and **303** in order to obtain a desired operating speed of the motors **106** and a desired capacity of the compressors **302** and **303**.

The control panel **110** executes a control algorithm(s) or software to control operation of the system **100** and to determine and implement an operating configuration for the inverters **206** of the VSD **104** to control the capacity of the compressors **102** and **104** in response to a particular output capacity requirement for the system **100**. In one embodiment, the control algorithm(s) can be computer programs or software stored in the non-volatile memory of the control panel **110** and can include a series of instructions executable by the microprocessor of the control panel **110**. While it is preferred that the control algorithm be embodied in a computer program(s) and executed by the microprocessor, it is to be understood that the control algorithm may be implemented and executed using digital and/or analog hardware by those skilled in the art. If hardware is used to execute the control algorithm, the corresponding configuration of the control panel **110** can be changed to incorporate the necessary components and to remove any components that may no longer be required.

FIG. **4** illustrates the basic capacity control process of the present invention. The process begins by monitoring the current operating conditions of the compressors and the corresponding chiller system at step **402**. One more sensors or other suitable monitoring devices are placed in the chiller system to monitor one or more operating conditions of the chiller system. The sensors provide signals to the control panel **110** corresponding to the measured system parameters. The measured system parameters of the chiller system can correspond to any suitable chiller system parameter that can be measured such as refrigerant temperature, refrigerant pressure, refrigerant flow, leaving chilled liquid temperature from the evaporator or any other suitable parameter.

Based on the monitored system conditions obtained in step **402**, the control process then determines if an initial system startup is required in step **404**. An initial system startup involves the starting of one or more compressors to transition the system from an inactive or shut-down state to an active or operational state. If an initial system startup is determined to be necessary, the control passes to a startup control process shown in FIG. **5** and described in greater detail below. If no initial system startup is necessary, usually because one or more compressors have been previously started, the control process moves to step **406** to determine if system loading or increased system capacity is required.

If the control process determines that system loading is required in response to a demand for additional system capacity based the monitored system conditions in step **402**, the control process proceeds to a system loading process shown in FIG. **6** and described in greater detail below to increase the load on the compressors in order to increase the system capacity. If system loading is not necessary, the control process moves to step **408** to determine if system unloading or decreased system capacity is required.

If the control process determines that system unloading is required in response to a decrease in the demand for system capacity based on the monitored system conditions in step **402**, the control process proceeds to a system unloading process shown in FIG. **7** and described in greater detail below to decrease the load on the compressors in order to decrease the system capacity. If system unloading is not necessary, the control process returns to step **402** and repeats the process.

The basic control process of FIG. **4** preferably uses a fuzzy logic control technique, but can use any suitable

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control technique for determining when to start the compressors of the chiller system, when to increase the capacity of the chiller system and when to decrease the capacity of the chiller system. The control processes of FIGS. **5**, **6** and **7** are preferably directed to the control process for the chiller system in response to one of the above-determinations being made by the basic control process of FIG. **4**.

FIG. **5** illustrates a startup control process for the present invention. The startup control process involves the starting of one or more compressors to transition the system from an inactive or shut-down state to an active or operational state. The process begins in step **502** by determining if all of the compressors are off, inactive or shut-down. If one of the compressors is active or operational in step **502**, the process returns to step **402** of FIG. **4** to further monitor system conditions because the startup process is not required because one or more of the compressors is operational. Next, after determining that all the compressors are inactive or off in step **502**, i.e., the compressors are not in operation, the startup control process determines if the leaving chilled liquid temperature (LCHLT) from the evaporator is greater than a setpoint temperature plus a predetermined offset or control range. The predetermined offset provides for a control region around the setpoint temperature, i.e., the desired LCHLT, to prevent frequent adjustments to the chiller system in response to very minor changes in system conditions.

The predetermined setpoint temperature and the predetermined offset can preferably be programmable or set by a user, but, it is to be understood that the predetermined setpoint temperature and the predetermined offset can also be preprogrammed into the system. The predetermined setpoint temperature can range between about 10° F. and about 60° F. depending on the particular liquid to be chilled in the evaporator. The predetermined setpoint temperature is preferably between about 40° F. and about 55° F. when water is to be chilled and is preferably between about 15° F. and about 55° F. when a glycol mixture is to be chilled. The predetermined offset can range between about $\pm 1^\circ$ F. and about $\pm 5^\circ$ F. and is preferably between about $\pm 1.5^\circ$ F. and about $\pm 2.5^\circ$ F.

If the LCHLT is greater than the setpoint temperature plus the predetermined offset in step **504**, then the number of compressors to be started is determined in step **506**. The number of compressors to start can be determined by any suitable technique and is usually determined in response to particular system features or parameters such as the LCHLT and the rate of change of the LCHLT. If the LCHLT is not greater than the setpoint temperature plus the predetermined offset in step **504**, then the process returns to step **402** of FIG. **4** to further monitor system conditions. After the number of compressors to start is determined, the compressors are tested in step **508** to determine if the compressors can be started or operated. In step **508**, the control panel **110** can preferably determine if the compressors cannot be started or operated or are otherwise inoperable based on internal compressor controls or signals that prevent the starting of a compressor, (e.g., a "no run permissive" signal is present, the compressor has been faulted or the compressor is locked out), or based on other system controls or signals relating to problems or restrictions in the system, (e.g., the system switch has been turned off, the system has been faulted, the system has been locked out, or the system anti-recycle timer is active). If all the compressors cannot be started in step **508**, the process returns to step **402** of FIG. **4** to further monitor system conditions. Once it is determined that all the compressors to be started are capable of being

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started and operated, the compressors are started in step **510** and operated at a frequency corresponding to the minimum frequency output by the VSD. The minimum frequency output by the VSD for compressor operation can range from 15 Hz to 75 Hz and is preferably 40 Hz. It is to be understood that the VSD may be capable of providing a minimum frequency output that is less than the minimum frequency output required for compressor operation. After the compressors are started in step **510**, the process returns to step **402** of FIG. 4 to begin the process again and monitor system conditions.

FIG. 6 illustrates a system loading control process for the present invention. The system loading control process involves either the activating or starting of one or more compressors in response to an increased load or demand on the system or the increasing of the output frequency from the VSD powering the compressors in order to increase the output capacity of the compressors in response to an increased load or demand on the system. The process begins in step **602** by determining if a load timer or counter has completed its count. In one embodiment of the present invention, the load timer is preferably set for 2 seconds. However, any suitable time duration can be used for the load timer. If the load timer has not completed its count, the system will not load any of the compressors and returns to step **402** of FIG. 4 to further monitor system conditions until the load timer is finished or system conditions change. The load timer is used to give the system adequate time to respond to a prior control instruction that started a new compressor or increased the output frequency of the VSD powering the compressors and their respective motors.

After the load timer has completed its count, the system loading control process then determines if there are any compressors that are not currently in operation that are capable of operation in step **604**. If there are any compressors that are not currently in operation, then the output frequency of the VSD, i.e., the operating frequency of the compressors, is compared to a stop frequency plus a predetermined offset frequency in step **606**. The stop frequency is preferably calculated as the VSD minimum frequency output, as discussed above, multiplied by the ratio of the number of operating compressors plus one divided by the number of operating compressors. The predetermined offset frequency can range from between about 0 Hz and about 50 Hz and is preferably between about 5 Hz and about 10 Hz. The comparison of the VSD output frequency to the stop frequency plus the offset frequency is used to determine if it would be appropriate to start another compressor. The addition of the offset frequency to the stop frequency is used to prevent the starting of a compressor by just satisfying the condition for starting a compressor, i.e., being at the stop frequency, and then having to shut off a compressor in response to a decreased load or demand on the system, i.e., a call to unload, because the compressors are operating at the minimum frequency. The addition of the offset to the stop frequency is used to have the compressors operating at a frequency above the minimum frequency, after an additional compressor is started, so there is room to unload the compressors by decreasing the output frequency of the VSD before a shutdown of a compressor is required.

After determining that the VSD output frequency is greater than the stop frequency plus the offset in step **606**, another compressor is started and the VSD is controlled to power the operating compressors at a start frequency in step **608**. The start frequency is preferably calculated as the VSD output frequency prior to starting the compressor multiplied by the ratio of the number of operating compressors (including

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the one to be started) minus one divided by the number of operating compressors (including the one to be started). Once the compressors are started and accelerated to the start frequency, the process returns to step **402** of FIG. 4 to further monitor system conditions.

Referring back to step **604**, if all the compressors are currently operating, it is determined in step **610** if the VSD output frequency powering the compressors is less than the maximum VSD output frequency. The VSD maximum output frequency can range between 120 Hz and 300 Hz and is preferably 200 Hz. However, it is to be understood that the VSD can have any suitable maximum output frequency. If the VSD output frequency is equal to the maximum VSD output frequency, then the process returns to step **402** of FIG. 4 to further monitor system conditions because no additional capacity can be generated by the system. However, if the VSD output frequency is less than the maximum VSD output frequency, then the compressors and their corresponding refrigerant circuits are checked or evaluated to determine if they are approaching an unload limit in step **612**. The unload limit is used to prevent damage to the compressors and corresponding refrigerant circuit by unloading the compressors when certain predetermined parameters or conditions are present.

If no compressors or corresponding refrigerant circuits are approaching an unload limit, then the VSD is controlled to power the compressors at an increased VSD output frequency equal to the current output frequency plus a predetermined increment amount in step **616**. The predetermined increment amount can be between about 0.1 Hz and about 25 Hz and is preferably between about 0.1 Hz and about 1 Hz. The predetermined increment amount can preferably be calculated by a fuzzy logic controller or control technique, however, any suitable controller or control technique, e.g., a PID control, can be used. The increased VSD output frequency can be increased up to the maximum VSD output frequency. Once the compressors are accelerated to the increased VSD output frequency, the process returns to step **402** of FIG. 4 to further monitor system conditions. Referring back to step **612**, if it is determined that one or more compressors and corresponding refrigerant circuits are approaching an unload limit, then a limited load value based on information in a load limiting controls table is calculated for those compressors and corresponding refrigerant circuits in step **614**. Next, in step **616**, as described in detail above, the process adjusts the VSD output frequency for the compressors, subject to any load limits from step **614**, and returns to step **402** of FIG. 4 to further monitor system conditions.

FIG. 7 illustrates a system unloading control process for the present invention. The system unloading control process involves the deactivating or shutting down of one or more compressors in response to a reduced load or demand for the system or the decreasing of the output frequency from the VSD powering the compressors in order to decrease the output capacity of the compressors in response to a decreased load or demand on the system. The process begins in step **702** by determining if an unload timer or counter has completed its count. In one embodiment of the present invention, the unload timer is preferably set for 2 seconds. However, any suitable time duration can be used for the unload timer. If the unload timer has not completed its count, the system will not unload any of the compressors and returns to step **402** of FIG. 4 to further monitor system conditions until the unload timer is finished or system conditions change.

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The unload timer is used to give the system adequate time to respond to a prior control instruction that stopped an operating compressor or decreased the output frequency of the VSD powering the compressors and their respective motors. After the unload timer has completed its count, the compressor unloading control process then determines if only a single compressor or the lead compressor is currently in operation in step 704. If only a single compressor or the lead compressor is in operation, then the output frequency of the VSD is compared to the minimum VSD frequency to determine if the output frequency of the VSD is greater than the minimum VSD frequency in step 706. If the output frequency of the VSD is not greater than the minimum VSD frequency, then the LCHLT is evaluated to determine if it is less than the setpoint temperature minus the predetermined offset in step 708. If the LCHLT is less than the setpoint temperature minus the predetermined offset in step 708, then the process begins the shut down process for the compressor and the corresponding refrigeration system in step 710 and the process ends. The compressor is shut down if the LCHLT is less than the setpoint temperature minus the predetermined offset because the system has completed its operating objective, i.e., reaching the setpoint temperature, and, depending on the freezing point of the liquid in the chiller, to possibly avoid damaging the compressor or the corresponding refrigeration circuit by having too low a LCHLT. If the LCHLT is not less than the setpoint temperature minus the predetermined offset in step 708, then the compressor continues operating at the minimum speed and the process returns to step 402 for further monitoring.

If the output frequency of the VSD is greater than the minimum VSD frequency in step 706, then the VSD is controlled to power the compressor at a decreased VSD output frequency equal to the current output frequency minus a predetermined decrement amount in step 712. The predetermined decrement amount can be between about 0.1 Hz and about 25 Hz and is preferably between about 0.1 Hz and about 1 Hz. The predetermined decrement amount can preferably be calculated by a fuzzy logic control, however, any suitable control, e.g., a PID control, can be used. The decreased VSD output frequency can be decreased down to the minimum VSD output frequency. Once the compressor is adjusted to the decreased VSD output frequency, the process returns to step 402 of FIG. 4 to further monitor system conditions.

Referring back to step 704, if any of the compressors besides the lead compressor are in operation, it is determined in step 714 if the VSD output frequency powering the compressors is equal to the minimum VSD output frequency. If the VSD output frequency is equal to the minimum VSD output frequency, then a lag compressor is stopped or shut down and the VSD is controlled to power the remaining operating compressors at the stop frequency in step 716. As discussed above, the stop frequency is preferably calculated as the VSD minimum frequency output, multiplied by the ratio of the number of operating compressors plus one divided by the number of operating compressors. Once the remaining compressors are started and accelerated to the stop frequency, the process returns to step 402 of FIG. 4 to further monitor system conditions.

If the VSD output frequency is not equal to the minimum VSD output frequency in step 714, then the VSD is controlled to power the compressors at a decreased VSD output frequency equal to the current output frequency minus a predetermined decrement amount in step 712, as described in greater detail above. Once the compressors are adjusted to

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the decreased VSD output frequency, the process returns to step 402 of FIG. 4 to further monitor system conditions.

While the above control process discussed the controlling of the system capacity by adjusting the output frequency of the VSD provided to the motors, it is to be understood that the output voltage of the VSD can also be adjusted to control the system capacity. In the above control processes, the VSD is preferably controlled to maintain a constant volts/Hz or constant torque mode of operation. The constant flux or constant volts/Hz mode of motor operation, which is used for a load with a substantially constant torque profile, such as a screw compressor, requires any increases or decreases in frequency provided to the motor to be matched by corresponding increases and decreases in the voltages provided to the motor. For example, a four pole induction motor can deliver twice its rated output horsepower and speed when operated at twice its rated voltage and twice its rated frequency. When in the constant flux or constant volts/Hz mode, any increase in the voltage to the motor results in an equivalent increase in the output horsepower of the motor. Similarly, any increase in the frequency to the motor results in an equivalent increase in the output speed of the motor.

When starting or stopping a compressor in order to adjust the capacity of the chiller system, such as described in steps 608 and 716, the VSD preferably follows the following procedure. First, the VSD is decelerated to a zero speed in a controlled stop. Next, the compressor to be added or removed is correspondingly enabled or disabled. The VSD is then controlled to provide output power to the compressors in operation at either the start frequency, when adding a compressor, or the stop frequency, when removing a compressor. It being understood that the VSD is also controlled to provide the appropriate voltage for the corresponding frequency. Finally, the VSD is accelerated to the appropriate frequency and voltage to power the compressors in operation.

While the invention has been described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. A method for controlling the capacity of a multiple compressor chiller system, the method comprising the steps of:

- providing a variable speed drive having a plurality of inverters, wherein each inverter is configured to power a corresponding compressor motor of a multiple compressor chiller system;
- monitoring at least one operating condition of a multiple compressor chiller system;
- determining whether to increase output capacity of a multiple compressor chiller system in response to the at least one monitored operating condition;
- adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system in response to a determination to increase output capacity;

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determining whether to decrease output capacity of a multiple compressor chiller system in response to the at least one monitored operating condition; and adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system in response to a determination to decrease output capacity.

2. The method of claim 1 further comprising the steps of: determining whether to start a predetermined number of inverters of the plurality of inverters in response to the at least one monitored operating condition; and starting the predetermined number of inverters of the plurality of inverters in response to a determination to start the predetermined number of compressors.

3. The method of claim 2 wherein the step of starting the predetermined number of inverters of the plurality of inverters includes the steps of:

- determining whether the plurality of inverters are inactive;
- determining whether a chilled liquid temperature is greater than a setpoint temperature plus an offset temperature; and
- determining the predetermined number of inverters of the plurality of inverters to start in response to a determination that the plurality of inverters are inactive and a determination that a chilled liquid temperature is greater than a setpoint temperature plus an offset temperature.

4. The method of claim 3 wherein the step of starting the predetermined number of inverters of the plurality of inverters includes the step of starting the predetermined number of inverters at a predetermined frequency.

5. The method of claim 4 wherein the predetermined frequency is a frequency between about 15 Hz and about 75 Hz.

6. The method of claim 5 wherein the predetermined frequency is about 40 Hz.

7. The method of claim 5 wherein:

- the setpoint temperature is a temperature between about 15° F. and about 55° F.; and
- the offset temperature is a temperature between about $\pm 1^\circ$ F. and about $\pm 5^\circ$ F.

8. The method of claim 1 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system includes the step of determining whether any inverter of the plurality of inverters is inactive.

9. The method of claim 8 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system further includes the step of determining if an inverter operating frequency for the plurality of inverters is greater than a stop frequency plus a predetermined offset frequency.

10. The method of claim 9 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system further includes the step of starting an additional inverter of the plurality of inverters in response to a determination that any inverter of the plurality of inverters is inactive and a determination that an inverter operating frequency for the plurality of inverters is greater than a stop frequency plus a predetermined offset frequency.

11. The method of claim 10 wherein the step of starting an additional inverter of the plurality of inverters includes the step of configuring operating inverters of the plurality of inverters to operate at a predetermined frequency.

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12. The method of claim 11 wherein the predetermined frequency is the inverter operating frequency multiplied by a ratio of a number of operating inverters divided by the number of operating inverters plus one.

13. The method of claim 12 wherein:

- the minimum inverter frequency is a frequency between about 15 Hz and about 75 Hz; and
- the predetermined offset frequency is a frequency between about 0 Hz and about 50 Hz.

14. The method of claim 9 wherein the stop frequency is a minimum inverter frequency multiplied by a ratio of a number of operating inverters plus one divided by the number of operating inverters.

15. The method of claim 9 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system further includes the step of increasing the inverter operating frequency by a predetermined frequency amount in response to a determination that any inverter of the plurality of inverters is inactive and a determination that an inverter operating frequency of the plurality of inverters is not greater than a stop frequency plus a predetermined offset frequency.

16. The method of claim 8 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system further includes the step of determining whether an inverter operating frequency is less than a maximum inverter frequency.

17. The method of claim 16 wherein the step of adjusting an operating configuration of the plurality of inverters to increase the output capacity of a multiple compressor chiller system further includes the step of increasing the inverter operating frequency by a predetermined frequency amount in response to a determination that no inverter of the plurality of inverters is inactive and a determination that an inverter operating frequency is less than a maximum inverter frequency.

18. The method of claim 17 wherein the predetermined frequency amount is a frequency between about 0.1 Hz and about 25 Hz.

19. The method of claim 1 wherein the step of adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system includes the step of determining whether only one inverter of the plurality of inverters is operating.

20. The method of claim 19 wherein the step of adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of determining if an inverter operating frequency is greater than a minimum inverter frequency.

21. The method of claim 20 wherein the step of adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of determining whether a chilled liquid temperature is less than a setpoint temperature minus an offset temperature.

22. The method of claim 21 wherein the step of adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of stopping the only one operating inverter of the plurality of inverters in response to a determination that only one inverter of the plurality of inverters is operating, a determination that an inverter operating frequency is not greater than a minimum inverter

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frequency, and a determination that a chilled liquid temperature is less than a setpoint temperature minus an offset temperature.

23. The method of claim **22** wherein:

the minimum inverter frequency is a frequency between 5
about 15 Hz and about 75 Hz;

the setpoint temperature is a temperature between about
15° F. and about 55° F.; and

the offset temperature is a temperature between about $\pm 1^\circ$
F. and about $\pm 5^\circ$ F. 10

24. The method of claim **20** wherein the step of adjusting an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of decreasing the inverter operating frequency by a predetermined frequency amount 15
in response to a determination that only one inverter of the plurality of inverters is operating and a determination that an inverter operating frequency is greater than a minimum inverter frequency.

25. The method of claim **24** wherein the predetermined 20
frequency amount is a frequency between about 0.1 Hz and about 25 Hz and the inverter minimum frequency is a frequency between about 15 Hz and about 75 Hz.

26. The method of claim **19** wherein the step of adjusting 25
an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of determining if an inverter operating frequency is substantially equal to a minimum inverter frequency.

27. The method of claim **26** wherein the step of adjusting 30
an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of stopping an operating inverter of the plurality of inverters in response to a deter- 35
mination that more than one inverter of the plurality of inverters is operating and a determination that an inverter operating frequency is equal to a minimum inverter frequency.

28. The method of claim **27** wherein the step of stopping 40
an operating inverter of the plurality of inverters includes the step of configuring the remaining operating inverters of the plurality of inverters to operate at a predetermined frequency.

29. The method of claim **28** wherein the predetermined 45
frequency is a minimum inverter frequency multiplied by a ratio of the remaining operating inverters plus one divided by the remaining operating inverters.

30. The method of claim **29** wherein the minimum 50
inverter frequency is a frequency between about 15 Hz and about 75 Hz.

31. The method of claim **26** wherein the step of adjusting 55
an operating configuration of the plurality of inverters to decrease the output capacity of a multiple compressor chiller system further includes the step of decreasing the inverter operating frequency by a predetermined frequency amount in response to a determination that more than one inverter of the plurality of inverters is operating and a determination that an inverter operating frequency is not equal to a minimum inverter frequency. 60

32. A capacity control method for a multiple compressor chiller system, the method comprising the steps of:

providing a variable speed drive having a plurality of inverters, wherein each inverter is configured to power a corresponding compressor motor of a multiple com- 65
pressor chiller system at a preselected output frequency;

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monitoring at least one operating condition of a multiple compressor chiller system;

determining whether to increase capacity in the multiple compressor chiller system in response to the at least one monitored operating condition;

configuring the plurality of inverters to generate increased capacity in the multiple compressor chiller system in response to a determination to increase capacity, wherein the step of configuring the plurality of inverters to generate increased capacity includes:

determining whether to enable an additional inverter of the plurality of inverters in order to start an additional compressor motor of the multiple compressor chiller system;

enabling an additional inverter of the plurality of inverters in response to a determination to enable an additional inverter; and

adjusting the preselected output frequency of each operating inverter of the plurality of inverters;

determining whether to decrease capacity in the multiple compressor chiller system in response to the at least one monitored operating condition; and

configuring the plurality of inverters to generate decreased capacity in the multiple compressor chiller system in response to a determination to decrease capacity, wherein the step of configuring the plurality of inverters to generate decreased capacity includes:

determining whether to disable an operating inverter of the plurality of inverters in order to stop a compressor motor of the multiple compressor chiller system;

disabling an operating inverter of the plurality of inverters in response to a determination to disable an operating inverter; and

decreasing the preselected output frequency of each operating inverter of the plurality of inverters.

33. The capacity control method of claim **32** further comprising the steps of:

determining whether to start a predetermined number of inverters of the plurality of inverters in response to the at least one monitored operating condition; and

starting the predetermined number of inverters of the plurality of inverters in response to a determination to start the predetermined number of compressors.

34. The capacity control method of claim **33** wherein the step of starting the predetermined number of inverters of the plurality of inverters includes the steps of:

determining whether the plurality of inverters are disabled;

determining whether a chilled liquid temperature is greater than a setpoint temperature plus an offset temperature; and

determining the predetermined number of inverters of the plurality of inverters to start in response to a determination that the plurality of inverters are disabled and a determination that a chilled liquid temperature is greater than a setpoint temperature plus an offset temperature.

35. The capacity control method of claim **34** wherein the step of starting the predetermined number of inverters of the plurality of inverters includes the step of operating the predetermined number of inverters at a predetermined frequency.

36. The capacity control method of claim **32** wherein the step of determining whether to enable an additional inverter of the plurality of inverters includes the steps of:

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determining whether any inverter of the plurality of
inverters is disabled; and
determining whether an inverter operating frequency for
the plurality of inverters is greater than a stop fre-
quency plus a predetermined offset frequency. 5
37. The capacity control method of claim 32 wherein the
step of adjusting the preselected output frequency of each
operating inverter of the plurality of inverters includes the
steps of:
determining whether any inverter of the plurality of 10
inverters is disabled;
determining whether an inverter operating frequency of
the plurality of inverters is less than a stop frequency
plus a predetermined offset frequency; and
increasing the inverter operating frequency by a prede- 15
termined frequency amount in response to a determi-
nation that any inverter of the plurality of inverters is
disabled and a determination that an inverter operating
frequency of the plurality of inverters is less than a stop
frequency plus a predetermined offset frequency. 20
38. The capacity control method of claim 32 wherein the
step of determining whether to disable an operating inverter
of the plurality of inverters includes the steps of:
determining whether only one inverter of the plurality of
inverters is enabled; 25
determining whether an inverter operating frequency is
less than a minimum inverter frequency; and
determining whether a chilled liquid temperature is less
than a setpoint temperature minus an offset tempera-
ture. 30
39. The capacity control method of claim 32 wherein the
step of decreasing the preselected output frequency of each
operating inverter of the plurality of inverters includes the
steps of:
determining whether only one inverter of the plurality of 35
inverters is enabled;
determining whether an inverter operating frequency is
greater than a minimum inverter frequency; and
decreasing the inverter operating frequency by a prede-
termined frequency amount in response to a determi-

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nation that only one inverter of the plurality of inverters
is operating and a determination that an inverter oper-
ating frequency is greater than a minimum inverter
frequency.
40. The capacity control method of claim 32 wherein the
step of adjusting the preselected output frequency of each
operating inverter of the plurality of inverters includes the
steps of:
determining whether all inverters of the plurality of
inverters are enabled;
determining whether an inverter operating frequency is
less than a maximum inverter frequency; and
increasing the inverter operating frequency by a prede-
termined frequency amount in response to a determi-
nation that all inverters of the plurality of inverters are
enabled and a determination that an inverter operating
frequency is less than a maximum inverter frequency.
41. The capacity control method of claim 32 wherein the
step of determining whether to disable an operating inverter
of the plurality of inverters includes the steps of:
determining whether more than one inverter of the plu-
rality of inverters is enabled; and
determining whether an inverter operating frequency is
equal to a minimum inverter frequency.
42. The capacity control method of claim 32 wherein the
step of decreasing the preselected output frequency of each
operating inverter of the plurality of inverters includes the
steps of:
determining whether more than one inverter of the plu-
rality of inverters is enabled;
determining whether an inverter operating frequency is
not equal to a minimum inverter frequency; and
decreasing the inverter operating frequency by a prede-
termined frequency amount in response to a determi-
nation that more than one inverter of the plurality of
inverters is enabled and a determination that an inverter
operating frequency is not equal to a minimum inverter
frequency.

* * * * *