

(19) World Intellectual Property Organization
International Bureau



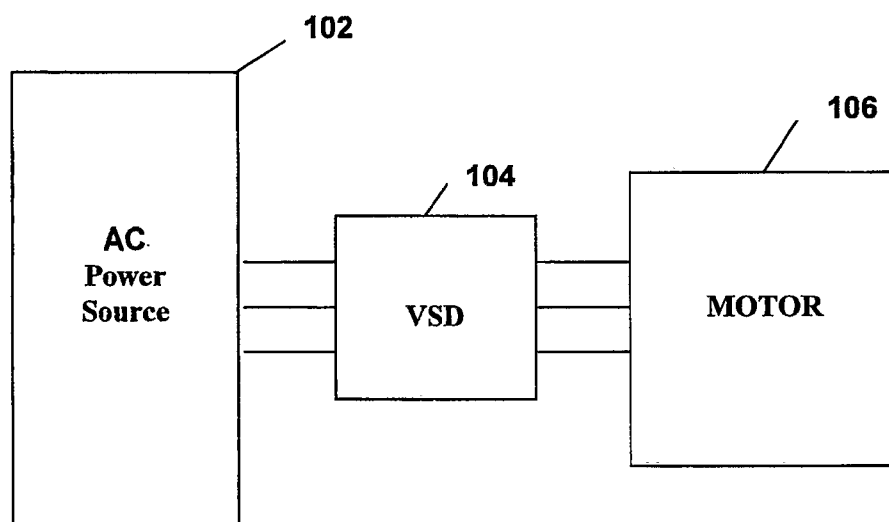
(43) International Publication Date
13 December 2007 (13.12.2007)

PCT

(10) International Publication Number
WO 2007/143217 A2

- (51) International Patent Classification: Not classified
- (21) International Application Number: PCT/US2007/013417
- (22) International Filing Date: 7 June 2007 (07.06.2007)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data: 11/422,668 7 June 2006 (07.06.2006) US
- (71) Applicant (for all designated States except US): **JOHNSON CONTROLS TECHNOLOGY COMPANY** [US/US]; 915 East 32nd Street, Holland, MI 49423 (US).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **SCHNETZKA, Harold R.** [US/US]; 4495 Estate Drive, York, Pennsylvania 17404 (US). **JADRIC, Ivan** [US/US]; 487 Linden Avenue, York, Pennsylvania 17404 (US).
- (74) Agents: **SMITH, William P.** et al.; McNees Wallace & Nurick LLC, 100 Pine St., P.O. Box 1166, Harrisburg, Pennsylvania 17108-1166 (US).
- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
- Published:**
— without international search report and to be republished upon receipt of that report
- For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: RIDE-THROUGH METHOD AND SYSTEM FOR HVAC&R CHILLERS



(57) Abstract: A method of providing ride-through capability in a chiller/refrigeration system employs a variable speed drive with an active converter stage, a DC link stage and an inverter stage for providing variable frequency and voltage to power at least one motor. An induction motor is coupled to the output of the inverter stage for driving a compressor in the chiller/refrigeration system. The ride-through method comprises operating the active converter to regulate the DC link voltage of the DC link stage to a predetermined voltage level until the current through the active converter equals a predetermined current limit, then transferring regulation of the DC link to the inverter upon reaching the current limit of the converter. The compressor is unloaded, and the power flow through the inverter is reversed to maintain the voltage level of the DC link stage. Pre-rotation vanes, slide valve, or check valve are used to unload the compressor.

WO 2007/143217 A2

RIDE-THROUGH METHOD AND SYSTEM FOR HVAC&R CHILLERS

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This Application is a continuation-in-part of Application No. 11/218,757, filed September 2, 2005.

BACKGROUND OF THE INVENTION

[0002] The present invention relates generally to variable speed drives, and more specifically, to variable speed drives with voltage-sag ride through capability for use in heating, ventilation, air conditioning and refrigeration (HVAC&R) equipment.

[0003] Variable speed drives (VSDs) are used in HVAC&R systems to provide variable magnitude and variable frequency AC voltage to motors driving refrigeration compressors. VSDs are typically comprised of an input rectifier, a DC link and an inverter. Line AC voltage, supplied at a fixed magnitude and fixed frequency by an electric utility, is rectified by the VSDs input rectifier into a DC voltage. This DC voltage is filtered and stabilized by the passive components with energy storage capability (such as capacitors) at the DC link. The DC link voltage is then inverted to a variable magnitude, variable frequency AC voltage, which feeds the electrical load. In HVAC&R equipment, the electrical load is normally an electric motor coupled to a compressor. VSDs are particularly susceptible to undervoltage conditions, referred to as voltage sags, occurring on the utility supply input. Such voltage sags are reflected through to the DC link voltage and to the load unless corrected or compensated in other ways. The majority of line voltage sags occur for short durations, on the order of several milliseconds to a few seconds. Such voltage sags may cause the DC link voltage to sag, and the VSD system to shut down. The ability of a VSD to ride through a voltage sag without shutting down, and to resume operation after the input voltage is recovered, is considered advantageous in a VSD as it reduces the HVAC&R equipment's downtime. For VSDs based on voltage source inverter (VSI) technology, ride-through capability is typically achieved by maintaining the DC link voltage at or near the rated value. The VSD is then able to provide a sufficient voltage to drive the electric motor. Otherwise, if the DC link falls sufficiently below its rated value, the VSD and chiller control system will shut down to prevent irregular and potentially harmful motor or compressor operation.

[0004] The most common type of rectifier used in VSDs, however, is a passive rectifier. A passive rectifier typically includes a three-phase diode bridge. With a passive rectifier, the DC link voltage is directly proportional to the input line voltage. A passive rectifier therefore does not compensate for the variations in input line voltage. Consequently, a voltage sag will cause the DC link voltage to drop, which, in turn, may cause the VSD to shutdown.

[0005] When a passive rectifier is used in the VSD, one possible way of improving ride-through capability is to provide an additional source of power connected to the DC link, as described in Annette von Jouanne et al., Assessment of Ride-Through Alternatives for Adjustable-Speed Drives, 35 IEEE Transactions on Industry Applications 908 (1999), which is incorporated herein by reference. Such an additional source of power can be provided by additional capacitors, a DC boost converter, batteries, supercapacitors, motor-generator sets, flywheels, superconductive magnetic energy storage systems, fuel cells, etc. All of these require additional hardware and therefore significantly increase the cost of a VSD. A relatively inexpensive way of increasing the ride-through capability of a VSD with passive front end is to use the load inertia to generate power during a voltage sag (also described in Annette von Jouanne et al. cited above). In order to achieve this way of increasing the ride through capability, the inverter output frequency during a voltage sag is adjusted to a value slightly below the motor load frequency. This causes the motor to act as a generator and to maintain the DC link voltage at a desired level. This method typically requires motor speed and current sensors, which may add to the cost of a VSD.

[0006] U.S. Patent No. 6,686,718 describes various techniques of increasing the ride through capability of a VSD. For example, another possible way of increasing ride-through capability of a VSD is to use an Active Rectifier. Such a rectifier is able to compensate for the variations in the input line voltage, through the use of power devices capable of switching on and off the line currents, together with specialized control methods. The DC link voltage can therefore be kept at a value sufficiently large to prevent VSD shutdowns. This technique is described in Annabelle van Zyl et al., Voltage Sag Ride-Through for Adjustable-Speed Drives with Active Rectifiers, 34 IEEE Transactions on Industry Applications 1270 (1998), which is incorporated herein by reference.

[0007] One such Active Rectifier employs a pulse-width modulated (PWM) boost rectifier. The DC link voltage may be tightly regulated at a nominal value during a decrease or sag in the input line voltage. However, the input AC current of the boost rectifier

increases as the line voltage decreases. Due to the practical current conduction and current switching limitations of the boost rectifier components, the input AC current cannot be allowed to increase indefinitely. Rather, it must be controlled (through boost rectifier control algorithms) so that it never exceeds a predetermined limit, which is referred to as the boost rectifier current limit. As long as the boost rectifier's input current is below or at the current limit, the boost rectifier's output DC voltage may be tightly controlled at a nominal setpoint. However, if the line voltage continues to drop after the current limit of the boost rectifier is reached, the boost rectifier is no longer capable of regulating the output DC voltage to the setpoint value although the input current remains controlled at the current limit level. As the inverter section of the VSD continues to draw current from the DC link capacitors to drive the motor at the same power level prior to the inception of the voltage sag, the energy stored in the DC link capacitors is transferred to the load, and the voltage of the DC link decreases. If this situation continues for a sufficient period of time, the DC link voltage will decrease below a predetermined fault threshold and the chiller system will eventually shut down.

[0008] Therefore what is needed is a method for increasing the ride-through capability of a VSD applied to an HVAC&R system beyond the current ride-through capability of state-of-the-art general purpose VSDs described above. This new method is based upon boosting and controlling the voltage of the DC link to maximize the period of VSD and HVAC&R system operational time during a voltage sag, capturing and maintaining the maximum amount of energy stored in the inertia of the rotating motor and compressor in order to preserve the energy in the DC link circuit, and utilizing the energy stored in the refrigerant and water circuits of the HVAC&R system to maximize the ride-through capability of the system during an input voltage sag.

SUMMARY OF THE INVENTION

[0009] The present invention discloses a method of providing ride-through capability in a VSD for an HVAC&R system, comprising a motor mechanically coupled with a compressor, and a variable speed drive for powering the motor. The variable speed drive includes an Active Rectifier stage and an inverter stage electrically coupled by a DC link stage. The line AC voltage, input AC current, DC link voltage, and motor AC current are all monitored and/or sensed by the system. The DC voltage of the DC link stage is regulated to a setpoint via the Active Rectifier during normal operation and during a voltage sag. The regulation of the DC voltage of the DC link stage is further transferred from the Active Rectifier stage to

the inverter stage in response to the input current into the Active Rectifier stage reaching a predetermined current limit value, and the work done by the compressor in the refrigerant system is stopped. The DC voltage of the DC link stage is then controlled via the inverter by reversing the power flow from the motor to DC link. The control of the DC voltage of the DC link stage is transferred back to the Active Rectifier stage in response to the monitored line AC voltage recovering to a predetermined threshold voltage value.

[0010] In one aspect of the invention, there is disclosed a method for controlling a variable speed drive to ride-through a voltage sag. The method includes the steps of providing a motor and a compressor coupled to a mechanical load, providing a variable speed drive to power the motor, the variable speed drive including an active converter stage and an inverter stage electrically coupled by a DC link stage, monitoring a DC voltage of the DC link stage, monitoring an input parameter of the active converter stage, regulating the DC voltage of the DC link stage with the active converter in response to a change in the monitored DC link voltage, transferring the regulation of the DC voltage of the DC link stage to the inverter stage in response to the DC voltage being less than a predetermined first threshold voltage, removing the mechanical load from the compressor; and controlling the DC voltage of the DC link stage with the inverter stage by reversing power flow from the motor to the DC link stage.

[0011] In another aspect the invention is directed to a method for increasing voltage sag ride-through capability in a chiller system, comprising the steps of providing a motor and a compressor mechanically coupled together; providing a variable speed drive to power the motor, the variable speed drive including an active converter stage and an inverter stage electrically coupled by a DC link stage; monitoring a DC voltage of the DC link stage; monitoring an input parameter of the active converter stage; regulating the DC voltage of the DC link stage through the active converter stage; regulating the motor speed through the inverter stage; transferring the regulation of the DC voltage of the DC link stage to the inverter stage in response to the DC voltage of the DC link stage being less than a predetermined first threshold voltage; unloading the compressor; disabling the active converter stage; and controlling the DC voltage of the DC link stage with the inverter stage by reversing power flow from the motor to the DC link.

[0012] The invention is also directed to a chiller system comprising a compressor, a condenser, and an evaporator connected in a closed refrigerant loop; an unloading device for

unloading the compressor in response to a decrease in the operational speed of the compressor; motor connected to the compressor to power the compressor; and a variable speed drive connected to the motor, the variable speed drive being configured to receive an input AC power at a fixed input AC voltage and a fixed input frequency and provide an output power at a variable voltage and variable frequency to the motor, the variable voltage having a maximum voltage greater in magnitude than the fixed input AC voltage and the variable frequency having a maximum frequency greater than the fixed input frequency, the variable speed drive comprising: a converter stage connected to an AC power source providing the input AC power, the converter stage being configured to convert the input AC voltage to a DC voltage; a DC link connected to the converter stage, the DC link being configured to filter the DC voltage and store energy from the converter stage; an inverter stage connected to the DC link, the inverter stage being configured to convert the DC voltage from the DC link into the output power for the motor having the variable voltage and the variable frequency; a control panel to control operation of the variable speed drive, the control panel being configured to regulate the DC voltage of the DC link stage with the inverter stage in response to the DC voltage being less than a predetermined first threshold voltage; wherein the control panel regulates the DC voltage of the DC link stage with the inverter stage by providing control signals to mechanically unload the compressor; and reverse power flow from the motor to the DC link stage to control the DC voltage of the DC link stage.

[0013] One advantage of the present invention is the ability to provide improved input voltage sag ride-through capabilities to prevent chiller system shut downs during input voltage sags.

[0014] Another advantage of the present invention is the ability to minimize the discharge of the DC link capacitors during a voltage sag, maintain the energy stored in the rotating mass of the motor and compressor through the mechanical unloading of the chiller system, relying upon the thermal storage capability of the refrigerant and chilled water or brine systems to maximize the thermal ride-through capability of the HVAC&R system.

[0015] Still another advantage of the present invention is the ability to reverse the flow of energy between rotating mass of the motor and compressor and the DC link, to supply energy to the DC link.

[0016] 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

[0017] Figure 1 illustrates schematically a general system configuration of the present invention.

[0018] Figure 2 illustrates schematically one embodiment of a variable speed drive used in the present invention.

[0019] Figure 3 illustrates schematically a refrigeration system that can be used with the present invention.

[0020] Figure 4 illustrates a simplified block diagram of the invention.

[0021] Figure 5A illustrates a flow diagram of an embodiment of the present invention.

[0022] Figure 5B illustrates a flow diagram of a preferred embodiment of the present invention.

[0023] Figures 6 through 9 illustrate portions of the flow diagram shown in Figure 5A.

[0024] Figure 10 illustrates portions of the flow diagram of Figure 5B.

[0025] 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

[0026] Figure 1 illustrates generally the system configuration of the present invention. An AC power source 102 supplies fixed voltage and frequency AC power to a variable speed drive (VSD) 104, which in turn, supplies variable voltage and frequency AC power to a motor 106. The motor 106 is preferably used to drive a corresponding compressor of a refrigeration or chiller system (see generally, Figure 3). 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 grid can be supplied directly from an electric utility or can be supplied from one or more transforming substations between the electric utility and the AC power grid. The AC power source 102 can preferably supply a three phase AC voltage or line voltage of 200 V, 230 V, 380 V, 460 V, or 575 V, at a line frequency of 50 Hz or 60 Hz to the VSD 104 depending on the corresponding AC power grid. It is to be understood that the AC power source 102 can provide any suitable fixed line voltage or fixed line frequency to the VSD 104 depending on the configuration of the AC power grid. In addition, a particular site can have multiple AC power grids that can satisfy different line voltage and line frequency requirements. For example, a site may have 230 VAC power grid to handle certain applications and a 460 VAC power grid to handle other applications.

[0027] 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 the motor 106 at a desired voltage and desired frequency, both of which can be varied to satisfy particular requirements. Preferably, the VSD 104 can provide AC power to the motor 106 having higher voltages and frequencies or lower voltages and frequencies than the fixed voltage and fixed frequency received from the AC power source 102. Figure 2 illustrates schematically some of the components in one embodiment of the VSD 104. The VSD 104 can have three stages: a rectifier/converter stage 202, a DC link stage 204 and an inverter stage 206. The rectifier/converter 202 converts the fixed frequency, fixed magnitude AC voltage from the AC power source 102 into DC voltage. The DC link 204 filters the DC power from the converter 202 and provides energy storage components such as capacitors and/or inductors. Finally, the inverter 206 converts the DC voltage from the DC link 204 into variable frequency, variable magnitude AC voltage for the motor 106.

[0028] Since the VSD 104 can provide a variable output voltage and variable frequency to the motor 106, the motor can be operated at a variety of different conditions, for instance in constant flux or constant volts/Hz mode depending on the particular load of the motor. Preferably, a control panel, microprocessor or controller can provide control signals to the VSD 104 to control the operation of the VSD 104 and motor 106 to provide the optimal operational setting for the VSD 104 and motor 106, depending on the particular sensor readings received by the control panel. For example, in the refrigeration system 300 of Figure 3, the control panel 308 can adjust the output voltage and frequency of the VSD 104 to correspond to changing conditions in the refrigeration system, i.e., the control panel 308 can

increase or decrease the output voltage and frequency of the VSD 104 in response to increasing or decreasing load conditions on the compressor 302 in order to obtain a desired operating speed of the motor 106 and a desired output load of the compressor 302.

[0029] In a preferred embodiment, the rectifier/converter 202 is a three-phase pulse width modulated boost rectifier having insulated gate bipolar transistors (IGBTs) to provide a boosted DC voltage to the DC link 204 to obtain a maximum RMS output voltage from the VSD 104 greater than the input voltage of the VSD 104. In an alternate embodiment, the converter 202 can be a diode or thyristor rectifier, possibly coupled to a boost DC/DC converter 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. In another embodiment, the rectifier/converter 202 may be a passive diode or thyristor rectifier without voltage-boosting capability.

[0030] In a preferred embodiment of the present invention, the VSD 104 can provide output voltages and frequencies that are at least 1.04 times and 3 times the fixed voltage and fixed frequency, respectively, provided to the VSD 104. Furthermore, it is to be understood that the VSD 104 can incorporate different components from those shown in Figure 2 so long as the VSD 104 can provide the motor 106 with appropriate output voltages and frequencies.

[0031] The VSD 104 can also include a precharge system (not shown) that can control the rise of the DC link voltage from 0 V to a value close to the peak of the AC line voltage to avoid a large inrush current in the VSD 104 when the AC voltage is first applied to the VSD 104, which inrush current can be damaging to the components of the VSD 104. The precharge system can include a precharge contactor that is used to connect precharge resistors between the input AC power source 102 and the rectifier/converter 202 or, sometimes, between the output of the rectifier/converter 202 and the DC link 204. These precharge resistors limit the inrush current to a manageable level. After the precharge is completed, the precharge resistors are excluded from the circuit by opening the precharge contactor, and the input AC power source 102 is connected directly to the converter 202 by the closing of another contactor, referred to as the supply contactor. The supply contactor remains closed during the operation of the system. Alternately precharge means may be incorporated into the design of the rectifier/converter 202, through the use of the appropriate power semiconductor devices, coupled together with the appropriate precharge control means.

[0032] In addition, the VSD 104 can provide the HVAC&R system with power having about a unity power factor. Finally, the ability of the VSD 104 to adjust both the voltage and frequency received by the motor 106 to be higher or lower than the fixed line voltage and fixed line frequency received by the VSD 104, permits the HVAC&R system to be operated on a variety of foreign and domestic power grids without having to alter the motor 106 or the VSD 104 for different power sources.

[0033] The motor 106 is preferably an induction motor that is capable of being driven at variable speeds. The induction motor can have any suitable pole arrangement including two poles, four poles or six poles. The induction motor is used to drive a load, preferably a compressor of a refrigeration system as shown in Figure 3.

[0034] As shown in Figure 3, the HVAC, refrigeration or liquid chiller system 300 includes a compressor 302, a condenser 304, an evaporator 306, and a control panel 308. The control panel 308 can include a variety of different components such as an analog to digital (A/D) converter, a microprocessor, a non-volatile memory, and an interface board, to control operation of the refrigeration system 300. The control panel 308 can also be used to control the operation of the VSD 104 and the motor 106. The conventional refrigeration system 300 includes many other features that are not shown in Figure 3. These features have been purposely omitted to simplify the drawing for ease of illustration.

[0035] Compressor 302 compresses a refrigerant vapor and delivers the vapor to the condenser 304 through a discharge line. The compressor 302 is preferably a centrifugal compressor, but can be any suitable type of compressor, e.g., screw compressor, reciprocating compressor, etc. The refrigerant vapor delivered by the compressor 302 to the condenser 304 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 304 flows through an expansion device (not shown) to an evaporator 306.

[0036] The compressor 302 can include a load-varying device 303 for varying the mechanical load of the compressor 302. In a centrifugal compressor the load-varying device 303 may be pre-rotation vanes. At the inlet or suction line 301 to the compressor 302 from the evaporator 306, there are one or more pre-rotation vanes or inlet guide vanes 303 that control the flow of refrigerant to the compressor 302. An actuator is used to open the pre-

rotation vanes 303 to increase the amount of refrigerant to the compressor 302 and thereby increase the cooling capacity of the system 300. Similarly, an actuator is used to close the pre-rotation vanes 303 to decrease the amount of refrigerant to the compressor 302 and thereby decrease the cooling capacity of the system 300. In a screw compressor the load-varying device 303 may be a slide valve. The discharge line 307 of the compressor may have a check valve 305 connected thereto for preventing reverse flow of refrigerant, as described in more detail below. In an alternate configuration, the check valve 305 may be connected to the compressor 302 at the suction line 301.

[0037] The evaporator 306 can include connections for a supply line and a return line of a cooling load. A secondary liquid, e.g., water, ethylene, calcium chloride brine or sodium chloride brine, travels into the evaporator 306 via return line and exits the evaporator 306 via supply line. The liquid refrigerant in the evaporator 306 enters into a heat exchange relationship with the secondary liquid to lower the temperature of the secondary liquid. The refrigerant liquid in the evaporator 306 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 306 exits the evaporator 306 and returns to the compressor 302 by a suction line to complete the cycle. It is to be understood that any suitable configuration of condenser 304 and evaporator 306 can be used in the system 300, provided that the appropriate phase change of the refrigerant in the condenser 304 and evaporator 306 is obtained.

[0038] The HVAC, refrigeration or liquid chiller system 300 can include many other features that are not shown in Figure 3. These features have been purposely omitted to simplify the drawing for ease of illustration. Furthermore, while Figure 3 illustrates the HVAC, refrigeration or liquid chiller system 300 as having one compressor connected in a single refrigerant circuit, it is to be understood that the system 300 can have multiple compressors, powered by a single VSD, connected into each of one or more refrigerant circuits.

[0039] The control panel 308 incorporates a compressor control unit 406 (see Figure 4) that determines and implements the position of a mechanical loading device 303 for the compressor, for example, the pre-rotation vanes in a centrifugal compressor or the slide valve in a screw compressor. The control panel 308 also controls the speed of the compressor 302 and the motor 106, in response to cooling demand signals generated by the control panel 308 for the chiller system. The control panel 308 sends the motor speed command to the inverter

control unit 404 (see Figure 4.), which controls the inverter 206 to output the voltage and frequency to the motor 106 to produce the desired compressor speed. The inverter control unit 404 preferably uses a vector control algorithm to control the speed of the motor 106 via direct torque control, by separately and independently controlling flux-producing and torque-producing components of the motor current.

[0040] In the following control descriptions, the DC link voltage, V_{DC} , DC link voltage first setpoint, V_{STPT1} , DC link voltage first threshold V_{TH1} , DC link voltage second setpoint V_{STPT2} and DC link voltage cutout threshold V_{UNDER} , are DC values, where $V_{STPT1} > V_{TH1} > V_{STPT2} > V_{UNDER}$ and the sensed input AC line voltage V_{INAC} and input AC voltage threshold V_{TH_IN} are RMS values. The preferred method of the present invention generally comprises a two-step operating mode to provide ride-through during a voltage sag at the input to the VSD 104. In the first step, as the magnitude of the AC line voltage decreases, the rectifier/converter 202 (in this embodiment a boost rectifier) regulates the DC link voltage to its rated value, as if under normal full voltage operation. The boost rectifier compensates for the input AC voltage sag by increasing the input AC current into the boost rectifier, to maintain the DC link voltage at its setpoint (V_{STPT1}). The boost rectifier continues to compensate for the sag in voltage by increasing the input current until it reaches a predetermined current limit. When the boost rectifier reaches the predetermined current limit, if the line voltage has not recovered to an acceptable level, the second step of the method commences as two substantially simultaneous responses, first by unloading the compressor and second by supplying power to the DC link from the stored energy in the rotating mass of the motor and compressor.

[0041] Referring to Figure 4, the compressor control unit 406 actuates the mechanical unloading device 303 of the compressor 302 to minimize the power consumed by the refrigeration load from the DC link capacitors and the inertia of the rotating mass of the motor rotor and compressor. While the mechanical load is being uncoupled by the compressor control unit 406 in order to conserve the energy stored in the rotating masses, the inverter control unit 404 switches from the motor speed control mode to DC link voltage control mode and controls the magnitude of the DC link voltage to a level of V_{STPT2} by controlling the motor speed. During the duration of the voltage sag the command received from the control panel, microprocessor or controller 308 to provide the optimal operational setting for the VSD 104 and motor 106 depending on the particular sensor readings received

by the control panel 308 is ignored by the VSD 104. This forces the motor 106 and compressor 302 to act as a generator which causes the necessary amount of energy stored in their inertia to be transferred to the DC link capacitors. The rotor speed of the motor 106 decreases during the ride-through, while the DC link voltage is maintained at V_{SPT2} . If the energy stored in the rotating mass continues to deplete prior to the restoration of the line input voltage to normal range, the DC link voltage will drop below a predetermined threshold, denoted as V_{UNDER} , and the system will shut down.

[0042] In a system where multiple inverters and compressor motors are connected to the same DC link, the inverter control unit(s) operates in a similar fashion as explained above for the single inverter case. The main difference is in the fact that each inverter may have its own threshold V_{TH1} (e.g. V_{TH1a} , V_{TH1b} , V_{TH1c} , where a, b, c stand for different inverters) and its own setpoint V_{SPT2} (e.g. V_{SPT2a} , V_{SPT2b} , V_{SPT2c}). This separation of threshold values and setpoint values among different inverters and compressor motors is needed in order to prevent potential instability when multiple inverters try to control the DC link voltage at the same time.

[0043] The VSD includes an Active Rectifier 202 which may be a pulse width modulated boost rectifier or other boost rectifier type. The DC link stage 204 provides a control signal V_{DC} at a node 400, which is transmitted to the rectifier control unit 402 and the inverter control unit 404. Control units 402 and 404 also receive other control signals in addition to the DC link voltage, which are omitted in this Figure for ease of illustration. Control units 402 and 404 are typically located inside the VSD cabinet, but may be located within the control panel 308, or may be separately mounted on the respective equipment.

[0044] One embodiment of the ride-through method of the present invention is shown in Figure 5A. A flow diagram 500 generally illustrating one aspect of the method of the present invention begins in step 502 representing the system initialization. After the system is initialized it runs in normal operation as shown in step 504 provided the line voltage from the AC power source is near the nominal line voltage – i.e., no voltage sag – or the line voltage is beginning to sag below the nominal line voltage but the input current into the boost rectifier is below the current limit value and the DC link voltage is maintained at the setpoint V_{SPT1} . The boost rectifier is regulating the DC link voltage in step 504a; the inverter continues as normal to regulate the speed of the compressor in step 504b; and monitoring of the DC link voltage is performed by the control hardware and software in step 504c (See Fig. 6). Steps

504a-504c may be carried out concurrently or in sequence as shown in step 504. The order indicated in Figure 6 is for illustrative purposes only. The input current of the boost rectifier is equal to or less than the RMS current limit value of the boost rectifier in step 504.

[0045] In step 506, V_{DC} is compared to a predetermined threshold value V_{TH1} . The magnitude of V_{TH1} is less than the nominal setpoint of the DC link voltage V_{STPT1} . As an example, if the nominal DC link voltage is $V_{STPT1}=950$ V, V_{TH1} could be selected as 900 V. If V_{DC} is less than V_{TH1} , this indicates that boost rectifier has reached its current limit and is no longer capable of regulating the DC link voltage to its setpoint value, and hence the system proceeds to step 508 (Figs. 7 & 8) to unload the compressor 302, disable the boost rectifier 202 and precharge devices, and transition the inverter 206 to control the DC link voltage. Otherwise, the system returns to step 504. Monitoring of the DC link voltage V_{DC} may be performed continuously or in sequence, and is indicated as a discrete step herein if a change in the value of V_{DC} triggers a response in the system.

[0046] Steps 508a-508c are carried out in Step 508 as illustrated in Fig. 7. The compressor control unit 406 mechanically unloads the compressor in step 508a through actuation of the vanes in a centrifugal compressor, through the actuation of a slide valve in a screw compressor, or by inserting a check valve in the discharge line of a centrifugal compressor or a screw compressor. By unloading the compressor, the stored rotational energy in the motor is conserved for the ride through operation, as described below, and minimal rotational energy is expended to the refrigerant load of the chiller system 300. During the brief ride-through period the thermal energy stored in the refrigerant loop and secondary evaporative cooling loop is used to provide the necessary cooling to the HVAC&R system load. At approximately the same time, in step 508b, the IGBTs in the boost rectifier are disabled, and in step 508c the precharge devices associated with the boost rectifier are disabled. The system is now in the second stage of Phase 2 ride-through operation, described in steps 510a - 510c. Steps 508a-508c may be carried out concurrently or sequentially.

[0047] Steps 510a - 510c are also carried out in step 508. Referring to Figure 8, in step 510a the inverter is striving to regulate the DC link voltage to a nominal value V_{STPT2} . The value chosen for V_{STPT2} is lower than the value chosen for V_{TH1} . As an example, if V_{TH1} is 900 V, V_{STPT2} may be 850 V. The inverter is operated as a rectifier by the inverter control unit 404. The energy stored in the rotating mass of the motor 106 and compressor 302 flows in the reverse direction from normal motor operation, through the inverter 206 to the DC link

204. The motor 106 and compressor 302 effectively become a generator supplying power to the DC link. In this way, the DC link voltage is supported by energy stored in the electro-mechanical load comprising the motor 106 and compressor 302. Capacitors (not shown) that are connected to the DC link for storing electrical energy are maintained in a charged state by the energy flowing through the inverter 206 from the motor 106. In this embodiment of the present invention, in step 508b, the boost rectifier is disabled, so that all of the energy supplied to the DC link is provided through the inverter from the stored energy in the motor 106 and compressor 302. The DC link 204 is thus isolated from the input power source, and control hardware and software monitor the DC link voltage V_{DC} in step 510b, and the input line voltage V_{INAC} in step 510c. Steps 510a-510c may be carried out concurrently or sequentially in step 508, and the order indicated in Figure 8 is for illustration purposes only. Step 508 continues until one of the following occurs in steps 512 or 516 shown in Figure 5A.

[0048] In step 512, the DC link voltage V_{DC} is being continuously monitored, and if V_{DC} decreases below a predetermined fault threshold voltage V_{UNDER} (which is lower than V_{STPT2}), a system fault is indicated. The VSD is immediately shut down in step 514. Otherwise, the system proceeds to step 516, in which the input line voltage V_{INAC} is monitored at the input power source. If V_{INAC} is greater than the predetermined input line threshold voltage V_{TH_IN} , this indicates that the voltage sag condition no longer exists, and the system proceeds to step 518 to reset the system to normal operation. As shown in Figure 9, steps 518a-518e are carried out in step 518. In step 518a, precharge devices at the front end of the VSD are enabled to control the increase of the DC link voltage. In steps 518b and 518c, the boost rectifier switches are enabled to further increase the DC link voltage to a predetermined value V_{STPT1} . In step 518d inverter control mode is transferred back to controlling the speed of the motor from the command received from the control panel, microprocessor or controller to provide the optimal operational setting for the VSD 104 and motor 106 depending on the particular sensor readings received by the control panel, and the DC link is again controlled by the rectifier control unit 402. Finally, in step 518e, the compressor is mechanically loaded. The system then resumes regular operation in step 504.

[0049] Referring to Figure 5B, the preferred embodiment for the ride-through sequence is now described. In this aspect of the invention, the boost rectifier remains enabled during the entire ride-through, supplying current to the capacitors of the DC link 202 concurrently with the regeneration of energy from the motor 106. The initial steps 502 through 506 of this

alternate method remain the same as illustrated in Figs. 5A and 6, discussed above. In the alternate method of the present invention, if V_{DC} is less than V_{TH1} , in step 506, the system proceeds to step 608; otherwise, the system returns to step 504. As an example, if the nominal DC link voltage is $V_{STP1} = 950$ V, V_{TH1} could be selected as 900 V. Steps 508, 516 and 518 are replaced by steps 608, 616 and 618 as described below.

[0050] Steps 508a, 510a, 608a and 510c are carried out in step 608 shown in Figure 10. In step 508a, the compressor control unit 406 mechanically unloads the compressor in the same manner described above. In step 510a the inverter control unit 404 begins to regulate the DC link voltage V_{DC} to the value V_{STP2} and stops regulating the speed of the compressor motor 106 by ignoring the command received from the control panel, microprocessor or controller that provides the optimal operational setting for the VSD 104 and motor 106 depending on the particular sensor readings received by the control panel. The value chosen for V_{STP2} is lower than the value chosen for V_{TH1} . As an example, if V_{TH1} is 900 V, V_{STP2} may be 850 V. In step 608a, the boost rectifier continues to strive to regulate the DC link to the value V_{STP1} operating in current limit, in contrast with the method set forth in Figure 7. Steps 508a, 510a and 510c may be carried out concurrently or sequentially in step 608, and the order indicated in Figure 10 is for illustration purposes only.

[0051] In step 510a the inverter is operating as a rectifier to regulate the DC link voltage to a predetermined value V_{STP2} . The DC link voltage is supported both by the energy conducted through the rectifier/converter and by the energy stored in the electro-mechanical load comprising the motor 106 and compressor 302. In this preferred embodiment, in step 608a, the boost rectifier remains active at its current limit and is also striving to regulate the DC link voltage, but to the higher setpoint value of V_{STP1} . The operation in current limit prevents the boost rectifier from actually being able to achieve V_{STP1} at its output. When the input AC voltage rises to a sufficient magnitude the Active Rectifier can supply sufficient energy to permit V_{STP1} be achieved. In other words, the boost rectifier's voltage control loop is saturated when operating in current limit (which prevents system instability when both the boost rectifier and the inverter operate in closed loop trying to control DC link voltage), but power continues to flow from the input AC line into the DC link. Thus power is supplied to the DC link stage from both the input voltage source through the converter, and from the load through the inverter, permitting the maximum energy to be retained during the voltage sag and thus maximizing the ride-through capability of the system. The alternate method

proceeds to step 512 as described in Figure 5A above and also shown in Fig. 5B, until reaching step 616. In step 616 the DC link voltage V_{DC} is compared with the V_{TH1} limit and a decision is made to either continue to loop back to Phase 2 operation or cease ride-through operation at step 618. If V_{DC} is greater than V_{TH1} , the Active Rectifier is no longer operating in current limit, which indicates that the input line voltage has recovered to within a predetermined percentage of the rated line voltage and the inverter control unit has reverted back to controlling the speed of the motor 106 in accordance with the command received from the control panel, microprocessor or controller that provides the optimal operational setting for the VSD 104 and motor 106 depending on the particular sensor readings received by the control panel. In step 618 the compressor 302 is mechanically loaded. The system then resumes regular operation in step 504.

[0052] While it is preferred that the control algorithm be embodied in a computer program(s) and executed by a microprocessor located in the VSD 104, 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 VSD 104 can be changed to incorporate the necessary components and to remove any components that may no longer be required.

[0053] In yet another method according to the present invention, the converter 202 of the VSD 104 may be a passive rectifier – i.e., a diode or thyristor rectifier for converting the AC input power to DC power for the DC link stage. While the method of using a passive rectifier/converter 202 provides less ride through capability than the active rectifier/converter method, there is still an improved ride through achieved as a result of the unloading of the refrigerant load and the regeneration of energy from the motor/compressor load to the DC link 204. When a passive rectifier is used, the method described in Figure 5 is implemented, with ride through effectively beginning in step 508, wherein the DC link voltage has decayed below the threshold voltage V_{TH1} . In Figure 7 step 508b, and in Figure 9 step 518b, action is taken toward the passive rectifier rather than an active rectifier. In this case the DC link voltage cannot be controlled to a specific setpoint such as V_{STP1} through the input converter, but rather the DC link voltage magnitude is a function of the passive rectification of the input AC line voltage. In this case the magnitude of V_{TH1} is chosen to be at a level that is lower than the minimum expected DC voltage resulting from rectification of the input line voltage, over the operating input voltage range of the system. V_{STPT2} is chosen to be less than V_{TH1}

and the inverter control unit 404 regulates the DC link voltage V_{DC} to the value V_{STPT2} during the voltage sag.

[0054] Referring again to Figure 3, there are various devices that may be used to implement the mechanical unloading of the compressor 302. Pre-rotation vanes 303 are indicated by a broken line to indicate application in centrifugal compressors only. Pre-rotation vanes 303 are coupled to the compressor inlet in a centrifugal compressor 302. The pre-rotation vanes 303 are operable to vary the loading of the compressor 302. Preferably, a high-speed actuator (not shown) may be employed to quickly close the pre-rotation vanes 303 in response to a power sag. Similarly, where the compressor is a screw compressor, a slide valve 303 may be used to vary the load as the pre-rotation vanes 303 do in the centrifugal compressor arrangement. The slide valve 303 is indicated by a broken line to indicate application in screw compressors only. A high-speed actuator for the slide valve 303 is also preferred, to allow the system to respond quickly to a voltage sag. When a voltage sag occurs, mechanical unloading of the compressor is accomplished by closing the pre-rotation vanes 303.

[0055] Figure 3 also illustrates a check valve 305 inserted in the discharge line 307 of the compressor. Alternately, check valve 305 may be inserted in the suction line 301 of the compressor 302. The operation of the check valve 305 eliminates any need for action by the chiller control system to cause the compressor to mechanically shed load, i.e., the check valve 305 eliminates the need for a high-speed actuating device, e.g., a slide valve 303 in a screw compressor, or pre-rotation vanes 303 in a centrifugal compressor. The check valve 305 also minimizes the mechanical unloading time of the compressor 302. In an alternate embodiment, the check valve 305 may be omitted, and either the pre-rotation vanes or slide valve 303 used for mechanical unloading of the compressor 302. The check valve 305 may be used alone or in combination with one of the other types of mechanical unloading devices.

[0056] This rapid mechanical unloading of the compressor is particularly advantageous in a centrifugal compressor application, because the system is normally operating on the edge of compressor surge. Compressor surge occurs when the flow of the refrigerant in the chiller system reverses direction against the centrifugal impeller. If the compressor 302 is operating at or near the surge point, a decrease in the compressor operating speed will cause the compressor 302 to enter into the surge region. This reduction in operating speed is implemented according to the ride-through algorithm, as described above with respect to

Figures 5 through 10. A check valve 305 inserted in the discharge line of the compressor 302 prevents the refrigerant gas from flowing backwards, and thus prevents a surge condition of the compressor 302. The check valve 305 closes when the rotational speed of the impeller is reduced, because the pressurized refrigerant gas in the discharge lines immediately begins to equalize pressure by flowing backwards. Simultaneously the closing of the valve unloads the compressor system, thus maximizing the storage of energy in the rotating system and extending the ride through capability of the system.

[0057] When the input AC power 102 is restored to the nominal voltage, the RPM of the compressor impeller is restored to the rated operating RPM. The pressure in the compressor discharge line 307 is then controlled and returned to rated levels, forcing the check valve 305 to open, and the mechanical loading of the system is restored to the value prior to the voltage sag.

[0058] The system and method of the present invention does not require the sensing of motor speed to monitor and respond to voltage sag conditions, which reduces the cost and increases the reliability of the system. The control is achieved through sensing of the DC link voltage, input AC line voltage, input currents and motor currents.

[0059] 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.

We claim:

1. A method for controlling a variable speed drive to ride-through a voltage sag, comprising the steps of:
 - providing a motor and a compressor coupled to a mechanical load;
 - providing a variable speed drive to power the motor, the variable speed drive including an active converter stage and an inverter stage electrically coupled by a DC link stage;
 - monitoring a DC voltage of the DC link stage;
 - monitoring an input parameter of the active converter stage;
 - regulating the DC voltage of the DC link stage with the active converter in response to a change in the monitored DC link voltage;
 - in response to the DC voltage being less than a predetermined first threshold voltage, executing the steps of:
 - transferring the regulation of the DC voltage of the DC link stage to the inverter stage;
 - removing the mechanical load from the compressor; and
 - controlling the DC voltage of the DC link stage with the inverter stage by reversing power flow from the motor to the DC link stage.
2. The method of claim 1, wherein the step of removing the mechanical load from the compressor is implemented automatically by a check valve inserted in a refrigerant line of the compressor to prevent reverse refrigerant flow in response to a decrease in an operational speed of the compressor.
3. The method of claim 2, wherein the refrigerant line is a discharge line of the compressor.
4. The method of claim 2, wherein the refrigerant line is a suction line of the compressor.
5. The method of claim 1, wherein the compressor is a centrifugal compressor, and the step of removing the mechanical load from the compressor comprises operating a plurality of pre-rotation vanes to substantially eliminate the mechanical load of the compressor.
6. The method of claim 1, wherein the compressor is a screw compressor, and the step of removing the mechanical load from the compressor comprises operating a slide valve to substantially eliminate the mechanical load of the compressor.

7. The method of claim 1, further comprising the steps of:
 - monitoring an AC input voltage of an AC input power source; and
 - controlling the DC voltage of the DC link stage with the active converter stage in response to the monitored AC voltage being equal to or greater than a predetermined threshold voltage value.
8. A method for increasing voltage sag ride-through capability in a chiller system, comprising the steps of:
 - providing a motor and a compressor mechanically coupled together;
 - providing a variable speed drive to power the motor, the variable speed drive including an active converter stage and an inverter stage electrically coupled by a DC link stage;
 - monitoring a DC voltage of the DC link stage;
 - monitoring an input parameter of the active converter stage;
 - regulating the DC voltage of the DC link stage through the active converter stage;
 - regulating a motor speed through the inverter stage; and
 - in response to the DC voltage being less than a predetermined first threshold voltage, executing the steps of:
 - transferring the regulation of the DC voltage of the DC link stage to the inverter stage;
 - unloading the compressor;
 - disabling the active converter stage; and
 - controlling the DC voltage of the DC link stage with the inverter stage by reversing power flow from the motor to the DC link.
9. The method of claim 8, wherein the step of unloading the compressor is implemented by a check valve inserted in a refrigerant line of the compressor to prevent reverse refrigerant flow in response to a decrease in an operational speed of the compressor.
10. The method of claim 8, wherein the refrigerant line is a discharge line of the compressor.
11. The method of claim 8, wherein the refrigerant line is a suction line of the compressor.

12. The method of claim 8, wherein the compressor is a centrifugal compressor, and the step of unloading the compressor comprises varying the mechanical load of the compressor in response to a decrease in the DC link voltage by operating a plurality of pre-rotation vanes.
13. The method of claim 8, wherein the compressor is a screw compressor, and the step of unloading the compressor comprises varying the mechanical load of the compressor in response to a decrease in the DC link voltage by operating a slide valve.
14. The method of claim 8, further comprising the steps of:
 - monitoring an AC input voltage of an AC input power source; and
 - controlling the DC voltage of the DC link stage with the active converter stage in response to the monitored AC voltage being equal to or greater than a predetermined threshold voltage value.
15. A chiller system comprising:
 - a compressor, a condenser, and an evaporator connected in a closed refrigerant loop;
 - an unloading device for unloading the compressor in response to a decrease in the operational speed of the compressor;
 - a motor connected to the compressor to power the compressor; and
 - a variable speed drive connected to the motor, the variable speed drive being configured to receive an input AC power at a fixed input AC voltage and a fixed input frequency and provide an output power at a variable voltage and variable frequency to the motor, the variable voltage having a maximum voltage greater in magnitude than the fixed input AC voltage and the variable frequency having a maximum frequency greater than the fixed input frequency, the variable speed drive comprising:
 - a converter stage connected to an AC power source providing the input AC power, the converter stage being configured to convert the input AC voltage to a DC voltage;
 - a DC link stage connected to the converter stage, the DC link stage being configured to filter the DC voltage and store energy from the converter stage;
 - an inverter stage connected to the DC link stage, the inverter stage being configured to convert the DC voltage from the DC link stage into

the output power for the motor having the variable voltage and the variable frequency; and

a control panel to control operation of the variable speed drive, the control panel being configured to regulate the DC voltage of the DC link stage with the inverter stage in response to the DC voltage being less than a predetermined first threshold voltage;

wherein the control panel regulates the DC voltage of the DC link stage with the inverter stage by providing control signals to mechanically unload the compressor, and reverse power flow from the motor to the DC link stage to control the DC voltage of the DC link stage.

16. The system of claim 15, wherein the unloading device is a check valve, the check valve inserted in a refrigerant line of the compressor to prevent reverse refrigerant flow in response to a decrease in the operational speed of the compressor.
17. The system of claim 16, wherein the refrigerant line is a discharge line of the compressor.
18. The system of claim 16, wherein the refrigerant line is a suction line of the compressor.
19. The system of claim 14, wherein the compressor is a centrifugal compressor, and the unloading device is a plurality of pre-rotation vanes, the pre-rotation vanes having an actuator operable to substantially eliminate the mechanical load of the compressor.
20. The system of claim 14, wherein the compressor is a screw compressor and the unloading device is a slide valve, the slide valve operable to substantially eliminate the mechanical load of the compressor.

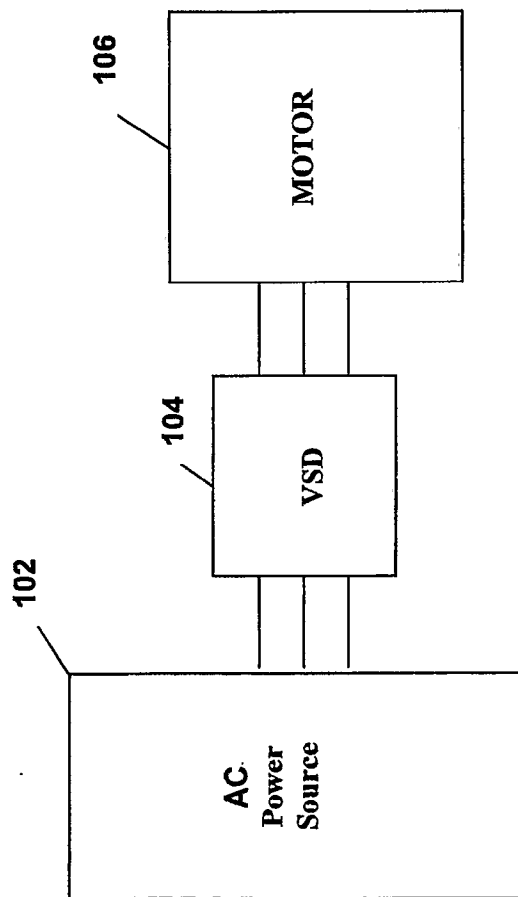


Figure 1

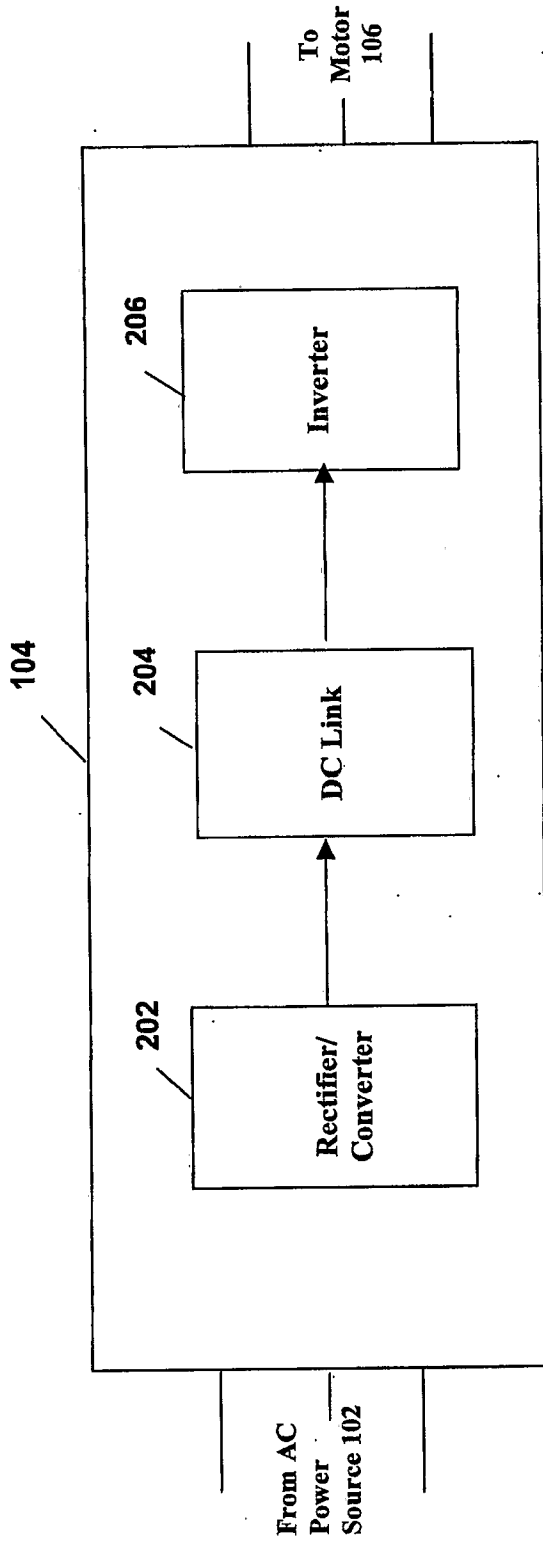


Figure 2

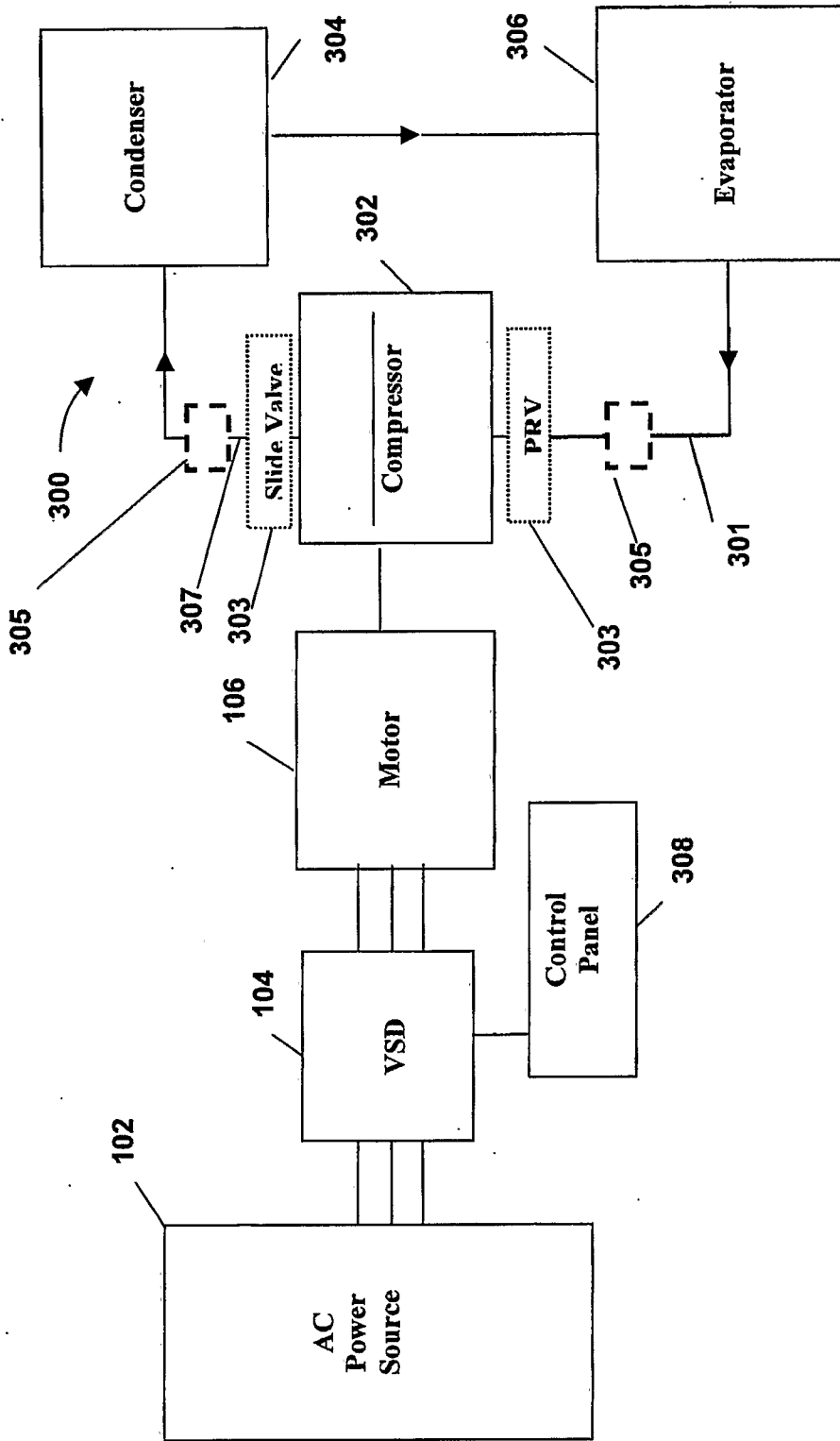


Figure 3

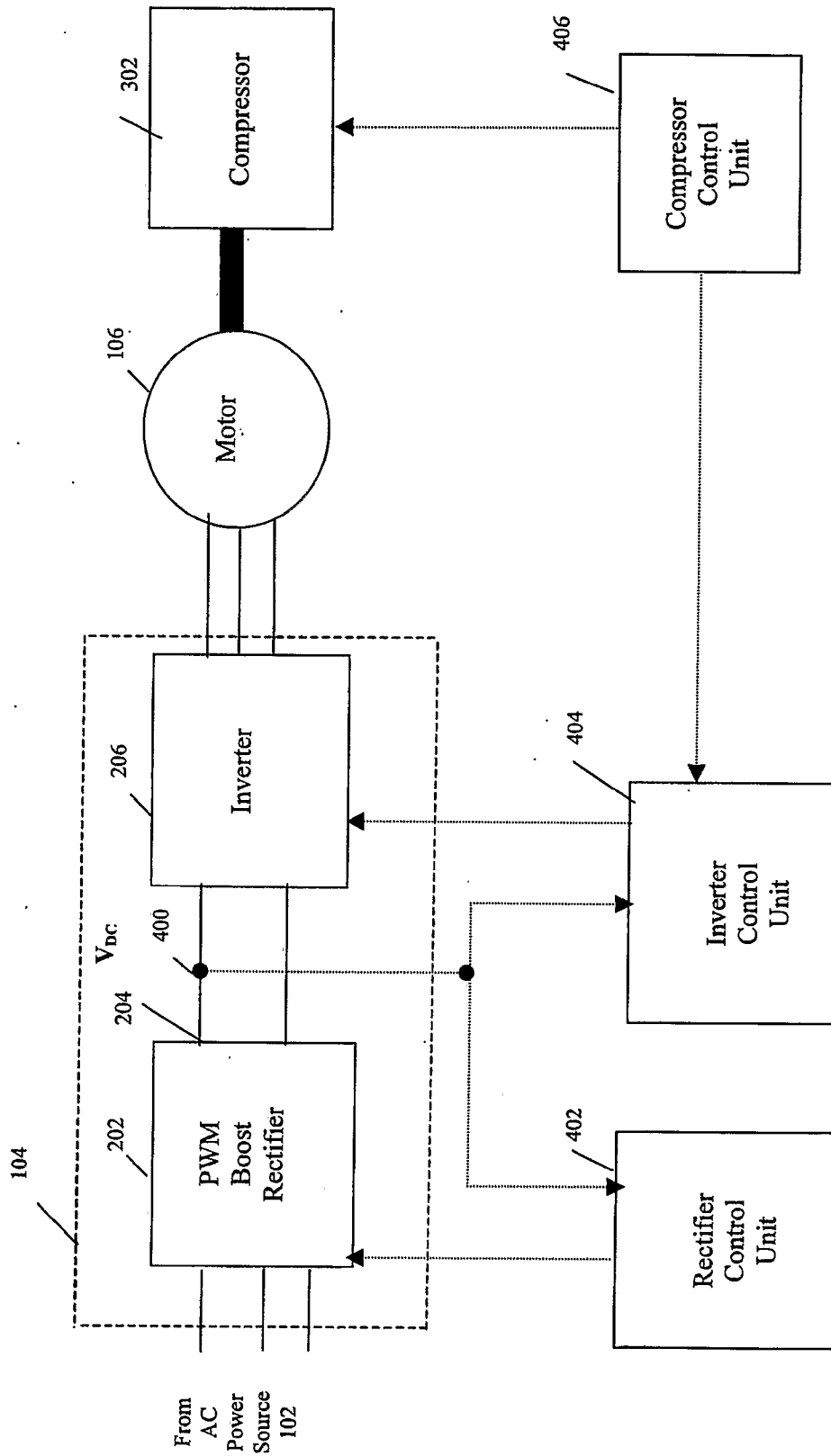


Figure 4

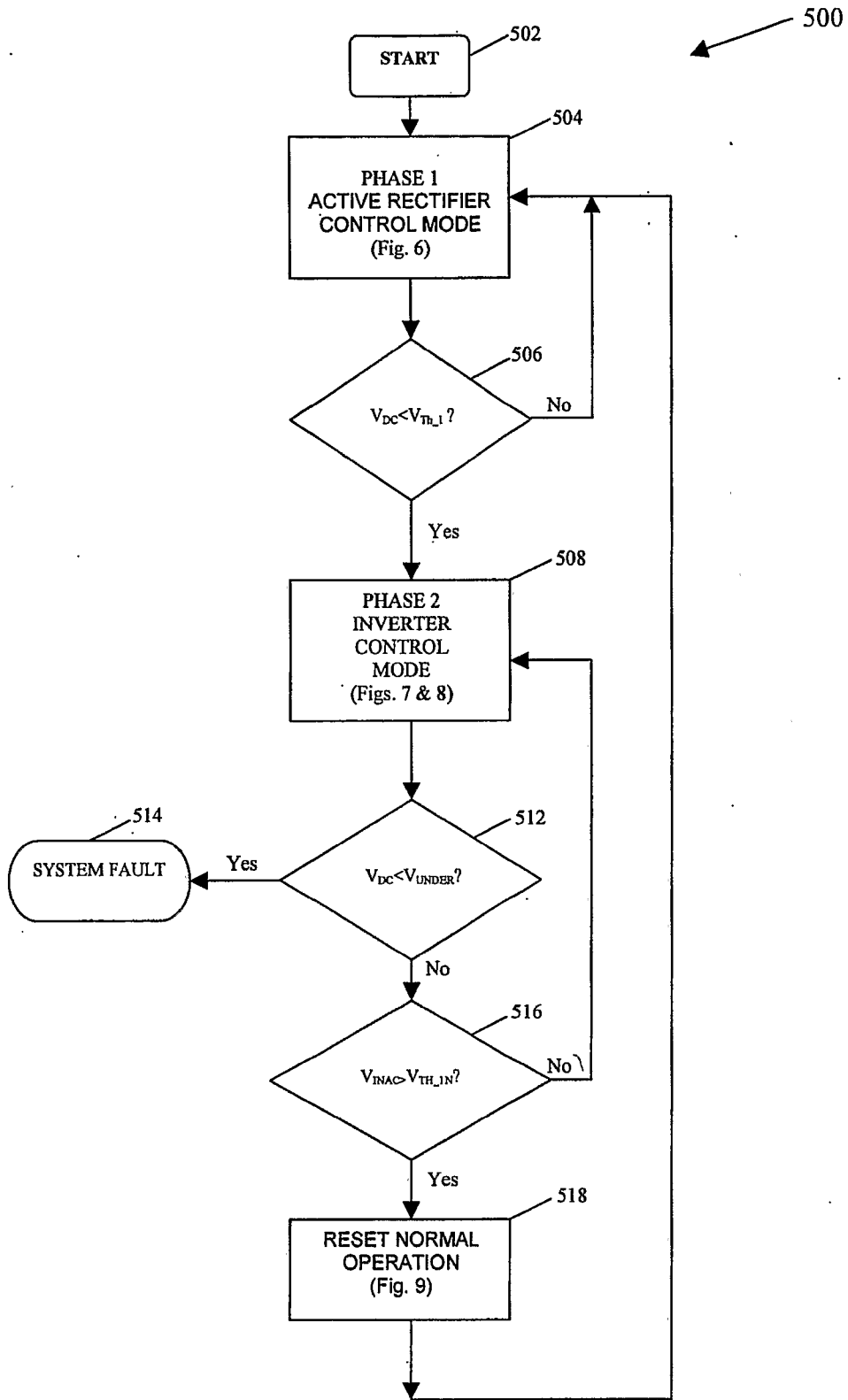


Figure 5A

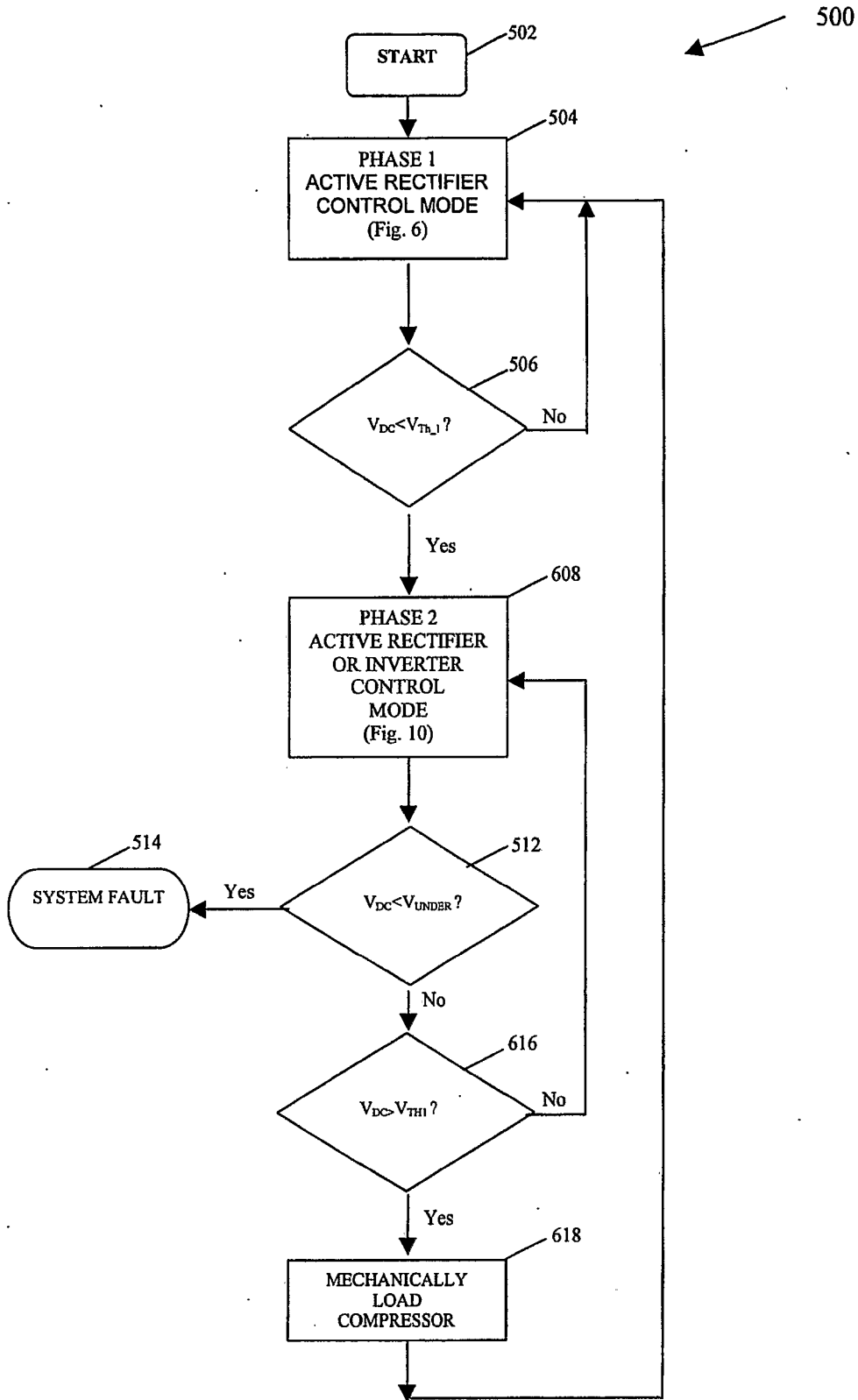


Figure 5B

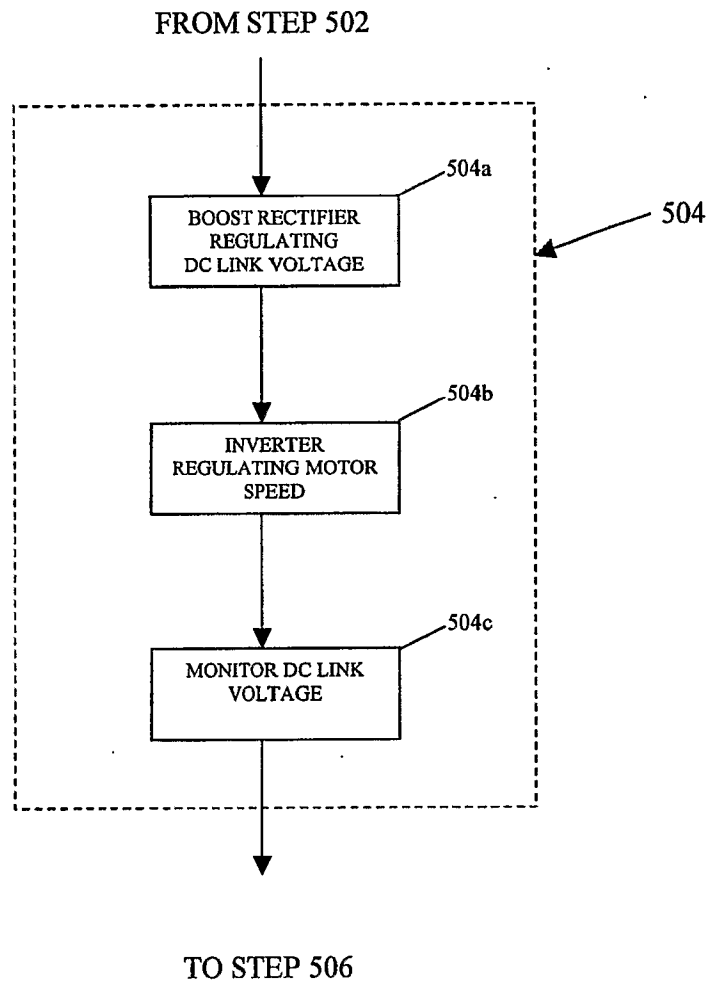


Figure 6

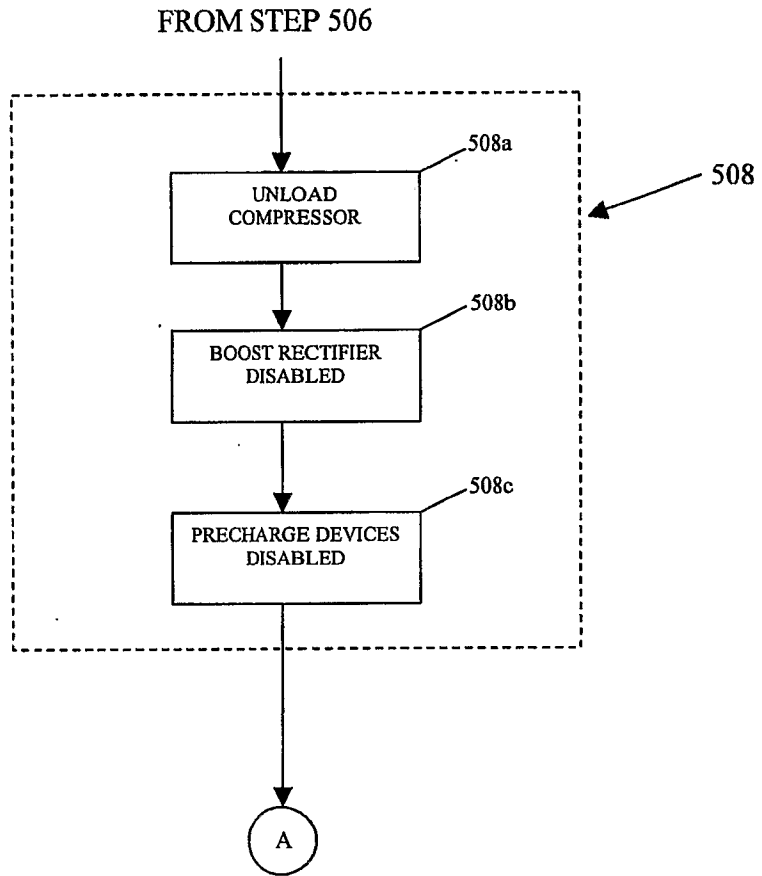
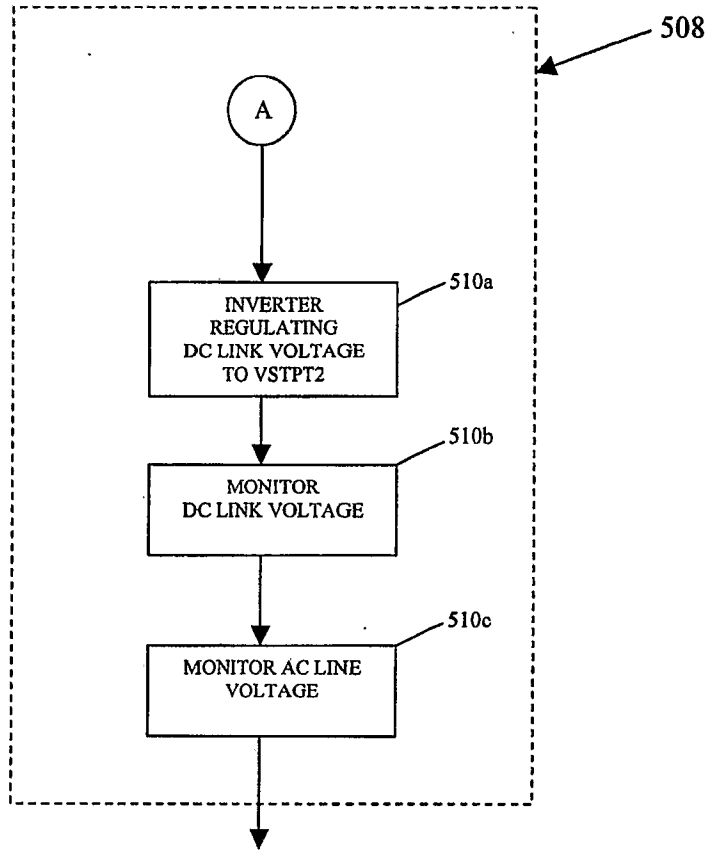


Figure 7



TO STEP 512

Figure 8

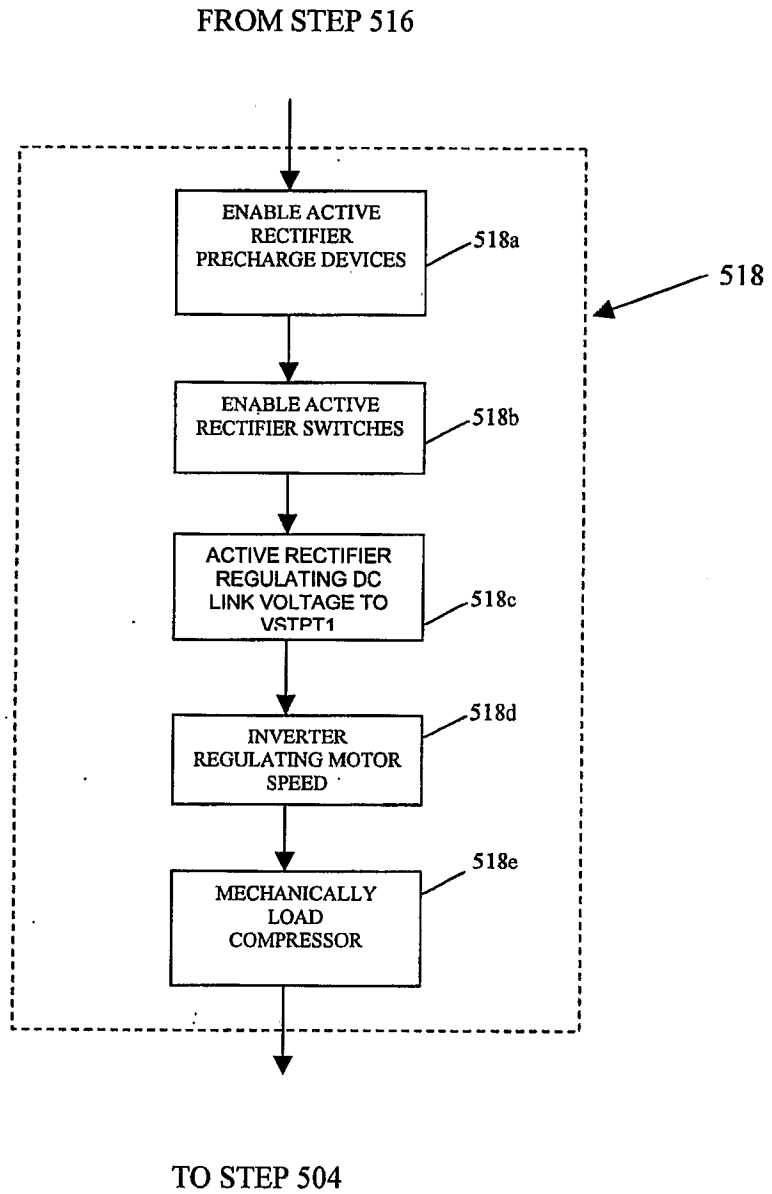


Figure 9

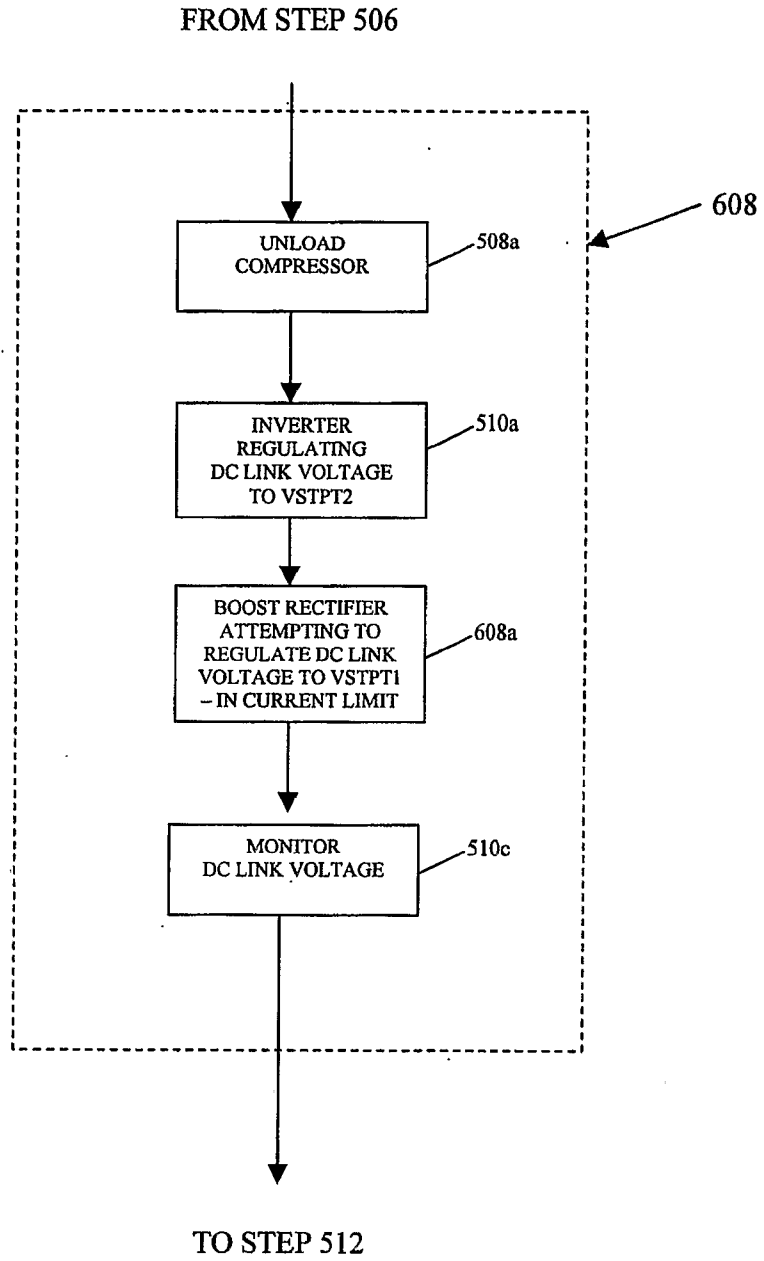


Figure 10