

1        **DIRECT DRIVE FAN SYSTEM WITH VARIABLE PROCESS CONTROL**

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3        CROSS-REFERENCE TO RELATED APPLICATIONS:

4            This application claims the benefit of U.S. provisional application no. 61/549,872, filed  
5        October 21, 2011. The entire disclosure of U.S. application no. 61/549,872 is hereby  
6        incorporated by reference.

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9        TECHNICAL FIELD:

10           The present invention generally relates to a method and system for efficiently managing  
11        the operation and performance of cooling towers, air-cooled heat exchangers (ACHE), HVAC,  
12        and mechanical towers and chillers.

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14        BACKGROUND ART:

15           Industrial cooling systems, such as wet-cooling towers and air-cooled heat exchangers  
16        (ACHE), are used to remove the heat absorbed in circulating cooling water used in power plants,  
17        petroleum refineries, petrochemical and chemical plants, natural gas processing plants and other  
18        industrial facilities. Wet-cooling towers and ACHEs are widely used in the petroleum refining  
19        industry. Refining of petroleum depends upon the cooling function provided by the wet-cooling  
20        towers and air-cooled heat exchangers. Refineries process hydrocarbons at high temperatures  
21        and pressures using processes such as Liquid Catalytic Cracking and Isomerization. Cooling  
22        water is used to control operating temperatures and pressures. The loss of cooling water  
23        circulation within a refinery can lead to unstable and dangerous operating conditions requiring an

1 immediate shut down of processing units. Wet-cooling towers and ACHEs have become  
2 “mission critical assets” for petroleum refinery production. Thus, cooling reliability has become  
3 mission critical to refinery safety and profit and is affected by many factors such as  
4 environmental limitations on cooling water usage, environmental permits and inelastic supply  
5 chain pressures and variable refining margins. As demand for high-end products such as  
6 automotive and aviation fuel has risen and refining capacity has shrunk, the refineries have  
7 incorporated many new processes that extract hydrogen from the lower value by-products and  
8 recombined them into the higher value products. These processes are dependent on cooling to  
9 optimize the yield and quality of the product. Over the past decade, many refineries have been  
10 adding processes that reform low grade petroleum products into higher grade and more profitable  
11 products such as aviation and automotive gasoline. These processes are highly dependent upon  
12 the wet-cooling towers and ACHEs to control the process temperatures and pressures that affect  
13 the product quality, process yield and safety of the process. In addition, these processes have  
14 tapped a great deal of the cooling capacity reserve in the towers leaving some refineries “cooling  
15 limited” on hot days and even bottlenecked. ACHE cooling differs from wet cooling towers in  
16 that ACHEs depend on air for air cooling as opposed to the latent heat of vaporization or  
17 “evaporative cooling”. Most U.S. refineries operate well above 90% capacity and thus,  
18 uninterrupted refinery operation is critical to refinery profit and paying for the process upgrades  
19 implemented over the last decade. The effect of the interruption in the operation of cooling units  
20 with respect to the impact of petroleum product prices is described in the report entitled  
21 "Refinery Outages: Description and Potential Impact On Petroleum Product Prices", March  
22 2007, U.S. Department of Energy.

23 Typically, a wet cooling tower system comprises a basin which holds cooling water that

1 is routed through the process coolers and condensers in an industrial facility. The cool water  
2 absorbs heat from the hot process streams that need to be cooled or condensed, and the absorbed  
3 heat warms the circulating water. The warm circulating water is delivered to the top of the  
4 cooling tower and trickles downward over fill material inside the tower. The fill material is  
5 configured to provide a maximum contact surface, and maximum contact time, between the  
6 water and air. As the water trickles downward over the fill material, it contacts ambient air  
7 rising up through the tower either by natural draft or by forced draft using large fans in the tower.  
8 Many wet cooling towers comprise a plurality of cells in which the cooling of water takes place  
9 in each cell in accordance with the foregoing technique. Cooling towers are described  
10 extensively in the treatise entitled "Cooling Tower Fundamentals", second edition, 2006, edited  
11 by John C. Hensley, published by SPX Cooling Technologies, Inc.

12 Many wet cooling towers in use today utilize large fans, as described in the foregoing  
13 discussion, to provide the ambient air. The fans are enclosed within a fan stack which is located  
14 on the fan deck of the cooling tower. Fan stacks are typically configured to have a parabolic  
15 shape to seal the fan and add fan velocity recovery. In other systems, the fan stack may have a  
16 cylindrical shape. Drive systems are used to drive and rotate the fans. The efficiency and  
17 production rate of a cooling tower is heavily dependent upon the efficiency of the fan drive  
18 system. The duty cycle required of the fan drive system in a cooling tower environment is  
19 extreme due to intense humidity, poor water chemistry, potentially explosive gases and icing  
20 conditions, wind shear forces, corrosive water treatment chemicals, and demanding mechanical  
21 drive requirements. In a multi-cell cooling tower, such as the type commonly used in the  
22 petroleum industry, there is a fan and fan drive system associated with each cell. Thus, if there is  
23 a shutdown of the mechanical fan drive system associated with a particular cell, then that cell

1 suffers a “cell outage”. A cell outage will result in a decrease in the production of refined  
2 petroleum. For example, a “cell outage” lasting for only one day can result in the loss of  
3 thousands of refined barrels of petroleum. If numerous cells experience outages lasting more  
4 than one day, the production efficiency of the refinery can be significantly degraded. The loss in  
5 productivity over a period of time can be measured as a percent loss in total tower-cooling  
6 potential. As more cell outages occur within a given time frame, the percent loss in total tower-  
7 cooling potential will increase. This, in turn, will decrease product output and profitability of the  
8 refinery and cause an increase in the cost of the refined product to the end user. It is not  
9 uncommon for decreases in the output of petroleum refineries, even if slight, to cause an increase  
10 in the cost of gasoline to consumers. There is a direct relationship between cooling BTUs and  
11 Production in barrels per day (BBL/Day).

12 One prior art drive system commonly used in wet-cooling towers is a complex,  
13 mechanical fan drive system. This type of prior art fan drive system utilizes a motor that drives  
14 a drive train. The drive train is coupled to a gearbox, gear-reducer or speed-reducer which is  
15 coupled to and drives the fan blades. Referring to FIG. 1, there is shown a portion of a wet-  
16 cooling tower 1. Wet-cooling tower 1 utilizes the aforesaid prior art fan drive system. Wet  
17 cooling tower 1 has fan stack 2 and fan 3. Fan 3 has fan seal disk 4, fan hub 5A and fan blades  
18 5B. Fan blades 5B are connected to fan hub 5A. The prior art fan drive system includes a  
19 gearbox 6 that is coupled to drive shaft 7 which drives gearbox 6. The prior art fan drive system  
20 includes induction motor 8 which rotates drive shaft 7. Shaft couplings, not shown but well  
21 known in the art, are at both ends of drive shaft 7. These shaft couplings couple the draft shaft 7  
22 to the gearbox 6 and to induction motor 8. Wet-cooling tower 1 includes fan deck 9 upon which  
23 sits the fan stack 2. Gearbox 6 and induction motor 9 are supported by a ladder frame or torque

1 tube (not shown) but which are well known in the art. Vibration switches are typically located  
2 on the ladder frame or torque tube. One such vibration switch is vibration switch 8A shown in  
3 FIG. 1. These vibration switches function to automatically shut down a fan that has become  
4 imbalanced for some reason. This prior art fan drive system is subject to frequent outages, a  
5 less-than-desirable MTBF (Mean Time Between Failure), and requires diligent maintenance,  
6 such as regular oil changes, in order to operate effectively. Coupling and shaft alignment are  
7 critical and require experienced craft labor. One common type of mechanical drive system used  
8 in the prior art gearbox-type fan drive utilizes five rotating shafts, eight bearings, three shaft  
9 seals (two at high speed), and four gears (two meshes). This drive train absorbs about 3% of the  
10 total power. Although this particular prior art fan drive system may have an attractive initial low  
11 cost, cooling tower end-users found it necessary to purchase heavy duty and oversized  
12 components such as composite gearbox shafts and couplings in order to prevent breakage of the  
13 fan drive components especially when attempting across-the-line starts. Many cooling tower  
14 end-users also added other options such as low-oil shutdown, anti-reverse clutches and oil bath  
15 heaters. Thus, the life cycle cost of the prior art mechanical fan drive system compared to its  
16 initial purchase price is not equitable. Once the end user has purchased the more expensive  
17 heavy duty and oversized components, the reliability of the prior art fan drive system is still quite  
18 poor even after they perform all the expensive and time consuming maintenance. Thus, this  
19 prior art gearbox-type drive system has a low, initial cost, but a high cycle cost with poor  
20 reliability. In a multi-cell cooling tower, such as the type commonly used in the petroleum  
21 industry, there is a fan and prior art mechanical fan drive system associated with each cell. Thus,  
22 if there is a shutdown of the mechanical fan drive system associated with a particular cell, then  
23 that cell suffers a “cell outage” which was described in the foregoing description. The loss in

1 productivity over a period of time due to the poor reliability of the prior art mechanical fan drive  
2 systems can be measured as a percent loss in refinery production (bbls/day). In one currently  
3 operating cooling tower system, data and analysis has shown that the loss of one cell is equated  
4 to the loss of 2,000 barrels per day.

5 Other types of prior art fan drive systems, such as V-belt drive systems, also exhibit  
6 many problems with respect to maintenance, MTBF and performance and do not overcome or  
7 eliminate the problems associated with the prior art gearbox-type fan drive systems. One attempt  
8 to eliminate the problems associated with the prior art gearbox-type fan drive system was the  
9 prior art hydraulically driven fan systems. Such a system is described in U.S. Patent No.  
10 4,955,585 entitled "Hydraulically Driven fan System for Water Cooling Tower".

11 Air Cooled Heat Exchangers (ACHE) are well known in the art and are used for cooling  
12 in a variety of industries including power plants, petroleum refineries, petrochemical and  
13 chemical plants, natural gas processing plants, and other industrial facilities that implement  
14 energy intensive processes. ACHE exchangers are used typically where there is lack of water, or  
15 when water-usage permits cannot be obtained. ACHEs lack the cooling effectiveness of "Wet  
16 Towers" when compared by size (a.k.a. footprint). Typically, an ACHE uses a finned-tube  
17 bundle. Cooling air is provided by one or more large fans. Usually, the air blows upwards  
18 through a horizontal tube bundle. The fans can be either forced or induced draft, depending on  
19 whether the air is pushed or pulled through the tube bundle. Similar to wet cooling towers, fan-  
20 tip speed typically does not exceed 12,000 feet per minute for aeromechanical reasons and may  
21 be reduced to obtain lower noise levels. The space between the fan(s) and the tube bundle is  
22 enclosed by a fan stack that directs the air (flow field) over the tube bundle assembly thereby  
23 providing cooling. The whole assembly is usually mounted on legs or a pipe rack. The fans are

1 usually driven by a fan drive assembly that uses an electric motor. The fan drive assembly is  
2 supported by a steel, mechanical drive support system. Vibration switches are typically located  
3 on the structure that supports the fan assembly. These vibration switches function to  
4 automatically shut down a fan that has become imbalanced for some reason. Airflow is very  
5 important in ACHE cooling to ensure that the air has the proper “flow field” and velocity to  
6 maximize cooling. Turbulence caused by current fan gear support structure can impair cooling  
7 efficiency. Therefore, mass airflow is the key parameter to removing heat from the tube and  
8 bundle system. ACHE cooling differs from wet cooling towers in that ACHEs depend on air for  
9 air cooling as opposed to the latent heat of vaporization or “evaporative cooling”.

10 Prior art ACHE fan drive systems use any one of a variety of fan drive components.  
11 Examples of such components include electric motors, steam turbines, gas or gasoline engines,  
12 or hydraulic motors. The most common drive device is the electric motor. Steam and gas drive  
13 systems have been used when electric power is not available. Hydraulic motors have also been  
14 used with limited success. Specifically, although hydraulic motors provide variable speed  
15 control, they have relatively low efficiencies. Motor and fan speed are sometimes controlled  
16 with variable frequency drives with mixed success. The most commonly used speed reducer is  
17 the high-torque, positive type belt drive, which uses sprockets that mesh with the timing belt  
18 cogs. They are used with motors up to 50 or 60 horsepower, and with fans up to about 18 feet in  
19 diameter. Banded V-belts are still often used in small to medium sized fans, and gear drives are  
20 used with very large motors and fan diameters. Fan speed is set by using a proper combination  
21 of sprocket or sheave sizes with timing belts or V-belts, and by selecting a proper reduction ratio  
22 with gears. In many instances, right-angle gear boxes are used as part of the fan drive system in  
23 order to translate and magnify torque from an offset electrical motor. However, belt drives,

1 pulleys and right-angle gear boxes have poor reliability. The aforesaid complex, prior art  
2 mechanical drive systems require stringent maintenance practices to achieve acceptable levels of  
3 reliability. In particular, one significant problem with ACHE fan systems is the poor reliability  
4 of the belt due to belt tension. A common practice is to upgrade to “timing belts” and add a  
5 tension system. One technical paper, entitled “*Application of Reliability Tools to Improve V-Belt*  
6 *Life on Fin Fan Cooler Units*”, by Rahadian Bayu of PT, Chevron Pacific Indonesia, Riau,  
7 Indonesia, presented at the 2007 International Applied Reliability Symposium, addresses the  
8 reliability and efficiency of V-belts used in many prior art fan drive systems. The reliability  
9 deficiencies of the belt and pulley systems and the gear reducer systems used in the ACHE fan  
10 drive systems often result in outages that are detrimental to mission critical industries such as  
11 petroleum refining, petro-chemical, power generation and other process intensive industries  
12 dependent on cooling. Furthermore, the motor systems used in the ACHE fan drive systems are  
13 complex with multiple bearings, auxiliary oil and lubrications systems, complex valve systems  
14 for control and operation, and reciprocating parts that must be replaced at regular intervals.  
15 Many petroleum refineries, power plants, petrochemical facilities, chemical plants and other  
16 industrial facilities utilizing prior art ACHE fan drive systems have reported that poor reliability  
17 of belt drive systems and right-angle drive systems has negatively affected production output.  
18 These industries have also found that service and maintenance of the belt drive and gearbox  
19 system are major expenditures in the life cycle cost, and that the prior art motors have  
20 experienced failure due to the incorrect use of high pressure water spray. The duty cycle  
21 required of an ACHE fan drive system is extreme due to intense humidity, dirt and icing  
22 conditions, wind shear forces, water washing (because the motors are not sealed, sometime they  
23 get sprayed by operators to improve cooling on hot days), and demanding mechanical drive

1 requirements.

2 In an attempt to increase the cooling performance of ACHE cooling systems, some end-  
3 users spray water directly on the ACHE system to provide additional cooling on process limiting,  
4 hot days. Furthermore, since fan blades can become “fouled” or dirty in regular service and lose  
5 performance, many end-users water-wash their ACHE system to maintain their cooling  
6 performance. However, directly exposing the ACHE system to high pressure water spray can  
7 lead to premature maintenance and/or failure of system components, especially since prior art  
8 drive systems are typically open thereby allowing penetration by water and other liquids. Thus,  
9 the efficiency and production rate of a process is heavily dependent upon the reliability of the  
10 ACHE cooling system and its ability to remove heat from the system.

11 Prior art fan systems have further drawbacks. Most of the currently installed fleet of  
12 cooling tower fans operates continuously at 100% speed. For a small percentage of applications,  
13 variable frequency drives (“VFD”) of Adjustable Speed Drives have been applied to an induction  
14 motor to simulate variable speed. However, the application of VFDs to induction motors has not  
15 been overly successful and not implemented on a wide scale due to poor success rates. In some  
16 cases this may also involve a two-speed induction motor. These applications have not been  
17 widely installed by end-users. In some cases, end-users have installed VFDs solely to provide  
18 “soft starts” to the system thereby avoiding “across the line starts” that can lead to failure or  
19 breakage of the gearbox system when maximum torque is applied to the system at start-up. This  
20 issue is further exacerbated by “fan windmilling” which occurs when the fan turns in reverse due  
21 to the updraft force of the tower on the pitch of the fan. Windmilling of the fan is not allowed  
22 due to the lubrication limitation of gearboxes in reverse and requires the addition of an anti-  
23 reverse mechanism.

1 Prior art variable speed induction motors are reactive to basin temperature and respond  
2 by raising the fan to 100% fan tip speed until basin temperature demand is met and then reducing  
3 the speed to a predetermined set speed which is typically 85% fan tip speed. Such systems  
4 utilize lagging feedback loops that result in fan speed oscillation, instability and speed hunting  
5 that consume large amounts of energy during abrupt speed changes and inertial changes which  
6 results in premature wear and failure of gear train parts that are designed for single speed, omni-  
7 direction operation.

8 Induction motors in variable speed duty require extra insulation, additional windings and  
9 larger cooling fans for part-load cooling which increases the cost and size. Application of  
10 induction motors on variable speed fans requires that the motor be able to generate the required  
11 torque to turn the fan to speed at part-load operation which can also require the motor to be  
12 larger than for a steady state application and thus increase the cost and size. In these variable  
13 speed fan systems, the fan speed is controlled by the basin temperature set point. This means  
14 that fan speed will increase according to a set algorithm when the basin temperature exceeds a  
15 temperature set point in order to cool the basin water. Once the basin temperature set point has  
16 been satisfied the fan speed will be reduced according to the programmed algorithms.  
17 Furthermore, motors and gearboxes are applied without knowledge of the cooling tower thermal  
18 performance and operate only as a function of the basin temperature set point which results in  
19 large speed swings of the fan wherein the fan speed is cycled from minimum fan speed to  
20 maximum fan speed over a short period of time. The speed swings that occur at maximum fan  
21 acceleration consume significant amounts of energy.

22 Typical prior art gearboxes are designed for one-way rotation as evidenced by the lube  
23 system and gear mesh design. These gearboxes were never intended to work in reverse. In order

1 to achieve reverse rotation, prior art gearboxes were modified to include additional lube pumps  
2 in order to lubricate in reverse due to the design of the oil slinger lubrication system which is  
3 designed to work in only one direction. These lube pumps are typically electric but can also be  
4 of other designs. The gear mesh of the gearbox is also a limiting factor for reverse rotation as the  
5 loading on the gear mesh is not able to bear the design load in reverse as it can in forward  
6 rotation. Typically, the modified gearboxes could operate in reverse at slow speed for no more  
7 than two minutes. End users in colder climates that require reverse rotation for de-icing the  
8 cooling tower on cold days have reported numerous failures of the gearbox drive train system. In  
9 addition, most operators have to manually reverse the system on each cell which may include an  
10 electrician. Since the gearbox and lubrication system are designed for one-way rotation typically  
11 at 100% fan speed, fan braking, gear train inertia and variable speed duty will accelerate wear  
12 and tear on the gearbox, drive shaft and coupling components as the inertial loads are directly  
13 reacted into the drive train, gearbox and motor.

14 Variable Speed Fan systems have not been widely adopted. However, in the interest of  
15 energy savings, more VFDs have been and are being applied to induction motors and fan  
16 gearbox systems with the hope of saving energy. However, these modifications require more  
17 robust components to operate the fan based upon the basin temperature set point. The DOE  
18 (Department of Energy) reports that the average energy savings of such applications is 27%.  
19 This savings is directly proportional to the fan laws and the reduced loading on the system as  
20 opposed to motor efficiency, which for an induction motor, drops off significantly in part-load  
21 operation.

22 Currently operating cooling towers typically do not use expensive condition-monitoring  
23 equipment that has questionable reliability and which has not been widely accepted by the end

1 users. Vibration safety in prior art fan systems is typically achieved by the placement of  
2 vibration switches on the ladder frame near the motor. An example of such a vibration switch is  
3 vibration switch 8A shown in FIG. 1. These vibration switches are isolated devices and are  
4 simply on-off switches that do not provide any kind of external signals or monitoring. These  
5 vibration switches have poor reliability and are poorly applied and maintained. Thus, these  
6 vibration switches provide no signals or information with respect to fan system integrity.  
7 Therefore, it is not possible to determine the source or cause of the vibrations. Such vibration  
8 switches are also vulnerable to malfunction or poor performance and require frequent testing to  
9 assure they are working. The poor reliability of these switches and their lack of fidelity to sense  
10 an impending blade failure continues to be a safety issue. In an alternate form, vibration switches  
11 have been installed on or in the gearbox itself but continue to suffer from a lack of vibration  
12 signal fidelity and filtering to perform condition monitoring and system shutdown to the  
13 satisfaction of the end-user and their wide spread application. Prior art fan balancing typically  
14 consist of static balancing done at installation.

15 In prior art multi-cell cooling systems that utilize a plurality fans with gearbox drives,  
16 each fan is operated independently at 100%, or variable speed controlled independently by the  
17 same algorithm. Cooling towers are typically designed at one design point: maximum hot day  
18 temperature, maximum wet-bulb temperature and thus operate the fans at 100% steady state to  
19 satisfy the maximum hot day temperature, maximum wet-bulb temperature design condition,  
20 regardless of environmental conditions.

21 Current practice (CTI and ASME) attempts to measure the cooling tower performance to  
22 a precision that is considered impractical for an operating system that is constantly changing with  
23 the surrounding temperature and wet-bulb temperature. Most refinery operators operate without

1 any measure of performance and therefore wait too long between service and maintenance  
2 intervals to correct and restore the performance of the cooling tower. It is not uncommon for  
3 some end-users to operate the tower to failure. Some end-users test their cooling towers for  
4 performance on a periodic basis, typically when a cooling tower is exhibiting some type of  
5 cooling performance problem. Such tests can be expensive and time consuming and typically  
6 normalize the test data to the tower design curve. Furthermore, these tests do not provide any  
7 trending data (multiple test points), load data or long-term data to establish performance,  
8 maintenance and service criteria. For example, excessive and wasted energy consumption occurs  
9 when operating fans that cannot perform effectively because the fill is clogged thus allowing  
10 only partial airflow through the tower. Poor cooling performance results in degraded product  
11 quality and/or throughput because reduced cooling is negatively affecting the process. Poor  
12 cooling tower performance can result in unscheduled downtime and interruptions in production.  
13 In many prior art systems, it is not uncommon for end-users to incorrectly operate the cooling  
14 tower system by significantly increasing electrical power to the fan motors to compensate for a  
15 clogged tower or to increase the water flow into the tower to increase cooling when the actual  
16 corrective action is to replace the fill in the tower. Poor cooling tower performance can lead to  
17 incorrect operation and has many negative side effects such as reduced cooling capability, poor  
18 reliability, excessive energy consumption, poor plant performance, and decrease in production  
19 and safety risks.

20 Therefore, in order to prevent supply interruption of the inelastic supply chain of refined  
21 petroleum products, the reliability and subsequent performance of wet-cooling towers and ACHE  
22 cooling systems must be improved and managed as a key asset to refinery safety, production and  
23 profit.

1           What is needed is a method and system that allows for the efficient operation and  
2 management of fans in wet-cooling towers and dry-cooling applications.

3  
4 DISCLOSURE OF THE INVENTION:

5           The present invention is directed to a system and method for efficiently managing the  
6 operation of fans in a cooling tower system including wet-cooling towers, or air-cooled heat  
7 exchanger (ACHE). The present invention is also applicable to managing the operation of fans  
8 in HVAC systems, mechanical towers and chillers. The present invention is based on the  
9 integration of the key features and characteristics such as (1) tower thermal performance, (2) fan  
10 speed and airflow, (3) motor torque, (4) fan pitch, (5) fan speed, (6) fan aerodynamic properties,  
11 and (7) pump flow.

12           The present invention is directed to a direct drive fan system and variable process control  
13 system for efficiently operating a fan in a wet-cooling tower or air-cooled heat exchanger  
14 (ACHE), HVAC system, mechanical tower, or chillers. The present invention is based on the  
15 integration of the key characteristics such as tower thermal performance, fan speed and airflow,  
16 motor torque, fan pitch, fan speed, fan aerodynamic properties, and pump flow rate. As used  
17 herein, the term "pump flow rate" refers to the flow rate of cooled process liquids that are  
18 pumped from the cooling tower for input into an intermediate device, such as condenser, and  
19 then to the process, then back to the intermediate device and then back to the cooling tower.  
20 The present invention uses a variable process control system wherein feedback signals from  
21 multiple locations are processed in order to control high-torque, variable speed motors which  
22 drive the fans and pumps. Such feedback signals represent certain operating conditions  
23 including motor temperature, basin temperature, vibrations and pump flow-rate. Thus, the

1 variable process control system continually adjust motor RPM, and hence fan and pump RPM, as  
2 the operators or users change or vary turbine back-pressure set point, condenser temperature set  
3 point process signal (e.g. crude cracker), and plant part-load setting. The variable process  
4 control processes these feedback signals to optimize the plant for cooling and to prevent  
5 equipment (turbine) failure or trip. The variable process control alerts the operators for the need  
6 to conduct maintenance actions to remedy deficient operating conditions such as condenser  
7 fouling. The variable process control of the present invention increases cooling for cracking  
8 crude and also adjusts the motor RPM, and hence fan and pump RPM, accordingly during plant  
9 part-load conditions in order to save energy.

10 The variable process control system of the present invention comprises a computer  
11 system. The computer system comprises a data acquisition device, referred to as DAQ device  
12 200 in the ensuing description. The computer system further comprises an industrial computer,  
13 referred to as industrial computer 300 in the ensuing description.

14 The variable process control system of the present invention includes a plurality of  
15 variable speed pumps, wherein each variable speed pumps comprises a permanent magnet motor.  
16 The variable process control system further comprises a Variable Frequency Drive (VFD) device  
17 which actually comprises a plurality of individual Variable Frequency Drives. Each Variable  
18 Frequency drive is dedicated to one permanent magnet motor. Therefore, one Variable  
19 Frequency Drive corresponds to the permanent magnet motor of the present invention which  
20 drives the fan, and each of the remaining Variable Frequency Drives is dedicated to controlling  
21 the permanent magnet motor of a corresponding variable speed pump. Thus, each permanent  
22 magnet motor is controlled independently.

23 The system of the present invention provides adaptive and autonomous variable speed

1 operation of the fan and pump with control, supervision and feedback with operator override. A  
2 computer system processes data including cooling tower basin temperature, current process  
3 cooling demand, condenser temperature set-point, tower aerodynamic characteristics, time of  
4 day, wet-bulb temperature, vibration, process demand, environmental stress (e.g. windspeed and  
5 direction) and historical trending of weather conditions to control the variable speed fan in order  
6 to control the air flow through the cooling tower and meet thermal demand. The Variable  
7 Process Control System anticipates process demand and increases or decreases the fan speed in  
8 pattern similar to a sine wave over a twenty four (24) hour period. The Variable Process Control  
9 System accomplishes this by using a Runge-Kutter algorithm (or similar algorithm) that analyzes  
10 historical process demand and environmental stress as well as current process demand and  
11 current environmental stress to minimize the energy used to vary the fan speed. This variable  
12 process control of the present invention is adaptive and learns the process cooling demand by  
13 historical trending as a function of date and time. The operators of the plant input basin  
14 temperature set-point data into the Plant DCS (Distributed Control System). The basin  
15 temperature set-point data can be changed instantaneously to meet additional cooling  
16 requirements such as cracking heavier crude, maintaining vacuum backpressure in a steam  
17 turbine or prevent heat exchanger fouling or derate the plant to part-load. In response to the  
18 change in the basin temperature set-point, the variable process control system of the present  
19 invention automatically varies the rotational speed of the permanent magnet motor, and hence  
20 the rotational speed of the fan, so that the process liquids are cooled such that the temperature of  
21 the liquids in the collection basin is substantially the same as the new basin temperature set-  
22 point. This feature is referred to herein as “variable process control”.

23 In an alternate embodiment, a condenser temperature set-point is inputted into the plant

1 Distributed Control System (DCS) by the operators. The DCS is in electronic signal  
2 communication with the Data Acquisition (DAQ) Device and/or Industrial Computer of the  
3 Variable Process Control System of the present invention. The Data Acquisition device then  
4 calculates a collection basin temperature set-point that is required in order to meet the condenser  
5 temperature set-point. The Variable Process Control system then operates the fan and variable  
6 speed pumps to maintain a collection basin temperature that meets the condenser temperature  
7 set-point inputted by the operators.

8         The variable process control system of the present invention utilizes variable speed  
9 motors to drive fans and pumps to provide the required cooling to the industrial process even as  
10 the environmental stress changes. Process parameters, including but not limited to, temperatures,  
11 pressures and flow rates are measured throughout the system in order to monitor, supervise and  
12 control cooling of liquids (e.g. water) used by the industrial process. The variable process  
13 control system continually monitors cooling performance as a function of process demand and  
14 environmental stress to determine available cooling capacity that can be used for additional  
15 process production (e.g. cracking of crude, hot-day turbine output to prevent brown-outs) or  
16 identify cooling tower expansions. The variable process control system automatically adjusts  
17 cooling capacity when the industrial process is at part-load conditions (e.g. outage, off-peak, cold  
18 day, etc.)

19         The present invention is applicable to multi-cell cooling towers. In a multi-cell system,  
20 the speed of each fan in each cell is varied in accordance with numerous factors such as  
21 Computational Liquid Dynamic Analysis, thermal modeling, tower configuration, environmental  
22 conditions and process demand.

23         The core relationships upon which the system and method of the present invention are

1 based are as follows:

2 A) Mass airflow (ACFM) is directly proportional to fan RPM;

3 B) Fan Static Pressure is directly proportional to the square of the fan RPM; and

4 C) Fan Horsepower is directly proportional to the cube of the fan RPM.

5 The system of the present invention determines mass airflow by way of the operation of a  
6 permanent magnet motor. The variable process control system of the present invention includes  
7 a plurality of pressure devices that are located in the cooling tower plenum. The data signals  
8 provided by these pressure devices, along with the fan speed data from the VFD, fan pitch and  
9 the fan map, are processed by an industrial computer and used to determine the mass airflow in  
10 the fan cell.

11 The variable process control system of the present invention monitors cooling tower  
12 performance in real time and compares the performance data to design data in order to formulate  
13 a performance trend over time. It has been found that trending is the best predictor of  
14 performance and therefore can be used to modify and optimize the fan variable speed schedule,  
15 and plan and implement cooling tower service, maintenance and improvements as a function of  
16 process loading, such as hot day or cold day limitations, or selection of the appropriate fill to  
17 compensate for poor water quality. Long term trending is an improvement in true performance  
18 prediction as opposed to periodic testing which is done in prior art systems.

19 The present invention is a unique, novel, and reliable approach to determining cooling  
20 tower performance. The present invention uses fan horsepower and permanent magnet motor  
21 current draw (i.e. amperes) in conjunction with a measured plenum pressure. The measured  
22 plenum pressure equates to fan inlet pressure. The present invention uses key parameters  
23 measured by the system including measured plenum pressure in combination with the fan speed,  
24 known from the VFD (Variable Frequency Drive), and the design fan map to determine mass

1    airflow and real time cooling performance. This system of the present invention is then used to  
2    recognize poor performance conditions and alert end-users to perform an inspection and identify  
3    the required corrective action. The plenum pressure is measured by a pressure device that is  
4    located in the fan deck.

5            The design criteria of the variable process control system of the present invention are  
6    based upon the thermal design of the tower, the process demand, environmental conditions and  
7    energy optimization. On the other hand, the prior art variable speed fan gearbox systems are  
8    applied without knowledge of the tower thermal capacity and are only controlled by the basin  
9    temperature set-point.

10           A very important feature of the permanent magnet motor of the present invention is that it  
11    may be used in new installations (e.g. new tower constructions or new fan assembly) or it can be  
12    used as a “drop-in” replacement. If the permanent magnet motor is used as a “drop-in”  
13    replacement, it will easily interface with all existing fan hubs and provide the required torque and  
14    speed to rotate all existing and possible fan configurations within the existing “installed” weight  
15    and fan height requirements.

16           The characteristics of the high, constant torque of the low variable speed permanent  
17    magnet motor of the present invention provide the flexibility of optimizing fan pitch for a given  
18    process demand.

19           The variable process control system of the present invention is programmed to operate  
20    based on the aforesaid criteria as opposed to prior art systems which are typically reactive to the  
21    basin temperature. Airflow generated by the variable process control system of the present  
22    invention is a function of fan blade pitch, fan efficiency and fan speed and is optimized for  
23    thermal demand (100% cooling) and energy consumption. Thermal demand is a function of the

1 process. The variable process control system of the present invention anticipates cooling  
2 demand based upon expected seasonal conditions, historical and environmental conditions, and  
3 is designed for variable speed, autonomous operation with control and supervision.

4 Since the permanent magnet motor of the present invention delivers constant high torque  
5 throughout its variable speed range, the fan pitch is optimized for expected hot-day conditions  
6 (max cooling) and maximum efficiency based on the expected and historical weather patterns  
7 and process demand of the plant location. With the constant high-torque produced by the  
8 permanent magnet motor of the present invention, increased airflow is achieved with greater fan  
9 pitch at slower speeds thereby reducing acoustic signature or fan noise in sensitive areas.

10 The variable process control system of the present invention also provides capability for  
11 additional airflow or cooling for extremely hot days and is adaptive to changes in process  
12 demand. The variable process control system of the present invention can also provide  
13 additional cooling to compensate for loss of a cooling cell in a multi-cell tower. This mode of  
14 operation of the variable process control system is referred herein to the "Compensation Mode".  
15 In the Compensation Mode, the fan speed of the remaining cells is increased to produce the  
16 additional flow through the tower to compensate for the loss of cooling resulting from the lost  
17 cells. The variable process control system of the present invention is programmed not to  
18 increase the fan speed greater than the fan tip speed when compensating for the loss of cooling  
19 resulting from the loss cell. The compensation mode feature is designed and programmed into  
20 the variable process control system of the present invention based upon the expected loss of a  
21 cell and its location in the tower. The variable process control system of the present invention  
22 varies the speed of the fans in the remaining cells in accordance with the configuration, geometry  
23 and flow characteristic of the cooling tower and the effect each cell has on the overall cooling of

1 the cooling tower. This provides the required cooling and manages the resultant energy  
2 consumption of the cooling tower. The variable process control system of the present invention  
3 manages the variable speed among cells thereby providing required cooling while optimizing  
4 energy consumption based upon the unique configuration and geometry of each cooling tower.

5 Operational characteristics of the variable process control system of the present invention  
6 include:

- 7 1) autonomous variable speed operation based on process demand, thermal demand, cooling  
8 tower thermal design and environmental conditions;
- 9 2) adaptive cooling that provides (a) regulated thermal performance based upon an  
10 independent parameter or signal such as lower basin temperature to improve cracking of  
11 heavier crude during a refining process, (b) regulated temperature control to  
12 accommodate steam turbine back-pressure in a power plant for performance and safety  
13 and (c) regulated cooling to prevent condenser fouling;
- 14 3) fan idle in individual cells of a multi-cell tower based on thermal demand and unique  
15 cooling tower design (i.e. fan idle) if thermal demand needs have been met;
- 16 4) real-time feedback;
- 17 5) operator override for stopping or starting the fan, and controlling basin temperature set-  
18 point for part-load operation;
- 19 6) uses fan speed, motor current, motor horsepower and plenum pressure in combination  
20 with environmental conditions such as wind speed and direction, temperature and wet-  
21 bulb temperature to measure and monitor fan airflow and record all operating data,  
22 process demand trend and environmental conditions to provide historical analysis for  
23 performance, maintenance actions, process improvements and expansions;

- 1       7) vibration control which provides 100% monitoring, control and supervision of the system  
2       vibration signature with improved signature fidelity that allows system troubleshooting,  
3       proactive maintenance and safer operation (post processing);
- 4       8) vibration control that provides 100% monitoring, control and supervision for measuring  
5       and identifying system resonances in real time within the variable speed range and then  
6       locking them out of the operating range;
- 7       9) vibration control that provides 100% monitoring, control and supervision for providing  
8       post processing of vibration signatures using an industrial computer and algorithms such  
9       as Fast Fourier Transforms (FFT) to analyze system health and provide system alerts to  
10      end users such as fan imbalance as well control signals to the DAQ (data acquisition)  
11      device in the case of operating issues such as impending failure;
- 12     10) provides for safe Lock-Out, Tag-Out (LOTO) of the fan drive system by controlling the  
13      deceleration of the fan and holding the fan at stop while all forms of energy are removed  
14      from the cell including cooling water to the cell so as to prevent an updraft that could  
15      cause the fan to windmill in reverse;
- 16     11) provides for a proactive maintenance program based on actual operating data, cooling  
17      performance, trending analysis and post processing of data using a Fast Fourier  
18      Transform to identify issues such as fan imbalance, impending fan hub failure, impending  
19      fan blade failure and provide service, maintenance and repair and replacement before a  
20      failure leads to a catastrophic event and loss of life, the cooling asset and production.
- 21     12) provides a predictive maintenance program based on actual operating data, cooling  
22      performance, trending analysis and environmental condition trending in order to provide  
23      planning for cooling tower maintenance on major cooling tower subsystems such as fill

1 replacement and identify cooling improvements for budget creation and planning for  
2 upcoming outages;

3 13) monitoring capabilities that alert operators if the system is functioning properly or  
4 requires maintenance or an inspection;

5 14) operator may manually override the variable control system to turn fan on or off;

6 15) provides an operator with the ability to adjust and fine tune cooling based on process  
7 demand with maximum hot-day override;

8 16) monitors auxiliary systems, such as pumps, to prevent excessive amounts of water from  
9 being pumped into the tower distribution system which could cause collapse of the  
10 cooling tower;

11 17) continuously measures current process demand and environmental stress;

12 18) varies the fan speed in gradual steps as the variable process control system learns from  
13 past process cooling demand as a function season, time, date and environmental  
14 conditions to predict future process demand, wherein the variation of fan speed in gradual  
15 steps minimizes energy draw and system wear;

16 19) since the permanent magnet motor of the system of the present invention is not limited in  
17 reverse operation, regenerative drive options may be used to provide power to the grid  
18 when fans are windmilling in reverse;

19 20) automatic deicing; and

20 21) reverse operation wherein the permanent magnet motor has the same operational  
21 characteristics as in forward operation.

1           The permanent magnet motor and variable process control system of the present  
2 invention are applicable to wet-cooling tower systems, air-cooled heat exchangers (ACHE),  
3 HVAC, mechanical towers and chillers, regardless of mounting configuration.

4           In one aspect, the present invention is directed to a wet-cooling tower system comprising  
5 a direct drive fan system and an integrated variable process control system. The wet-cooling  
6 tower system comprises a wet-cooling tower that comprises a tower structure that has fill  
7 material located within the tower structure, a fan deck located above the fill material, and a  
8 collection basin located beneath the fill material for collecting cooled liquid. A fan stack is  
9 positioned upon the fan deck and a fan is located within the fan stack. The fan comprises a hub  
10 to which are connected a plurality of fan blades. The direct drive fan system comprises a high-  
11 torque, low variable speed permanent magnet motor which has a rotatable shaft connected to the  
12 hub. In one embodiment, the permanent magnet motor has a rotational speed between 0 RPM  
13 and about 250 RPM. In another embodiment, the permanent magnet motor is configured to have  
14 rotational speeds that exceed 500 RPM. The permanent magnet motor is sealed and comprises a  
15 rotor, a stator and a casing. The rotor and stator are located within the casing. The variable  
16 process control system comprises a variable frequency drive device is in electrical signal  
17 communication with the permanent magnet motor to control the rotational speed of the  
18 permanent magnet motor. The variable frequency drive device comprises a variable frequency  
19 controller that has an input for receiving AC power and an output for providing electrical signals  
20 that control the operational speed of the high-torque, permanent magnet motor, and a signal  
21 interface in electronic data signal communication with the variable frequency controller to  
22 provide control signals to the variable frequency controller so as to control the motor RPM and  
23 to provide output motor status signals that represent the motor speed, motor current draw, motor

1 voltage, motor torque and the total motor power consumption. The variable process control  
2 system further comprises a data acquisition device in electrical signal communication with the  
3 signal interface of the variable frequency drive device for providing control signals to the  
4 variable frequency drive device and for receiving the motor status signals. The wet-cooling  
5 tower system further comprises a pair of vibration sensors that are in electrical signal  
6 communication with the data collection device. Each vibration sensor is located within the  
7 motor casing where it is protected from the environment and positioned on a corresponding motor  
8 bearing structure. As a result of the structure and design of the permanent magnet motor and the  
9 direct connection of the motor shaft to the fan hub, the resultant bearing system is stout (stiff and  
10 damped) and therefore results in a very smooth system with low vibration.

11 In comparison to the prior art, the vibration signature of the permanent magnet motor has  
12 a low amplitude with clear signature fidelity which allows for proactive service and maintenance  
13 and an improvement in safety and production. Trending of past cooling tower operation and post  
14 processing, vibration signal analysis (FFT) determines whether other vibration signatures are  
15 indicating such issues as a fan blade imbalance, fan blade pitch adjustment, lubrication issues,  
16 bearing issues and impending fan hub, fan blade and motor bearing failure, which are major  
17 safety issues. The location of the vibration sensors on the motor bearings also allows for  
18 programming of lower amplitude shut-off parameters.

19 As described in the foregoing description, the variable process control system of the  
20 present invention comprises a plurality of vibration sensors that may include accelerometers,  
21 velocity and displacement transducers or similar devices to monitor, supervise and control the  
22 vibration characteristics of the direct drive fan system and the direct-drive pump system that  
23 pumps water to and from the cooling tower.

1           The present invention has significantly less "frequency noise" because the present  
2 invention eliminates ladder frames, torque tubes, shafts, couplings, gearboxes and gearmesh that  
3 are commonly used in prior art systems. In accordance with the invention, vibration sensors are  
4 located at the bearings of the permanent magnet motor. Each vibration sensor outputs signals  
5 representing vibrations on the motor bearings. Thus, vibrations are read directly at the bearings  
6 that are directly coupled to the fan as opposed to the prior art technique of measuring the  
7 vibrations at the ladder frame. As a result of this important feature of the invention, the present  
8 invention can identify, analyze and correct for changes in the performance of the fan, thereby  
9 providing a longer running system that is relatively safer.

10           The variable process control system of the present invention further comprises a plurality  
11 of temperature sensors in electrical signal communication with the data collection device.  
12 Temperature sensors measure the temperature of the exterior of the motor casing or housing.  
13 Temperature sensors located within the casing of the motor to measure the temperature within  
14 the casing. Temperature sensors are located in the basin to measure temperature of liquid (e.g.  
15 water) within the basin. Temperature sensors also measure the environmental temperature (e.g.  
16 ambient temperature). Another temperature sensor measures the temperature of the air in the fan  
17 stack before the fan. The variable process control system of the present invention further  
18 includes at least one pressure sensor located in the fan deck that measures the pressure in the fan  
19 plenum, which equates to the pressure at the fan inlet. The variable process control system  
20 further comprises a computer in data signal communication with the data collection device. The  
21 computer comprises a memory and a processor to process the signals outputted by the vibration  
22 sensors, temperature sensors, pump flow and the motor status signals. The computer outputs

1 control signals to the data collection device for routing to the variable frequency drive device in  
2 order to control the speed of the motor in response to the processing of the sensor signals.

3 The variable process control system of the present invention comprises a plurality of  
4 vibration sensors which may include accelerometers, velocity and displacement transducers or  
5 similar devices to monitor, supervise and control vibration characteristics of the direct-drive fan  
6 and variable speed pump system. The aforesaid vibration sensors detect various regions of the  
7 motor and fan frequency band that are to be monitored and analyzed. The variable process  
8 control system also includes a leak detector probe for detecting leakage of gasses from heat  
9 exchanges and other equipment.

10 Some key features of the system of the present invention are:

- 11 1) reverse, de-ice, flying-start and soft-stop modes of operation with infinite control of fan speed  
12 in both reverse and forward directions;
- 13 2) variable process control, refining and power generation;
- 14 3) capability of part-load operation;
- 15 4) maintaining vacuum backpressure for a steam turbine and crude cracking;
- 16 5) prevents damage and fouling of heat exchangers, condensers and auxiliary equipment;
- 17 6) simplified installation using only four bolts and area classified quick disconnect  
18 communication cable and factory terminated power cable allow for "plug and play" installation;
- 19 7) line-replaceable units such as hazardous gas monitors, sensors, meter(s) or probes are  
20 integrated into the motor casing (or housing) to detect and monitor fugitive gas emissions in the  
21 fan air-steam accordance with the U.S. EPA (Environmental Protection Agency) regulations;
- 22 **8)** variable speed operation with low, variable speed capability;
- 23 9) cells in multi-cell tower can be operated independently to meet cooling and optimize energy;

- 1 10) 100% monitoring, autonomous control and supervision of the system;
- 2 11) automated and autonomous operation;
- 3 12) relatively low vibrations and high vibration fidelity due to system architecture and structure;
- 4 13) changes in vibration signals are detected and analyzed using trending data and post
- 5 processing;
- 6 14) vibration sensors are integrated into the permanent magnet motor and thus protected from
- 7 the surrounding harsh, humid environment;
- 8 15) uses a variable frequency drive (VFD) device that provides signals representing motor
- 9 torque and speed;
- 10 16) uses DAQ (data acquisition) device that collects signals outputted by the VFD and other
- 11 data signals;
- 12 17) uses a processor that processes signals collected by the DAQ device, generates control
- 13 signals, routes control signals back to VFD and implements algorithms (e.g. FFT) to process
- 14 vibration signals;
- 15 18) uses mechanical fan-lock that is applied directly to the shaft of the permanent magnet motor
- 16 to prevent rotation of the fan when power is removed for maintenance and hurricane service;
- 17 19) uses a Lock-Out-Tag-Out (LOTO) procedure wherein the fan is decelerated to 0.0 RPM
- 18 under power and control of the permanent magnet motor and VFD and the motor holds the fan at
- 19 0.0 RPM while a mechanical lock device is applied to the motor shaft to prevent rotation of the
- 20 fan, and then all forms of energy are removed per OSHA Requirements for Service, Maintenance
- 21 and Hurricane Duty (e.g. hurricane, tornado, shut-down, etc.);
- 22 20) produces regenerative power when the fan is windmilling;

21) the motor and VFD provide infinite control of the fan acceleration and can hold the fan at 0.0 RPM, and also provide fan deceleration and fan rotational direction;

22) allows fan to windmill in reverse due to cooling water updraft;

23) the permanent magnet motor can operate in all systems, e.g. wet-cooling towers, ACHEs, HVAC systems, chillers, blowers, etc.;

24) the permanent magnet motors directly drive the fan and pumps; and

25) the permanent magnet motor can be connected to a fan hub of a fan, or directly connected to a one-piece fan.

#### BRIEF DESCRIPTION OF THE DRAWINGS:

Although the scope of the present invention is much broader than any particular embodiment, a detailed description of the preferred embodiments follows together with illustrative figures, wherein like reference numerals refer to like components, and wherein:

FIG. 1 is a side view, in elevation, of a wet-cooling tower that uses a prior art fan drive system;

FIG. 2 is a block diagram of a variable process control system in accordance with one embodiment of the present invention, wherein the variable process control system controls the operation of a cooling tower;

FIG. 3 is a diagram of the feedback loops of the system of FIG. 2;

FIG. 4 is a block diagram illustrating the interconnection of the permanent magnet motor, data acquisition device and variable frequency drive device, all of which being shown in FIG. 2;

1 FIG. 5A is a diagram showing the internal configuration of a permanent magnet motor  
2 shown in FIG. 4, the diagram specifically showing the location of the bearings of the permanent  
3 magnet motor;

4 FIG. 5B is a diagram showing a portion of the permanent magnet motor of FIG. 5A, the  
5 diagram showing the location of the accelerometers within the motor housing;

6 FIG. 6 is a plot of motor speed versus horsepower for a high torque, low speed permanent  
7 magnet motor used in direct drive fan system of the present invention;

8 FIG. 7 is a graph illustrating a comparison in performance between the fan drive system  
9 of the present invention and a prior art gearbox-type fan drive system that uses a variable speed  
10 induction motor;

11 FIG. 8 is a side view, in elevation and partially in cross-section, of a wet-cooling tower  
12 employing the direct drive fan system of the present invention;

13 FIG. 9 is a graph showing a fan speed curve that is similar to a sine wave and represents  
14 the increase and decrease in the fan speed over a twenty-four hour period in accordance with the  
15 present invention, the bottom portion of the graph showing a fan speed curve representing  
16 changes in fan speed for a prior art variable speed fan drive system;

17 FIG. 10 is a side view, in elevation and partially in cross-section, of an ACHE that  
18 utilizes the direct drive fan system of the present invention;

19 FIG. 11A is a vibration bearing report, in graph form, resulting from a test of the  
20 permanent magnet motor and vibration sensing and analysis components of the present  
21 invention;

22 FIG. 11B is the same vibration bearing report of FIG. 11A, the vibration bearing report  
23 showing a trip setting of 0.024G of a prior art gearbox;

1 FIG. 11C is a vibration severity graph showing the level of vibrations generated by the  
2 permanent magnet motor of the present invention;

3 FIG. 12A is a side view, partially in cross-section, of the direct drive fan system of the  
4 present invention installed in a cooling tower;

5 FIG. 12B is a bottom view of the permanent magnet motor depicted in FIG. 12A, the  
6 view showing the mounting holes in the permanent magnet motor;

7 FIG. 13 shows an enlargement of a portion of the view shown in FIG. 12A;

8 FIG. 14 is a side view, in elevation, showing the interconnection of the permanent  
9 magnet motor shown in FIGS. 12A and 13 with a fan hub;

10 FIG. 15A is a diagram of a multi-cell cooling system that utilizes the fan direct-drive  
11 system of the present invention;

12 FIG. 15B is a top view of a multi-cell cooling system;

13 FIG. 15C is a block diagram of a motor-control center (MCC) that is shown in FIG. 15A;

14 FIG. 16A is a flowchart of a lock-out-tag-out (LOTO) procedure used to stop the fan in  
15 order to conduct maintenance procedures;

16 FIG. 16B is a flow chart a Flying-Start mode of operation that can be implemented by the  
17 permanent magnet motor and variable process control system of the present invention;

18 FIG. 16C is a graph of speed versus time for the Flying-Start mode of operation’

19 FIG. 17 is a graph of an example of condenser performance as a function of water flow  
20 rate (i.e. variable speed pumps and constant basin temperature);

21 FIG. 18 is a partial view of the permanent magnet motor shown in FIGS. 4 and 5A, the  
22 permanent magnet motor having mounted thereto a line-replaceable vibration sensor unit in  
23 accordance with another embodiment of the invention;

1 FIG. 19 is a partial view of the permanent magnet motor shown in FIGS. 4 and 5A, the  
2 permanent magnet motor having mounted thereto a line replaceable vibration sensor unit in  
3 accordance with a further embodiment of the invention;

4 FIG. 20 is partial view of the permanent magnet motor shown in FIGS. 4 and 5A having  
5 mounted thereto a line replaceable vibration sensor unit in accordance with a further embodiment  
6 of the invention;

7 FIG. 21A is a top, diagrammatical view showing a fan-lock mechanism in accordance  
8 with one embodiment of the invention, the fan lock mechanism being used on the rotatable shaft  
9 of the motor shown in FIGS. 4 and 5A, the view showing the fan lock mechanism engaged with  
10 the rotatable motor shaft in order to prevent rotation thereof;

11 FIG. 21B is a top, diagrammatical view showing the fan lock mechanism of FIG. 21A,  
12 the view showing the fan lock mechanism disengaged from the rotatable motor shaft in order to  
13 allow rotation thereof;

14 FIG. 21C is a side elevational view of the motor shown in FIGS. 4 and 5A, the view  
15 showing the interior of the motor and the fan-lock mechanism of FIGS. 21A and 21B mounted  
16 on the motor about the upper portion of the motor shaft, the view also showing an additional fan-  
17 lock mechanism of FIGS. 21A and 21B mounted to the motor about the lower portion of the  
18 motor shaft;

19 FIG. 22 is a side elevational view of the upper portion of the permanent magnet motor of  
20 FIGS. 4 and 5A, the permanent magnet motor having mounted thereto a caliper-type lock  
21 mechanism for engaging the upper portion of the shaft of the motor;

1 FIG. 23 is a side elevational view of the lower portion of the permanent magnet motor of  
2 FIGS. 4 and 5A, the permanent magnet motor having mounted thereto a caliper-type lock  
3 mechanism for engaging the lower portion of the shaft of the motor;

4 FIG. 24 is a side elevational view of the lower portion of the permanent magnet motor of  
5 FIGS. 4 and 5A, the permanent magnet motor having mounted thereto a band-lock mechanism  
6 for engaging the lower portion of the shaft of the motor;

7 FIG. 25 is a side elevational view of the upper portion of the permanent magnet motor of  
8 FIGS. 4 and 5A, the permanent magnet motor having mounted thereto a band-lock mechanism  
9 for engaging the upper portion of the shaft of the motor; and

10 FIG. 26 is a block diagram of the permanent magnet motor and variable process control  
11 system of the present invention used with a wet-cooling tower that is part of an industrial  
12 process.

13  
14 **BEST MODE FOR CARRYING OUT THE INVENTION:**

15 As used herein, the terms “process”, “plant process” or “industrial process” shall mean an  
16 industrial process such as a petroleum refinery, power plant, turbine, crude cracker, fertilizer  
17 plant, glass manufacturing plant, chemical plant, etc.

18 As used herein, the terms “process liquid” means the liquids, such as water or other  
19 coolant, that are used for cooling purposes in the process.

20 As used herein, the terms “process demand” or “process cooling demand” mean the  
21 amount of cooling liquids used by the process.

22 As used herein, the term “part-plant load” means process demand that is less than  
23 maximum process demand.

1           As used herein, the terms “basin temperature” or “collection basin temperature” mean the  
2 temperature of the water or other liquid that is in the collection basin of a wet-cooling tower;

3           As used herein, the term “Environmental Stress” shall mean, collectively, ambient  
4 temperature, relative humidity, dry-bulb temperature, wet-bulb temperature, wind speed, wind  
5 direction, solar gain and barometric pressure.

6           As used herein, the term “Cooling Tower Thermal Capacity” is the heat-rejection  
7 capability of the cooling tower. It is the amount of cold water that can be returned to the process  
8 for given temperature and flow rate at maximum hot-day and wet-bulb conditions. Cooling  
9 Tower Thermal Capacity will be reduced as the cooling tower components degrade, such as the  
10 fill material becoming clogged due to poor water quality. For a given  $\Delta T$  (difference between  
11 temperatures of hot and cold water) and the flow rate, the cooling tower fans will have to operate  
12 at higher speed and for longer amounts of time given the environmental stress in a degraded  
13 tower (that is being monitored and trended).

14           As used herein, the term “process thermal demand” or “thermal demand” means the heat  
15 that has to be removed from the process liquid (e.g. water) by the cooling tower. In its simplest  
16 terms, thermal demand of the process is expressed as the water temperature from the process (hot  
17 water) and water temperature returned to the process (cold water) for a give flow rate;

18           As used herein, the terms “fan map” and “fan performance curve” represent the data  
19 provided for fan blades with a given solidity. Specifically, the data represents the airflow of air  
20 moved by a specific fan diameter, model and solidity for a given fan speed and pitch at a given  
21 temperature and wet-bulb (air density).

22           As used herein, the terms “trending” or “trend” means the collection of cooling tower  
23 parameters, events and calculated values with respect to time that define operating characteristics

1 such as cooling performance as a function of environmental stress and Process Thermal Demand.

2 Referring to FIGS. 2 and 4, there is shown the variable process control system of the  
3 present invention for managing the operation of fans and pumps in cooling apparatus 10.

4 Cooling apparatus 10 can be configured as a wet-cooling tower, induced draft air-cooled heat  
5 exchanger (ACHE), chiller or a HVAC system which are commonly used to cool liquids used in  
6 an industrial process, e.g. petroleum refinery, chemical plant, etc. One example of a wet-cooling  
7 tower is described in international application no. PCT/US2008/077338, published under  
8 international publication no. WO 2009/048736. The disclosure of international publication no.  
9 WO 2009/048736 is hereby incorporated by reference. The same wet-cooling tower is described  
10 in U.S. Patent No. 8,111,028, the disclosure of which patent is hereby incorporated by reference.

11 One example of an air-cooled heat exchanger (ACHE) is described in international application  
12 no. PCT/US2009/037242, published under international publication no. WO 2009/120522. The  
13 disclosure of international publication no. WO 2009/120522 is hereby incorporated by reference.

14 The same type of air-cooled heat exchanger (ACHE) is disclosed in U.S. Patent No. 8,188,698,  
15 the disclosure of which patent is hereby incorporated by reference. For purposes of describing  
16 the system of the present invention, cooling apparatus 10 is described as being a wet-cooling

17 tower. An ACHE system is described later in the ensuing description. Cooling apparatus 10  
18 comprises fan 12 and fan stack 14. As is known in the field, cooling towers may utilize fill  
19 material which is described in the aforementioned international publication no. WO

20 2009/048736. Fan 12 comprises hub 16 and a plurality of fan blades 18 that are connected to  
21 and extend from hub 16. The system of the present invention comprises permanent magnet  
22 motor 20. Motor 20 comprises motor housing or casing 21A (see FIG. 4). Casing comprises top  
23 cover 21A and bottom cover 21B. Motor further comprises rotatable shaft 24. Motor shaft 24 is

1 directly connected to fan hub 16. The connection of motor shaft 24 to fan hub 16 is described in  
2 detail in the ensuing description.

3 Referring to FIG. 2, power cable 105 has one end that is terminated at motor 20.  
4 Specifically, power cable 105 is factory sealed to Class One, Division Two, Groups B, C and D  
5 specifications and extends through the motor housing 21 and is terminated within the interior of  
6 motor housing 21 during the assembly of motor 20. Therefore, when installing motor 20 in a  
7 cooling apparatus, it is not necessary for technicians or other personnel to electrically connect  
8 power cable 105 to motor 20. The other end of power cable 105 is electrically connected to  
9 motor disconnect junction box 106. Power cable 105 is configured as an area classified, VFD  
10 rated and shielded power cable. Motor disconnect junction box 106 includes a manual  
11 emergency shut-off switch. Motor disconnect junction box 106 is primarily for electrical  
12 isolation. Power cable 105 comprises three wires that are electrically connected to the shut-off  
13 switch in motor-disconnect junction box 106. Power cable 107 is connected between the shut-  
14 off switch in motor-disconnect junction box 106 and VFD device 22. Power cable 107 is  
15 configured as an area classified, VFD rated and shielded power cable. The electrical power  
16 signals generated by VFD device 22 are carried by power cable 107 which delivers these  
17 electrical power signals to junction box 106. Motor power cable 105 is connected to power cable  
18 107 at junction box 106. Thus, motor power cable 105 then provides the electrical power signals  
19 to motor 20.

20 Referring to FIGS. 2 and 4, quick-disconnect adapter 108 is connected to motor housing  
21 21. In one embodiment, quick-disconnect adapter 108 is a Turck Multifast Right Angle Stainless  
22 Connector with Lokfast Guard, manufactured by Turck Inc. of Minneapolis, MN. The sensors  
23 internal to motor housing 21 are wired to quick-disconnect adapter 108. Cable 110 is connected

1 to quick-disconnect adapter 108 and to communication data junction box 111. Communication  
2 data junction box 111 is located on the fan deck. The electronic components in communication  
3 data junction box 111 are powered by a voltage source (not shown). Cable 110 is configured as  
4 an area-classified multiple connector shielded flexible control cable. Cable 112 is electrically  
5 connected between communication data junction box 111 and data acquisition device 200  
6 (referred to herein as "DAQ device 200"). In one embodiment, cable 112 is configured as an  
7 Ethernet cable. As described in the foregoing description, VFD device 22 is in data  
8 communication with Data Acquisition Device (DAQ) device 200. VFD device 22 and DAQ  
9 device 200 are mounted within Motor Center Enclosure 26 (see FIGS. 2 and 4). A Motor Control  
10 Enclosure typically is used for a single motor or fan cell. The MCE 26 is typically located on the  
11 fan deck in close proximity to the motor. The MCE 26 houses VFD device 22, DAQ device 200,  
12 industrial computer 300 and the power electronics. In one embodiment, MCE 26 is a NEMA 4X  
13 Rated Cabinet. VFD device 22 and DAQ device 200 are discussed in detail in the ensuing  
14 description.

15 Referring to FIGS. 4 and 5A, the fan drive system of the present invention comprises  
16 high torque, low variable speed, permanent magnet motor 20. The fan drive system of the  
17 present invention is a direct drive system. Specifically, motor 20 is directly connected to the fan  
18 hub 16. Thus, permanent magnet motor 20 directly drives fan 12 without the loss characteristics  
19 and mechanical problems typical of prior art gearbox drive systems. Permanent magnet motor  
20 20 has a high flux density. Permanent magnet motor 20 is controlled only by electrical signals  
21 provided by VFD device 22. Thus, there are no drive shaft, couplings, gear boxes or related  
22 components which are found in the prior art gearbox-type fan drive systems. Permanent magnet  
23 motor 20 includes stator 32 and rotor 34. Permanent magnet motor 20 further comprises

spherical roller thrust bearing 40 which is located at the lower end of motor shaft 24. Spherical roller thrust bearing 40 absorbs the thrust load caused by the weight of fan 12 and fan thrust forces due to airflow. Permanent magnet motor 20 further comprises cylindrical roller bearing 42 which is located immediately above spherical roller thrust bearing 40. Cylindrical roller bearing 42 opposes radial loads at the thrust end of shaft 24. Radial loads are caused by fan assembly unbalance and yaw moments due to unsteady wind loads. Motor 20 further comprises tapered roller output bearing 44. Tapered roller output bearing 44 is configured to have a high radial load capability coupled with thrust capability to oppose the relatively low reverse thrust loads that occur during de-icing (reverse rotation) or high wind gust. Although three bearings are described, motor 20 is actually a two-bearing system. The “two bearings” are cylindrical roller bearing 42 and tapered roller output bearing 44 because these two bearings are radial bearings that locate and support the shaft relative to motor casing housing 21 and the mounting structure. Spherical roller thrust bearing 40 is a thrust bearing, which is specifically designed so that it does not provide any radial locating forces, but only axial location. Such a unique motor design is less complex than current art motors but yet provides relatively high reliability as well as reverse operation and improved cost-effective motor operation. The design of motor 20 has a reduced Life-Cycle Cost (LCC) as compared to the prior art gearbox fan drive systems described in the foregoing description. Bearing housing 50 houses bearing 44. Bearing housing 52 houses bearings 40 and 42. Bearing housings 50 and 52 are isolated from the interior of motor housing 21 by nitrile rubber, double lip-style radial seals. The combination of the low surface speed of the motor shaft and synthetic lubricant results in accurate predicted seal reliability and life. Motor 20 includes seal housing 53 which houses an Inpro™ seal bearing isolator. The motor shaft seal comprises an Inpro™ seal bearing isolator in tandem with a double radial lip seal. The

1 Inpro™ seal bearing isolator is mounted immediately outboard of the double radial lip seal. The  
2 function of the Inpro™ seal is to seal the area where shaft 24 penetrates top cover 21A of motor  
3 casing 21. The double radial lip seal excludes moisture and solid contaminants from the seal lip  
4 contact. In one embodiment, permanent magnet motor 20 has the following operational and  
5 performance characteristics:

6                   Speed Range: 0-250 RPM

7                   Maximum Power: 133 hp/100 KW

8                   Number of Poles: 16

9                   Motor Service Factor: 1:1

10                  Rated Current: 62 A (rms)

11                  Peak Current: 95 A

12                  Rated Voltage: 600 V

13                  Drive Inputs: 460 V, 3 phase, 60 Hz, 95A (rms max. continuous)

14                  Area Classification: Class 1, Division 2, Groups B, C, D

15                  Insulation Class H

16  
17 Permanent magnet motor 20 can be configured to have different operational characteristics.

18 However, it is to be understood that in all embodiments, motor 20 is designed to the

19 requirements of Class 1, Div. 2, Groups B, C and D. FIG. 6 shows a plot of speed vs.

20 horsepower for motor 20. However, it is to be understood that the aforesaid operational and

21 performance characteristics just pertain to one embodiment of permanent magnet motor 20 and

22 that motor 20 may be modified to provide other operational and performance characteristics that

23 are suited to a particular application. Referring to FIG. 7, there is shown a graph that shows

1 “Efficiency %” versus “Motor Speed (RPM)” for motor 20 and a prior art fan drive system using  
2 a variable speed, induction motor. Curve 100 pertains to motor 20 and curve 102 pertains to the  
3 prior art fan drive system. As can be seen in the graph, the efficiency of motor 20 is relatively  
4 higher than the prior art fan drive system for motor speeds between about 60 RPM and about 200  
5 RPM.

6 Motor 20 has relatively low maintenance with a five year lube interval. The design and  
7 architecture of motor 20 substantially reduces the man-hours associated with service and  
8 maintenance that would normally be required with a prior art, induction motor fan drive system.  
9 The bearing L10 life is calculated to be 875,000 hours. In some instances, motor 20 can  
10 eliminate up to 1000 man-hours of annual service and maintenance in a cooling tower.

11 In an alternate embodiment, motor 20 is configured with auto-lube grease options as well  
12 as grease fittings depending on the user. A typical prior art gearbox system has many moving  
13 parts, typically five rotating shafts, eight bearings, three shaft seals, four gears and two meshes.  
14 The open lubrication design of typical prior art gearbox systems is not suited for cooling tower  
15 service since the open lubrication system becomes contaminated from the chemicals, humidity  
16 and biological contamination in the cooling tower. The design and structure of motor 20  
17 eliminates these problems of prior art gearbox systems. Motor 20 eliminates shaft, coupling and  
18 related drive-train vibrations, torsional resonance and other limitations typically found in prior  
19 art drive systems and also eliminates the need for sprag-type clutches typically used to prevent  
20 opposite rotation of the fans. Motor 20 eliminates widely varying fan-motor power consumption  
21 problems associated with prior art gearboxes due to frictional losses caused by mechanical  
22 condition, wear and tear, and impact of weather on oil viscosity and other mechanical  
23 components. The high, constant torque of motor 20 produces the required fan torque to

1 accelerate the fan through the speed range.

2 Referring to FIGS. 2, 4 and 5A, shaft 24 of permanent magnet motor 20 rotates when the  
3 appropriate electrical signals are applied to permanent magnet motor 20. Rotation of shaft 24  
4 causes rotation of fan 12. VFD device 22 comprises a plurality of independently controlled  
5 programmable variable frequency drive (VFD) devices 23A, 23B, 23C, 23D and 23E (see FIG.  
6 26). VFD device 23A controls motor 20. The remaining VFD devices control the permanent  
7 magnet motors in the variable speed pumps (see FIG. 26). DAQ device 200 provides control  
8 signals to each of the VFD devices 23A, 23B, 23C, 23D and 23E. These features are discussed  
9 later in the ensuing description. VFD device 23A provides the appropriate electrical power  
10 signals to motor 20 via cables 107 and 105. There is two-way data communication between VFD  
11 device 22 and DAQ device 200. DAQ device 200 comprises a controller module which  
12 comprises a computer and/or microprocessor having computer processing capabilities, electronic  
13 circuitry to receive and issue electronic signals and a built-in keyboard or keypad to allow an  
14 operator to input commands. In one embodiment, DAQ device 200 comprises a commercially  
15 available CSE Semaphore TBox RTU System that comprises a data acquisition system,  
16 computer processors, communication modules, power supplies and remote wireless modules.  
17 The CSE Semaphore TBox RTU System is manufactured by CSE Semaphore, Inc. of Lake  
18 Mary, FL. In a preferred embodiment, the CSE Semaphore TBox RTU System is programmed  
19 with a commercially available computer software packages known as Dream Report™ and  
20 TView™ which analyze collected data. In an alternate embodiment, the CSE Semaphore TBox  
21 RTU System is programmed with a commercially available software known as TwinSoft™. In  
22 DAQ device 200 is described in detail in the ensuing description. VFD device 22 comprises a  
23 variable frequency controller 120 and signal interface 122. VFD device 22 controls the speed

1 and direction (i.e. clockwise or counterclockwise) of permanent magnet motor 20. AC voltage  
2 signals are inputted into variable frequency controller 120 via input 124. Variable frequency  
3 controller 120 outputs the power signals that are inputted into motor 20 via power cables 107 and  
4 105. Referring to FIG. 4, signal interface 122 is in electrical signal communication with DAQ  
5 device 200 via data signal bus 202 and receives signals to start, reverse, accelerate, decelerate,  
6 coast, stop and hold motor 20 or to increase or decrease the RPM of motor 20. In a preferred  
7 embodiment, signal interface 122 includes a microprocessor. Signal interface 122 outputs motor  
8 status signals over data bus 202 for input into DAQ device 200. These motor status signals  
9 represent the motor speed (RPM), motor current (ampere) draw, motor voltage, motor power  
10 dissipation, motor power factor, and motor torque.

11 VFD device 23A measures motor current, motor voltage and the motor power factor  
12 which are used to calculate energy consumption. VFD device 23A also measures motor speed,  
13 motor power and motor torque. VFD device 23A also measures Run Time/Hour Meter in order  
14 to provide a time stamp and time-duration value. The time stamp and time-duration are used by  
15 industrial computer 300 for failure and life analysis, FFT processing, trending, and predicting  
16 service maintenance. Industrial computer 300 is discussed in detail in the ensuing description.

17 Referring to FIGS. 4 and 26, VFD devices 23B, 23C, 23D and 23E outputs electrical  
18 power signals 1724, 1732, 1740 and 1754, respectively, for controlling the variable speed pumps  
19 1722, 1730, 1738 and 1752, respectively, that pump liquid (e.g. water) to and from the cooling  
20 tower. This aspect of the present invention is discussed in detail in the ensuing description.

21 In one embodiment, each of the VFD devices is configured as an ABB-ACS800 VFD  
22 manufactured by ABB, Inc.

23 Referring to FIG. 8, there is shown a partial view of a cooling tower 10 that utilizes the

1 direct drive fan system of the present invention. In this embodiment, cooling tower 10 comprises  
2 a wet-cooling tower. The wet-cooling tower comprises fan 12, fan stack 14, fan hub 16, and fan  
3 blades 18, all of which were discussed in the foregoing description. Fan stack 14 is supported by  
4 fan deck 250. Fan stack 14 can be configured to have a parabolic shape or a cylindrical (straight)  
5 shape as is well known in the field. Motor 20 is supported by a metal frame or ladder frame or  
6 torque tube that spans across a central opening (not shown) in fan deck 250. Motor shaft 24 is  
7 configured as a keyed shaft and is directly connected to fan hub 16 (see FIG. 14). Power cables  
8 105 and 107, motor-disconnect junction box 106 and quick-disconnect connector 108 were  
9 previously discussed in the foregoing description. Power cable 107 is connected between  
10 motor-disconnect junction box 106 and variable frequency controller 120 of VFD device 22 (see  
11 FIGS. 2 and 4) which is located inside MCE 26. Referring to FIGS. 2, 4 and 8, cable 110 is  
12 electrically connected between quick-disconnect adapter 108 and communication data junction  
13 box 111. These signals are fed to the DAQ device 200 located in MCE 26 via cable 112 as  
14 described in the foregoing description. Industrial computer 300 is also located within MCE 26.

15 Referring to FIG. 10, there is shown an air-cooled heat exchanger (ACHE) that utilizes  
16 the direct drive fan system of the present invention. This particular ACHE is an induced-draft  
17 ACHE. The remaining portion of the ACHE is not shown since the structure of an ACHE is  
18 known in the art. The ACHE comprises tube bundle 800, vertical support columns 801A and  
19 801B, parabolic fan stack 802, horizontal support structure 804, support members 805 and fan  
20 assembly 12. Fan assembly 12 comprises fan hub 16 and fan blades 18 that are attached to fan  
21 hub 16. Vertical shaft 806 is connected to fan hub 16 and coupled to motor shaft 24 with  
22 coupling 808. Motor 20 is connected to and supported by horizontal member 804. Additional  
23 structural supports 810A and 810B add further stability to motor 20. As described in the

1 foregoing description, one end of power cable 105 is terminated at motor 20 and the other end of  
2 power cable 105 is electrically connected to the motor disconnect junction box 106. Power cable  
3 107 is connected between motor disconnect junction box 106 and VFD device 22. As described  
4 in the foregoing description, cable 110 is electrically connected between quick-disconnect  
5 adapter 108 and communication data junction box 111, and cable 112 is electrically connected  
6 between communication data junction box 111 and DAQ device 200. VFD device 22 and DAQ  
7 device 200 are mounted within a Motor Control Enclosure (MCE) which is not shown in FIG. 10  
8 but which was described in the foregoing description.

9 Referring to FIG. 2, the system of the present invention further comprises industrial  
10 computer 300. Industrial computer 300 is always co-located with DAQ device 200. Industrial  
11 computer 300 is in data communication with data bus 302. Data bus 302 is in data  
12 communication with DAQ device 200. Industrial computer 300 is responsible for post-  
13 processing of performance data of the cooling tower and the system of the present invention.  
14 Included in this post-processing function are data logging and data reduction. Industrial  
15 computer 300 is programmed with software programs, an FFT algorithm and other algorithms  
16 for processing system performance data, environmental data and historical data to generate  
17 performance data reports, trend data and generate historical reports based on performance data it  
18 receives from DAQ device 200. Industrial computer 300 also stores data inputted by the  
19 operators through the plant DCS 315. Such stored data includes fan maps, fan pitch, Cooling  
20 Tower Design Curves, and Thermal Gradient analysis data. The wet-bulb temperature data is  
21 continually calculated from relative humidity and ambient temperature and is inputted into  
22 industrial computer 300. User input 304 (e.g. keyboard) 304 and display 306 (e.g. display  
23 screen) are in data signal communication with industrial computer 300. An operator uses user

1 input 304 to input commands into industrial computer 300 to generate specific types of processed  
2 data. Industrial computer 300 displays on display 306 real-time data relating to the operation of  
3 the cooling tower and the system of the present invention, including motor 20. Industrial  
4 computer 300 is also used to program new or revised data into DAQ device 200 in response to  
5 changing conditions such as variable process demand, motor status, fan condition, including fan  
6 pitch and balance, and sensor output signals. The sensor output signals are described in the  
7 ensuing description. In a preferred embodiment, industrial computer 300 is in data signal  
8 communication with host server 310. Host service 310 is in data signal communication with one  
9 or more remote computers 312 that are located at remote locations in order to provide off-site  
10 monitoring and analysis. Industrial computer 300 is also in data signal communication with the  
11 plant Distributed Control System (DCS) 315, shown in phantom in FIGS. 2 and 3. Users or  
12 operators can input data into DCS 315 including revised temperature set-points, or revised pump  
13 flow rates or even change the plant load setting from full plant load to part-plant load. This  
14 revised information is communicated to industrial computer 300 which then routes the  
15 information to DAQ device 200. DAQ device 200 and industrial computer 300 provide real-time  
16 cooling performance monitoring, real-time condition fault monitoring and autonomous ~~operator~~  
17 control of fan speed.

18 In a preferred embodiment, industrial computer 300 receives continuous weather data  
19 from the national weather surface or NOAA. Industrial computer 300 can receive this data  
20 directly via an Internet connection or it can receive the data via host server 310. Industrial  
21 computer 300 converts such weather data to a data form that can be processed by DAQ device  
22 200. In a preferred embodiment, as shown in FIG. 2, the variable process control system of the  
23 present invention further comprises on-site weather station 316 which is in data signal

1 communication with the Internet and DAQ device 200. On-site weather station 316 comprises  
2 components and systems to measure parameters such as wind speed and direction, relative  
3 humidity, ambient temperature, barometric pressure and wet-bulb temperature. These measured  
4 parameters are used by industrial computer 300 to determine Cooling Tower Thermal Capacity  
5 and also to determine the degree of icing on the tower. These measure parameters are also used  
6 for analysis of the operation of the cooling tower. On-site weather station 316 also monitor's  
7 weather forecasts and issues alerts such as high winds, freezing rain, etc.

8 In one embodiment, the VFD device 22, DAQ device 200, industrial computer 300 and  
9 power electronics are located in MCE 26. The Distributed Control System (DCS) 315 is  
10 integrated with industrial computer 300 at MCE 26. Operators would be able to log onto  
11 industrial computer 300 for trending information and alerts. DAQ device 200 automatically  
12 generates and issues alerts via email messages or SMS text messages to multiple recipients,  
13 including the Distributed Control System (DCS), with attached documents and reports with live  
14 and historical information as well as alarms and events.

15 In one embodiment, industrial computer 300 is programmed to allow an operator to shut  
16 down or activate the direct drive fan system from a remote location.

17 Referring to FIGS. 2 and 4, VFD device 22 controls the speed, direction and torque of fan  
18 12. DAQ device 200 is in electrical signal communication with VFD device 22 and provides  
19 signals to the VFD device 22 which, in response, outputs electrical power signals to motor 20 in  
20 accordance with a desired speed, torque and direction. Specifically, the DAQ device 200  
21 generates control signals for VFD device 22 that define the desired fan speed (RPM), direction  
22 and torque of motor 20. DAQ device 200 is also programmed to issue signals to the VFD device  
23 22 to operate the fan 12 in a normal mode of operation referred to herein as "energy optimization

1 mode". This "energy optimization mode" is described in detail in the ensuing description.

2 When acceleration of motor 20 is desired, DAC device 200 outputs signals to VFD device 22  
3 that define a programmed rate of acceleration. Similarly, when deceleration of motor 20 is  
4 desired, DAQ device 200 outputs signals to VFD device 22 that define a programmed rate of  
5 deceleration. If it is desired to quickly decrease the RPM of motor 20, DAQ device 200 outputs  
6 signals to VFD device 22 that define a particular rate of deceleration that continues until the  
7 motor comes to a complete stop (e.g. 0.0 RPM).

8 DAQ device 200 provides several functions in the system of the present invention. DAQ  
9 device 200 receives electronic data signals from all sensors and variable speed pumps (discussed  
10 in the ensuing description). DAQ device 200 also continuously monitors sensor signals sent to  
11 the aforesaid sensors to verify that these sensors are working properly. DAQ device 200 is  
12 programmed to issue an alert if there is a lost sensor signal or a bad sensor signal. DAQ device  
13 200 automatically adjusts the RPM of motor 20 in response to the sensor output signals.

14 Accordingly, the system of the present invention employs a feedback loop to continuously adjust  
15 the RPM of motor 20, and hence fan 12, in response to changes in the performance of the fan,  
16 cooling tower characteristics, process load, thermal load, pump flow-rate and weather and  
17 environmental conditions. A diagram of the feedback loop is shown in FIG. 3. DAQ device 200  
18 is programmable and can be programmed with data defining or representing the tower  
19 characteristics, trend data, geographical location of the cooling tower, weather and  
20 environmental conditions. DAQ device 200 is configured with internet compatibility (TCP/IP  
21 compatibility) and automatically generates and issues email messages or SMS text messages to  
22 multiple recipients, including the Distributed Control System (DCS), with attached documents  
23 and reports with live and historical information as well as alarms and events. In a preferred

embodiment, DAQ device 200 comprises multiple physical interfaces including Ethernet, RS-232, RS-485, fiber optics, Modbus, GSM/GPRS, PSTN modem, private line modem and radio. Preferably, DAQ device 200 has SCADA compatibility. In one embodiment, DAQ device 200 is configured as a commercially available data acquisition system. In an alternate embodiment, DAQ device 200 is configured to transmit data to industrial computer 300 via telemetry signals.

Referring again to FIG. 3, the feedback loops effect continuous monitoring of the operation of motor 20, fan 12 and the variable speed pumps and also effect automatic adjustment of the RPM of motor 20 and of the permanent magnet motors in the variable speed pumps (see FIG. 26). The feedback loops shown in FIG. 3 allows motor 20 to be operated in any one of a plurality of modes of operation which are discussed in the ensuing description.

#### Flying Start Mode

The variable process control system of the present invention is configured to operate in a “Flying Start Mode” of operation with infinite control of fan 12. A flow chart of this mode of operation is shown in FIGS. 16B. In this mode of operation, VFD device 22 senses the direction of the fan 12 (i.e. clockwise or counter-clockwise) and then: (a) applies the appropriate signal to motor 20 in order to slow fan 12 to a stop (if rotating in reverse), or (b) ramps motor 20 to speed, or (c) catches fan 12 operating in the correct direction and ramps to speed. The graph in FIG. 16C illustrates the “Flying Start Mode”. The nomenclature in FIG. 16C is defined as follows:

“A” is a desired, fixed or constant speed for motor 20 (i.e. constant RPM);

“B” is the Time in seconds for VFD device 22 to bring motor 20 from 0.0 RPM to desired RPM (i.e. Ramp-Up Time).

“C” is the Time in seconds for VFD device 22 to bring motor 20 from desired RPM to

0.0 RPM (i.e. Ramp-Down Time).

“Angle D” is the acceleration time in RPM/second and is defined as “ $\cos(A/B)$ ”;

“Angle E” is the deceleration time in RPM/second and is defined as “ $\cos(A/C)$ ”;

Angle D and Angle E may be identical, but they do not have to be.

The “Flying Start” mode may be implemented if any of the following conditions exist:

Condition #2: Motor 20 is detected at 0.0 RPM. The VFD device 22 accelerates motor 20 to desired RPM in “B” seconds.

Condition #1: Motor 20 is detected running in reverse direction. The VFD device 22 calculates time to bring motor 20 to 0.0 RPM at rate of D. Motor 20 is then accelerated to “A” RPM. Total time for motor to reach “A” RPM is greater than “B” seconds.

Condition #3: Motor 20 is detected running in forward direction. VFD device 22 calculates position of motor 20 on ramp and uses rate “D” to accelerate motor to “A” RPM. Total time for motor 20 to reach “A” RPM is less than “B” seconds.

Condition #4 – Motor is detected running greater than “A” RPM. VFD device 22 calculates time to decelerate motor to “A” RPM using rate E.

This Flying Start mode of operation is possible because the bearing design of permanent magnet motor 20 allows windmilling in reverse.

#### Soft Start Mode

The variable process control system of the present invention is configured to operate in a “Soft Start Mode” of operation. In this mode of operation, with VFD device 22 is programmed to initiate acceleration in accordance with predetermined ramp rate. Such a controlled rate of acceleration eliminates breakage of system components with “across the line starts”. Such

1 “breakage” is common with prior art gearbox fan drive systems.

## 2 Hot Day Mode

3 Another mode of operation that can be implemented by the variable process control  
4 system of the present invention is the “hot day” mode of operation. The “hot day” mode of  
5 operation is used when more cooling is required and the speed of all fans is increased to 100%  
6 maximum fan tip speed. The “hot day” mode of operation can also be used in the event of an  
7 emergency in order to stabilize an industrial process that may require more cooling.

## 9 Energy Optimization Mode

10 The variable process control system of the present invention is configured to operate in  
11 an “Energy Optimization Mode”. In this mode of operation, the fan 12 and the variable speed  
12 pumps 1722, 1730, 1738, and 1752 (see FIG. 26) are operated to maintain a constant basin  
13 temperature. The control of fan speed is based upon the cooling tower design, predicted and  
14 actual process demand and historical environmental conditions with corrections for current  
15 process and environmental conditions. Industrial computer 300 uses historical data to predict the  
16 process demand for a current day based on historical process demand patterns and historical  
17 environmental conditions, and then calculates a fan speed curve as a function of time. The  
18 calculated fan speed curve represents the minimal energy required to operate the fan throughout  
19 the variable speed range for that current day in order to meet the constant basin temperature  
20 demand required by the industrial process. In real time, the variable process control system  
21 processes the actual environmental conditions and industrial process demand and provides  
22 predictions and corrections that are used to adjust the previously calculated fan speed curve as a  
23 function of time. VFD device 22 outputs electrical power signals in accordance with the

1 corrected fan speed curve. The system utilizes logic based on current weather forecasts, from  
2 on-site weather station 316, as well as historical trends pertaining to past operating data, past  
3 process demand, and past environmental conditions (e.g. weather data, temperature and wet-bulb  
4 temperature) to calculate the operating fan speed curve. In this Energy Optimization Mode, the  
5 fan operation follows the changes in the daily wet-bulb temperature. Fan operation is  
6 represented by a sine wave over a 24 hour period, as shown in the top portion of the graph in  
7 FIG. 9, wherein the fan speed transitions are smooth and deliberate and follow a trend of  
8 acceleration and deceleration. In FIG. 9, the “Y” axis is “Motor Speed” and the “X” axis is  
9 “Time”. The fan speed curve in the top portion of the graph in FIG. 9 (Energy Optimization  
10 Mode” is directly related to wet-bulb temperature. The duration of time represented by the “X”  
11 axis is a twenty-four period. The variable process control system of the present invention uses a  
12 Runge-Kutter algorithm that analyzes historical process demand and environmental stress as well  
13 as current process demand and environmental stress to generate a fan speed curve that results in  
14 energy savings. This control of the fan speed is therefore predictive in nature so as to optimize  
15 energy consumption as opposed to being reactive to past data. Such a process minimizes the  
16 energy consumed in varying the fan speed. Such smooth fan speed transitions of the present  
17 invention are totally contrary to the abrupt fan speed transitions of the prior art fan drive systems,  
18 which are illustrated at the bottom of the graph in FIG. 9. The fan speed transitions of the prior  
19 art fan drive system consist of numerous, abrupt fan-speed changes occurring over a twenty-four  
20 period in short spurts. Such abrupt fan speed changes are the result of the prior art variable  
21 speed logic which is constantly “switching” or accelerating and decelerating the fan to satisfy the  
22 basin temperature set point.

23 Therefore, the Energy Optimization Mode of the present invention uses the cooling tower

1 data, process demand, geographical location data, current environmental data and historical  
2 trends to predict fan speed according to loading so as to provide a smooth fan-speed curve  
3 throughout the day. Such operation minimizes the fan speed differential and results in optimized  
4 energy efficiency.

#### 5 “Soft-Stop Mode”

6 The variable process control system and motor 20 of the present invention are configured  
7 to operate in a “Soft-Stop Mode” of operation. In this mode of operation, DAQ device 200  
8 provides signals to VFD device 22 to cause VFD device 22 to decelerate motor 20 under power  
9 RPM in accordance with a predetermined negative ramp rate to achieve a controlled stop. This  
10 mode of operation also eliminates breakage of and/or damage to system components. This  
11 “Soft-Stop Mode” quickly brings the fan to a complete stop thereby reducing damage to the fan.  
12 The particular architecture of motor 20 allows the fan to be held at zero RPM to prevent the fan  
13 from windmilling in reverse. Such a feature prevents the fan from damaging itself or damaging  
14 other components during high winds and hurricanes. Such a “Soft Stop Mode” of operation is  
15 not found in prior art fan drive systems using induction motors.

#### 16 Fan Hold Mode

17 The variable process control system and motor 20 of the present invention are configured  
18 to operate in a “Fan-Hold Mode”. This mode of operation is used during a lock-out, tag-out  
19 (LOTO) procedure which is discussed in detail in the ensuing description. “If a LOTO  
20 procedure is to be implemented, then motor 20 is first brought to 0.00 RPM using the “Soft-Stop  
21 Mode”, then the “Fan-Hold Mode” is implemented in order to prevent the fan from windmilling.  
22 Fan-hold is a function of the design of permanent magnet motor 20. DAQ device 200 provides  
23

1 signals to VFD device 22 to cause VFD device 22 to decelerate motor 20 under power at a  
2 predetermined negative ramp rate to achieve a controlled stop of fan 12 in accordance with the  
3 “Soft-Stop Mode”. VFD device 22 controls motor 20 under power so that fan 12 is held  
4 stationary. Next, the motor shaft 24 is locked with a locking mechanism (as will be described in  
5 the ensuing description). Then, all forms of energy (e.g. electrical power) are removed according  
6 to the Lock-Out-Tag-Out (LOTO) procedure and then fan 12 can be secured. In prior art drive  
7 systems using induction motors, attempting to brake and hold a fan would actually cause damage  
8 to the induction motor. However, such problems are eliminated with the “Soft-Stop and “Fan-  
9 Hold Modes”.

10 The variable process control system and motor 20 of the present invention can also  
11 implement a “Reverse Operation Mode”. In this mode of operation, permanent magnet motor 20  
12 is operated in reverse. This mode of operation is possible since there are no restrictions or  
13 limitations on motor 20 unlike prior art gearbox fan drive systems which have many limitations  
14 (e.g. lubrication limitations). The unique bearing system of motor 20 allows unlimited reverse  
15 rotation of motor 20. Specifically, the unique design of motor 20 allows design torque and speed  
16 in both directions.

#### 17 Reverse Flying Start Mode

18 The variable process control system and motor 20 of the present invention can also  
19 implement a “Reverse Flying-Start Mode” of operation. In this mode of operation, the Flying  
20 Start mode of operation is implemented to obtain reverse rotation. The motor 20 is first  
21 decelerated under power until 0.00 RPM is attained than then reverse rotation is immediately  
22 initiated. This mode of operation is possible since there are no restrictions or limitations on  
23 motor 20 in reverse. This mode of operation is useful for de-icing.

### Lock-Out Tag Out

In accordance with the invention, a particular Lock-Out Tag-Out (LOTO) procedure is used to stop fan 12 in order to conduct maintenance on fan 12. A flow-chart of this procedure is shown in FIG. 16. Initially, the motor 20 is running at the requested speed. In one embodiment, in order to initiate the LOTO procedure, an operator uses the built-in keypad of DAQ device 200 to implement "Soft-Stop Mode" so as to cause motor 20, and thus fan 12, to decelerate to 0.0 RPM. Once the RPM of motor 20 is at 0.0 RPM, the "Fan-Hold Mode" is implemented to allow VFD device 22 and motor 20 hold the fan 12 at 0.0 RPM under power. A fan lock mechanism is then applied to motor shaft 24. All forms of energy (e.g. electrical energy) are then removed so as to lock out VFD 22 and motor 20. Operator or user interaction can then take place. The fan lock mechanism can be either manually, electrically, mechanically or pneumatically operated, and either mounted to or built-in to motor 20. This fan lock will mechanically hold and lock the motor shaft 24 thereby preventing the fan 12 from rotating when power is removed. Such a fan lock can be used for LOTO as well as hurricane service. Fan lock configurations are discussed in the ensuing description. Once the maintenance procedures are completed on the fan or cooling tower, all safety guards are replaced, the fan lock is released and the mechanical devices are returned to normal operation. The operator then unlocks and powers up VFD device 22. Once power is restored, the operator uses the keypad of DAQ device 200 to restart and resume fan operation. This LOTO capability is a direct result of motor 20 being directly coupled to fan hub 16. The LOTO procedure provides reliable control of fan 12 and is significantly safer than prior art techniques. This LOTO procedure complies with the National Safety Council and OSHA guidelines for removal of all forms of energy.

1           One example of a fan lock mechanism that may be used on motor 20 is shown in FIGS.  
2   21A, 21B and 21C. The fan lock mechanism is a solenoid-actuated pin-lock system and  
3   comprises enclosure or housing 1200, which protects the inner components from environmental  
4   conditions, stop-pin 1202 and solenoid or actuator 1204. The solenoid or actuator 1204 receives  
5   an electrical actuation signal from DAQ device 200 when it is desired to prevent fan rotation.  
6   The fan lock mechanism may be mounted on the drive portion of motor shaft 24 that is adjacent  
7   the fan hub, or it may be mounted on the lower, non-drive portion of the motor shaft 24. FIG.  
8   21B shows solenoid 1204 so that stop-pin 1202 engages rotatable shaft 24 of motor 20 so as to  
9   prevent rotation of shaft 24 and the fan. In FIG. 21A, solenoid 1204 is deactivated so that stop  
10   pin 1202 is disengaged from rotatable shaft 24 so as to allow rotation of shaft 24 and the fan.  
11   FIG. 21C shows the fan-lock mechanism on both the upper, drive end of shaft 24, and the lower,  
12   non-drive end of shaft 24.

13           In an alternate embodiment, the fan-lock mechanism shown in FIGS. 21A and 21B can  
14   be cable-actuated. In a further embodiment, the fan-lock mechanism shown in FIGS. 21A and  
15   21B is actuated by a flexible shaft. In yet another embodiment, the fan-lock mechanism shown  
16   in FIGS. 21A and 21B is motor-actuated.

17           Referring to FIG. 22, there is shown a caliper type fan-lock mechanism which can be  
18   used with motor 20. This caliper type fan lock mechanism comprises a housing or cover 1300  
19   and a caliper assembly, indicated by reference numbers 1302 and 1303. The caliper type fan  
20   lock mechanism also includes discs 1304 and 1305, flexible shaft cover 1306 and a shaft or  
21   threaded rod 1308 that is disposed within the flexible shaft cover 1306. The caliper type fan  
22   lock mechanism further includes fixed caliper block 1310 and movable caliper block 1311. In an  
23   alternate embodiment, a cable is used in place of the shaft or threaded rod 1308. In alternate

embodiments, the fan lock mechanism can be activated by a motor (e.g. screw activated) or a pull-type locking solenoid. FIG. 22 shows the fan lock mechanism mounted on top of the motor 20 so it can engage the upper portion of motor shaft 24. FIG. 23 shows the fan lock mechanism mounted at the bottom of motor 20 so the fan lock mechanism can engage the lower, non-drive end 25 of motor shaft 24.

Referring to FIG. 25, there is shown a band-type fan-lock mechanism which can be used with motor 20. This band-type fan lock mechanism comprises housing or cover 1600, flexible shaft cover 1602 and a shaft or threaded rod 1604 that is disposed within the flexible shaft cover 1604. The band-type fan lock mechanism further includes fixed lock bands 1606 and 1610 and lock drum 1608. In an alternate embodiment, a cable is used in place of the shaft or threaded rod 1604. In alternate embodiments, the band-type fan lock mechanism can be activated by a motor (e.g. screw activated) or a pull-type locking solenoid. FIG. 25 shows the fan lock mechanism mounted on top of the motor 20 so it can engage the upper portion of motor shaft 24. FIG. 24 shows the fan lock mechanism mounted at the bottom of motor 20 so the fan lock mechanism can engage the lower, non-drive end 25 of motor shaft 24.

In another embodiment, the fan lock is configured as the fan lock described in U.S. Patent Application Publication No. 2006/0292004, the disclosure of which published application is hereby incorporated by reference.

## De-Ice Mode

The variable process control system and motor 20 are also configured to implement a “De-Ice Mode” of operation wherein the fan is operated in reverse. Icing of the fans in a cooling tower may occur depending upon thermal demand (i.e. water from the industrial process and the

1 return demand) on the tower and environmental conditions (i.e. temperature, wind and relative  
2 humidity). Operating cooling towers in freezing weather is described in the January, 2007  
3 “Technical Report”, published by SPX Cooling Technologies. The capability of motor 20 to  
4 operate in reverse in order to reverse the fan direction during cold weather will de-ice the tower  
5 faster and completely by retaining warm air in the cooling tower as required by the  
6 environmental conditions. Motor 20 can operate in reverse without limitations in speed and  
7 duration. However, prior art gear boxes are not designed to operate in reverse due to the  
8 limitations of the gearbox’s bearing and lubrication systems. One prior art technique is to add  
9 lubrication pumps (electrical and gerotor) to the prior art gearbox in order to enable lubrication  
10 in reverse operation. However, even with the addition of a lubrication pump, the gearboxes are  
11 limited to very slow speeds and are limited to a typical duration of no more than two minutes in  
12 reverse operation due to the bearing design. For most cooling towers, the fans operate  
13 continuously at 100% fan speed. In colder weather, the additional cooling resulting from the  
14 fans operating at 100% fan speed actually causes the cooling tower to freeze which can lead to  
15 collapse of the tower. One prior art technique utilized by cooling tower operators is the use of  
16 two-speed motors to drive the fans. With such a prior art configuration, the two-speed motor is  
17 continually jogged in a forward rotation and in a reverse rotation in the hopes of de-icing the  
18 tower. In some cases, the gearboxes are operated beyond the two minute interval in order to  
19 perform de-icing. However, such a technique results in gearbox failure as well as icing damage  
20 to the tower. If the motors are shut off to minimize freezing of the towers, the fan and its  
21 mechanical system will ice and freeze. Another prior art technique is to de-ice the towers late at  
22 night with fire hoses that draw water from the cooling tower basin. However, this is a dangerous  
23 practice and often leads to injuries to personnel. In order to solve the problems of icing in a

1 manner that eliminates the problems of prior art de-icing techniques, the present invention  
2 implements an automatic de-icing operation without operator involvement and is based upon the  
3 cooling tower thermal design, thermal gradient data, ambient temperature, relative humidity,  
4 wet-bulb temperature, wind speed and direction. Due to the bearing design and architecture of  
5 motor 20 and design torque, fan 12 is able to rotate in either direction (forward or reverse). This  
6 important feature enables the fan 12 to be rotated in reverse for purposes of de-icing. DAQ  
7 device 200 and VFD device 22 are configured to operate motor 20 at variable speed which will  
8 reduce icing in colder weather. This variable speed characteristic combined with design torque  
9 and fan speed operation in forward or reverse minimizes and eliminates icing of the tower. DAQ  
10 device 200 is programmed with temperature set points, tower design parameters, plant thermal  
11 loading, and environmental conditions and uses this programmed data and the measured  
12 temperature values provided by the temperature sensors to determine if de-icing is necessary. If  
13 DAQ device 200 determines that de-icing is necessary, then the de-icing mode is automatically  
14 initiated without operator involvement. When such environmental conditions exist, DAQ device  
15 200 generates control signals that cause VFD device 22 to ramp down the RPM of motor 20 to  
16 0.0 RPM. The Soft-Stop Mode can be used to ramp the motor RPM down to 0.00 RPM. Next,  
17 the motor 20 is operated in reverse so as to rotate the fan 12 in reverse so as to de-ice the cooling  
18 tower. The Reverse Flying Start mode can be used to implement de-icing. Since motor 20 does  
19 not have the limitations of prior art gearboxes, supervision in this automatic de-ice mode is not  
20 necessary. Upon initiation of de-icing, DAQ device 200 issues a signal to industrial computer  
21 300. In response, display screen 306 displays a notice that informs the operators of the de-icing  
22 operation. This de-icing function is possible because motor 20 comprises a unique bearing  
23 design and lubrication system that allows unlimited reverse operation (i.e. 100% fan speed in

reverse) without duration limitations. The unlimited reverse operation in combination with variable speed provides operators or end users with infinite speed range in both directions to match ever changing environmental stress (wind and temperatures) while meeting process demand. Since DAQ device 200 can be programmed, the de-icing program may be tailored to the specific design of a cooling tower, the plant thermal loading and the surrounding environment. In a preferred embodiment, DAQ device 200 generates email or SMS text messages to notify the operators of initiation of the de-ice mode. In a preferred embodiment, DAQ device 200 generates a de-icing schedule based on the cooling tower design, the real time temperature, wet-bulb temperature, wind speed and direction, and other environmental conditions. In an alternate embodiment, temperature devices maybe installed within the tower to monitor the progress of the de-icing operation or to trigger other events. The variable process control system of the present invention is configured to allow an operator to manually initiate the De-Ice mode of operation. The software of the DAQ device 200 and industrial computer 300 allows the operator to use either the keypad at the DAQ device 200, or user input device 304 which is in data signal communication with industrial computer 300. In alternate embodiment, the operator initiates the De-Icing mode via Distributed Control System 315. In such an embodiment, the control signals are routed to industrial computer 300 and then DAQ device 200.

In a multi-cell system, there is a separate VFD device for each permanent magnet motor but only one DAQ device for all of the cells. This means that every permanent magnet motor, whether driving a fan or part a variable speed pump, will receive control signals from a separate, independent, dedicated VFD device. Such a multi-cell system is described in detail in the ensuing description. The DAQ device is programmed with the same data as described in the foregoing description and further includes data representing the number of cells. The DAQ

1 device controls each cell individually such that certain cells may be dwelled, idled, held at stop  
2 or allowed to windmill while others may function in reverse at a particular speed to de-ice the  
3 tower depending upon the particular design of the cooling tower, outside temperature, wet bulb,  
4 relative humidity, wind speed and direction. Thus, the DAQ device determines which cells will  
5 be operated in the de-ice mode. Specifically, DAQ device 200 is programmed so that certain  
6 cells will automatically start de-icing the tower by running in reverse based upon the cooling  
7 tower design requirements. Thus, the fan in each cell can be operated independently to retain  
8 heat in the tower for de-icing while maintaining process demand.

9 In either the single fan cooling tower, or a multi-cell tower, temperature sensors in the  
10 cooling towers provide temperature data to the DAQ device 200 processes these signals to  
11 determine if the De-Ice mode should be implemented. In a multi-cell tower, certain cells may  
12 need de-icing and other cells may not. In that case, the DAQ device sends the de-icing signals to  
13 only the VFDs that correspond to fan cells requiring de-icing.

14 The DAQ device is also programmed to provide operators with the option of just  
15 reducing the speed of the fans in order to achieve some level of de-icing without having to stop  
16 the fans and then operate in reverse.

17 In another embodiment of the invention, VFD device 22 is configured as a regenerative  
18 (ReGen) drive device. A regenerative VFD is a special type of VFD with power electronics that  
19 return power to the power grid. Such a regenerative drive system captures any energy resulting  
20 from the fan “windmilling” and returns this energy back to the power grid. “Windmilling”  
21 occurs when the fan is not powered but is rotating in reverse due to the updraft through the  
22 cooling tower. The updraft is caused by water in the cell. Power generated from windmilling  
23 can also be used to limit fan speed and prevent the fan from turning during high winds, tornados

1 and hurricanes. The regenerative VFD device is also configured to generate control signals to  
2 motor 20 that to hold the fan at 0.00 RPM so as to prevent windmilling in high winds such as  
3 those experienced during hurricanes.

4 Referring to FIG. 2, the variable process control system of the present invention further  
5 comprises a plurality of sensors and other measurement devices that are in electrical signal  
6 communication with DAQ device 200. Each of these sensors has a specific function. Each of  
7 these functions is now described in detail. Referring to FIG. 4 and 5B, motor 20 includes  
8 vibration sensors 400 and 402 which are located within motor casing 21. Sensor 400 is  
9 positioned on bearing housing 50 and sensor 402 is positioned on bearing housing 52. In a  
10 preferred embodiment, each sensor 400 and 402 is configured as an accelerometer, velocity and  
11 displacement. As described in the foregoing description, sensors 400 and 402 are electrically  
12 connected to quick-disconnect adapter 108 and cable 110 is electrically connected to quick-  
13 disconnect adapter 108 and communication data junction box 111. Cable 112 is electrically  
14 connected between communication data junction box 111 and DAQ device 200. Vibration  
15 sensors 400 and 402 provide signals that represent vibrations experienced by fan 12. Vibrations  
16 caused by a particular source or condition have a unique signature. All signals emanating from  
17 sensors 400 and 402 are inputted into DAQ device 200 which processes these sensor signals.  
18 Specifically, DAQ device 200 includes a processor that executes predetermined vibration-  
19 analysis algorithms that process the signals provided by sensors 400 and 402 to determine the  
20 signature and source of the vibrations. Such vibration-analysis algorithms include a FFT (Fast  
21 Fourier Transform). Possible reasons for the vibrations may be an unbalanced fan 12, instability  
22 of motor 20, deformation or damage to the fan system, resonant frequencies caused by a  
23 particular motor RPM, or instability of the fan support structure, e.g. deck. If DAQ device 200

1 determines that the vibrations sensed by sensors 400 and 402 are caused by a particular RPM of  
2 permanent magnet motor 20, DAQ device 200 generates a lock-out signal for input to VFD  
3 device 22. The lock-out signal controls VFD device 22 to lock out the particular motor speed (or  
4 speeds) that caused the resonant vibrations. Thus, the lock-out signals prevent motor 20 from  
5 operating at this particular speed (RPM). DAQ device 200 also issues signals that notify the  
6 operator via DCS 315. It is possible that there may be more than one resonant frequency and in  
7 such a case, all motor speeds causing such resonant frequencies are locked out. Thus, the motor  
8 20 will not operate at the speeds (RPM) that cause these resonant frequencies. Resonant  
9 frequencies may change over time. However, vibration sensors 400 and 402, VFD device 22 and  
10 DAQ device 200 constitute an adaptive system that adapts to the changing resonant frequencies.  
11 The processing of the vibration signals by DAQ device 200 may also determine that fan  
12 balancing may be required or that fan blades need to be re-pitched.

13 Fan trim balancing is performed at commissioning to identify fan imbalance, which is  
14 typically a dynamic imbalance. Static balance is the norm. Most fans are not dynamically  
15 balanced. This imbalance causes the fan to oscillate which results in wear and tear on the tower,  
16 especially the bolted joints. In prior art fan drive systems, measuring fan imbalance can be  
17 performed but requires external instrumentation to be applied to the outside of the prior art  
18 gearbox. This technique requires entering the cell. However, unlike the prior art systems, DAQ  
19 device 200 continuously receives signals outputted by vibration sensors 400 and 402. Dynamic  
20 system vibration can be caused by irregular fan pitch, fan weight and or installation irregularities  
21 on the multiple fan blade systems. Fan pitch is usually set by an inclinometer at commissioning  
22 and can change over time causing fan imbalance. If the pitch of any of the fan blades 18 deviates  
23 from a predetermined pitch or predetermined range of pitches, then a maintenance action will be

1 performed on fan blades 18 in order to re-pitch or balance the blades. In a preferred  
2 embodiment, additional vibration sensors 404 and 406 are located on bearing housings 50 and  
3 52, respectively, of motor 20 (see FIG. 4). Each vibration sensor 404 and 406 is configured as an  
4 accelerometer or a velocity probe or a displacement probe. Each vibration sensor 404 and 406  
5 has a particular sensitivity and a high fidelity that is appropriate for detecting vibrations resulting  
6 from fan imbalance. Signals emanating from sensors 404 and 406 are inputted into DAQ device  
7 200 via cable 110, communication data junction box 111 and cable 112. Sensors 404 and 406  
8 provide data that allows the operators to implement correct fan trim balancing. Fan trim  
9 balancing provides a dynamic balance of fan 12 that extends cooling tower life by reducing or  
10 eliminating oscillation forces or the dynamic couple that causes wear and tear on structural  
11 components caused by rotating systems that have not been dynamically balanced. If the  
12 measured vibrations indicate fan imbalance or are considered to be in a range of serious or  
13 dangerous vibrations indicating damaged blades or impending failure, then DAQ device 200  
14 automatically issues an emergency stop signal to VFD device 20. If the vibrations are serious,  
15 then DAQ device 200 issues control signals to VFD device 22 that causes motor 20 to coast to a  
16 stop. The fan would be held using the Fan-Hold mode of operation. Appropriate fan locking  
17 mechanisms would be applied to the motor shaft 24 so that the fan could be inspected and  
18 serviced. DAQ device 200 then issues alert notification via email or SMS text messages to the  
19 DCS 315 to inform the operators that then fan has been stopped due to serious vibrations. DAQ  
20 device 200 also issues the notification to industrial computer 300 for display on display 306. If  
21 the vibration signals indicate fan imbalance but the imbalance is not of a serious nature, DAQ  
22 device 200 issues a notification to the DCS 315 to alert the operators of the fan imbalance. The  
23 operators would have the option cease operation of the cooling tower or fan cell so that the fan

1 can be inspected and serviced if necessary. Thus, the adaptive vibration-monitoring and  
2 compensation function of the variable process control system of the present invention combines  
3 with the bearing design and structure of motor 20 to provide low speed, dynamic fan trim  
4 balance thereby eliminating the “vibration couple”.

5 The adaptive vibration feature of the variable process control system provides 100%  
6 monitoring, supervision and control of the direct drive fan system with the capability to issue  
7 reports and alerts to DCS 315 via e-mail and SMS. Such reports and alerts notify operators of  
8 operating imbalances, such as pitch and fan imbalance. Large vibrations associated with fan and  
9 hub failures, which typically occur within a certain vibration spectrum, will result in motor 20  
10 being allowed to immediately coast down to 0.0 RPM. The fan-hold mode is then implemented.  
11 Industrial computer 300 then implements FFT processing of the vibration signals in order to  
12 determine the cause of the vibrations and to facilitate prediction of impending failures. As part of  
13 this processing, the vibration signals are also compared to historic trending data in order to  
14 facilitate understanding and explanation of the cause of the vibrations.

15 In an alternate embodiment, the variable process control system of the present invention  
16 uses convenient signal pick-up connectors at several locations outside the fan stack. These  
17 signal pick-up connectors are in signal communication with sensors 400 and 402 and can be used  
18 by operators to manually plug in balancing equipment (e.g. Emerson CSI 2130) for purposes of  
19 fan trim.

20 In accordance with the invention, when sensors 400, 402, 404 and 406 are functioning  
21 properly, the sensors output periodic status signals to DAQ device 200 in order to inform the  
22 operators that sensors 400, 402, 404 and 406 are working properly. If a sensor does not emit a  
23 status signal, DAQ device 200 outputs a sensor failure notification that is routed to DCS 315 via

1 email or SMS text messages. The sensor failure notifications are also displayed on display  
2 screen 306 to notify the operators of the sensor failure. Thus, as a result of the continuous 100%  
3 monitoring of the sensors, lost sensor signals or bad sensor signals will cause an alert to be  
4 issued and displayed to the operators. This feature is a significant improvement over prior art  
5 systems which require an operator to periodically inspect vibration sensors to ensure they are  
6 working properly. When a sensor fails in a prior art fan drive system, there is no feedback or  
7 indication to the operator that the sensor has failed. Such deficiencies can lead to catastrophic  
8 results such as catastrophic fan failure and loss of the cooling tower asset. However, the present  
9 invention significantly reduces the chances of such catastrophic incidents from ever occurring.  
10 In the present invention, there is built-in redundancy with respect to the sensors. In a preferred  
11 embodiment, all sensors are Line Replaceable Units (LRU) that can easily be replaced. In a  
12 preferred embodiment, the Line Replaceable Units utilize area classified Quick Disconnect  
13 Adapters such as the Turck Multifast Right Angle Stainless Connector with Lokfast Guard,  
14 which was described in the foregoing description.

15 Examples of line replaceable vibration sensor units that are used to detect vibrations at  
16 motor 20 are shown in FIGS. 18, 19 and 20. Referring to FIG. 18, there is shown a line-  
17 replaceable vibration sensor unit that is in signal communication with instrument junction box  
18 900 that is connected to motor housing or casing 21. This vibration sensor unit comprises cable  
19 gland 902, accelerometer cable 904 which extends across the exterior surface of the upper  
20 portion 906 of motor casing 21. Accelerometer 908 is connected to upper portion 906 of motor  
21 casing 21. In a preferred embodiment, accelerometer 908 is connected to upper portion 906 of  
22 motor casing 21 with a Quick Disconnect Adapters such as the Turck Multifast Right Angle  
23 Stainless Connector with Lokfast Guard which was described in the foregoing description.

1 Sensor signals from accelerometer 908 are received by DAQ device 200 for processing. In a  
2 preferred embodiment, sensor signals from accelerometer 908 are provided to DAQ device 200  
3 via instrument junction box 900. In such an embodiment, instrument junction box 900 is  
4 hardwired to DAQ device 200.

5 Another line-replaceable vibration sensor unit is shown in FIG. 19. This line-replaceable  
6 vibration sensor unit that is in signal communication with instrument junction box 900 that is  
7 connected to motor housing or casing 21 and comprises cable gland 1002, and accelerometer  
8 cable 1004 which extends across the exterior surface of the upper portion 1006 of motor casing  
9 21. This vibration sensor unit further comprises accelerometer 1008 that is joined to upper  
10 portion 1006 of motor casing 21. Accelerometer 1008 is joined to upper portion 1006 of motor  
11 casing 21. In a preferred embodiment, accelerometer 1008 is hermetically sealed to upper  
12 portion 1006 of motor casing 21. Sensor signals from accelerometer 1008 are received by DAQ  
13 device 200 for processing. In one embodiment, sensor signals from accelerometer 1008 are  
14 provided to DAQ device 200 via instrument junction box 900. In such an embodiment,  
15 instrument junction box 900 is hardwired to DAQ device 200.

16 Another line-replaceable vibration sensor unit is shown in FIG. 20. This line-replaceable  
17 vibration sensor unit that is in signal communication with instrument junction box 900 that is  
18 connected to motor housing or casing 21 and comprises cable gland 1102, and accelerometer  
19 cable 1104 which extends across the exterior surface of the upper portion 1110 of motor casing  
20 21. This vibration sensor unit further comprises accelerometer 1108 that is joined to upper  
21 portion 1110 of motor casing 21. Accelerometer 1108 is joined to upper portion 1100 of motor  
22 casing 21. In a preferred embodiment, accelerometer 1108 is hermetically sealed to upper  
23 portion 1100 of motor casing 21. Sensor signals from accelerometer 1108 are received by DAQ

1 device 200 for processing. In one embodiment, sensor signals from accelerometer 1108 are  
2 provided to DAQ device 200 via instrument junction box 900. In such an embodiment,  
3 instrument junction box 900 is hardwired to DAQ device 200.

4 Referring to FIGS. 2 and 4, the variable process control system of the present invention  
5 further comprises a plurality of temperature sensors that are positioned at different locations  
6 within the variable process control system and within cooling apparatus 10. In a preferred  
7 embodiment, each temperature sensor comprises a commercially available temperature probe.  
8 Each temperature sensor is in electrical signal communication with communication data junction  
9 box 111. Temperature sensors located within motor casing 21 are electrically connected to  
10 quick-disconnect adapter 108 which is in electrical signal communication with communication  
11 data junction box 111 via wires 110. The temperature sensors that are not located within motor  
12 casing 21 are directly hardwired to communication data junction box 111. The functions of these  
13 sensors are as follows:

- 14 1) sensor 420 measure the temperature of the interior of motor casing 21 (see FIG. 4);
- 15 2) sensors 421A and 421B measure the temperature at the motor bearing housings 50  
16 and 52, respectively (see FIG. 4);
- 17 3) sensor 422 measures the temperature of stator 32, end turns, laminations, etc. of  
18 motor 20 (see FIG. 4);
- 19 4) sensor 426 is located near motor casing 21 to measure the ambient temperature of the  
20 air surrounding motor 20 (see FIG. 2);
- 21 5) sensor 428 is located in a collection basin (not shown) of a wet-cooling tower to  
22 measure the temperature of the water in the collection basin (see FIG. 2);
- 23 6) sensor 430 measures the temperature at DAQ device 200 (see FIGS. 2 and 4);

1           7) sensor 432 measures the wet-bulb temperature (see FIG. 2);

2           8) sensor 433 measures the temperature of the airflow created by the fan (see FIG. 4);

3           9) sensor 434 measures the external temperature of the motor casing (see FIG. 4);

4           10) sensor 435 detects gas leaks or other emissions (see FIG. 4).

5   In a preferred embodiment, there are a plurality of sensors that perform each of the aforesaid  
6   tasks. For example, in one embodiment, there are a plurality of sensors 428 that measure the  
7   temperature of the water in the collection basin.

8           Sensors 426, 428, 430, 432, 433, 434 and 435 are hard wired directly to communication  
9   data junction box 111 and the signals provided by these sensors are provided to DAQ device 200  
10   via cable 112. Since sensors 421A, 421B and 422 are within motor casing 21, the signals from  
11   these sensors are fed to quick-disconnect adapter 108. The internal wires in motor 20 are not  
12   shown in FIG. 2 in order to simplify the diagram shown in FIG. 2. A sudden rise in the  
13   temperatures of motor casing 21 or motor stator 32 (stator, rotor, laminations, coil, end turns)  
14   indicates a loss of airflow and/or the cessation of water to the cell. If such an event occurs, DAQ  
15   device 200 issues a notification to the plant DCS 315 and also simultaneously activates alarms,  
16   such as alarm device 438 (see FIG. 2), and also outputs a signal to industrial computer 300. This  
17   feature provides a safety mechanism to prevent motor 20 from overheating.

18           In an alternate embodiment, sensor 430 is not hardwired to communication data junction  
19   box 111, but instead, is directly wired to the appropriate input of DAQ device 200.

20           Thus, DAQ device 200, using the aforesaid sensors, measures the parameters set forth in  
21   Table I:

TABLE I

| Parameter Measured                                                                       | Purpose                                                                                                                                          |
|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Internal motor temperature: end turns, coil lamination, stator, internal air and magnets | Monitoring, supervision, health analysis; detect motor overheating; detect wear or damage of coil, stator, magnets; detect lack of water in cell |
| External motor temperature                                                               | Monitoring, supervision, health analysis; detect motor overheating; detect lack of water in cell                                                 |
| Bearing Temperature                                                                      | Monitoring, supervision, health analysis; detect bearing wear or impending failure; detect lubrication issues; FFT processing                    |
| Fan Stack Temperature                                                                    | Monitoring, supervision, health analysis; determine Cooling Tower Thermal Capacity; determine existence of icing; operational analysis           |
| Plenum Pressure                                                                          | Monitoring, supervision, health analysis; plenum pressure equated to fan inlet pressure for mass airflow calculation                             |
| Motor Load Cells                                                                         | Determine fan yaw loads; system weight; assess bearing life; FFT processing                                                                      |
| Bearing Vibration                                                                        | Monitoring, supervision, health analysis; trim balance; adaptive vibration monitoring; modal testing                                             |
| Gas Leaks or Emissions                                                                   | Monitoring, supervision, health analysis; detect fugitive gas emissions; monitoring heat exchanger and condenser for gas emissions               |

The desired temperature of the liquid in the collection basin, also known as the basin temperature set-point, can be changed by the operators instantaneously to meet additional cooling requirements such as cracking heavier crude, maintain vacuum backpressure in a steam turbine, prevent fouling of the heat exchanger or to derate the plant to part-load. Industrial computer 300 is in electronic signal communication with the plant DCS (Distributed Control System) 315 (see FIG. 2). The operators use plant DCS 315 to input the revised basin temperature set-point into industrial computer 300. Industrial computer 300 communicated this

1 information to DAQ device 200. Sensor 428 continuously measures the temperature of the  
2 liquid in the collection basin in order to determine if the measure temperature is above or below  
3 the basin temperature set-point. DAQ device 200 processes the temperature data provided by  
4 sensor 428, the revised basin temperature set point, the current weather conditions, thermal and  
5 process load, and pertinent historical data corresponding to weather, time of year and time of  
6 day.

7 In one embodiment, wet-bulb temperature is measured with suitable instrumentation such  
8 as psychrometers, thermohygrometers or hygrometers which are known in the art.

9 As a result of the adaptive characteristics of the variable process control system of the  
10 present invention, a constant basin temperature is maintained despite changes in process load,  
11 Cooling Tower Thermal Capacity, weather conditions or time of day. DAQ device 200  
12 continuously generates updated sinusoidal fan speed curve in response to the changing process  
13 load, Cooling Tower Thermal Capacity, weather conditions or time of day.

14 Temperature sensor 430 measures the temperature at DAQ device 200 in order to detect  
15 overheating cause by electrical overload, short circuits or electronic component failure. In a  
16 preferred embodiment, if overheating occurs at DAQ device 200, then DAQ device 200 issues an  
17 emergency stop signal to VFD device 22 to initiate an emergency "Soft Stop Mode" to  
18 decelerate motor 20 to 0.00 RPM and to activate alarms (e.g. alarm 438, audio alarm, buzzer,  
19 siren, horn, flashing light, email and text messages to DCS 315, etc.) to alert operators to the fact  
20 that the system is attempting an emergency shut-down procedure due to excessive temperatures.

21 In one embodiment of the present invention, if overheating occurs at DAQ device 200, DAQ  
22 device 200 issues a signal to VFD device 22 to maintain the speed of motor 20 at the current  
23 speed until the instrumentation can be inspected.

1           The operating parameters of motor 20 and the cooling tower are programmed into DAQ  
2 device 200. DAQ device 200 comprises a microprocessor or mini-computer and has computer  
3 processing power. Many of the operating parameters are defined over time and are based on the  
4 operating tolerances of the system components, fan and tower structure. Gradual heating of  
5 motor 20 (stator, rotor, laminations, coil, end turns, etc.) in small increments as determined by  
6 trending over months, etc. as compared with changes (i.e. reductions) in horsepower or fan  
7 torque over the same time interval, may indicate problems in the cooling tower such as clogged  
8 fill, poor water distribution, etc. Industrial computer 300 will trend the data and make a decision  
9 as to whether to display a notice on display 306 that notifies the operators that an inspection of  
10 the cooling tower is necessary. A sudden rise in motor temperature as a function of time may  
11 indicate that the cell water has been shut-off. Such a scenario will trigger an inspection of the  
12 tower. The variable process control system of the present invention is designed to notify  
13 operators of any deviation from operating parameters. When deviations from these operating  
14 parameters and tolerances occur (relative to time), DAQ device 200 issues signals to the  
15 operators in order to notify them of the conditions and that an inspection is necessary. Relative  
16 large deviations from the operating parameters, such as large vibration spike or very high motor  
17 temperature, would cause DAQ device 200 to generate a control signal to VFD device 22 that  
18 will enable motor 20 to coast to complete stop. The fan is then held by the Fan Hold mode of  
19 operation. DAQ device 200 simultaneously issues alerts and notifications via email and/or text  
20 messages to DCS 315.

21           As described in the foregoing description, VFD device 22, DAQ device 200 and  
22 industrial computer 300 are housed in Motor Control Enclosure (MCE) 26. The variable process  
23 control system includes a purge system that maintains a continuous positive pressure on cabinet

1 26 in order to prevent potentially explosive gases from being drawn into MCE 26. Such gases  
2 may originate from the heat exchanger. The purge system comprises a compressed air source  
3 and a device (e.g. hose) for delivering a continuous source of pressurized air to MCE 26 in order  
4 to create a positive pressure which prevents entry of such explosive gases. In an alternate  
5 embodiment, MCE 26 is cooled with Vortex coolers that utilize compressed air. In a further  
6 embodiment, area classified air conditioners are used to deliver airflow to MCE 26.

7 Referring to FIG. 2, in a preferred embodiment, the system of the present invention  
8 further includes at least one pressure measurement device 440 that is located on the fan deck and  
9 which measures the pressure in the cooling tower plenum. In a preferred embodiment, there are  
10 a plurality of pressure measurement devices 400 to measure the pressure in the cooling tower  
11 plenum. Each pressure measurement device 440 is electrically connected to communication data  
12 junction box 111. The measured pressure equates to the pressure before the fan (i.e. fan inlet  
13 pressure). The measured pressure is used to derive fan pressure for use in cooling performance  
14 analysis.

15 It is critical that the fan be located at the correct fan height in order to produce the  
16 requisite amount of design fan pressure. The fan must operate at the narrow part of the fan stack  
17 in order to operate correctly, as shown in FIG. 13. Many prior art fan drive systems do not  
18 maintain the correct fan height within the existing parabolic fan stack installation. Such a  
19 misalignment in height causes significant degradation in cooling capacity and efficiency. An  
20 important feature of the fan drive system of the present invention is that the design architecture  
21 of motor 20 maintains or corrects the fan height in the fan stack. Referring to FIGS. 13 and 14,  
22 there is shown a diagram of a wet cooling tower that uses the fan drive system of the present  
23 invention. The wet cooling tower comprises fan stack 14 and fan deck 250. Fan stack 14 is

1 supported by fan deck 250. Fan stack 14 has a generally parabolic shape. In other embodiments,  
2 fan stack 14 can have a straight cylinder shape (i.e. cylindrical shape). Fan stack 14 and fan deck  
3 250 were discussed in the foregoing description. A parabolic fan stack 14 requires that the motor  
4 height accomodate the proper fan height in the narrow throat section of fan stack 14 in order to  
5 seal the end of the fan blade at the narrow point of the parabolic fan stack 14. This assures that  
6 the fan will operate correctly and provide the proper fan pump head for the application. The wet  
7 cooling tower includes fan assembly 12 which was described in the foregoing description. Fan  
8 assembly 12 comprises fan hub 16 and fan blades 18 that are connected to fan hub 16. Fan  
9 assembly 12 further comprises fan seal disk 254 that is connected to the top of fan hub 16. Fan  
10 hub 16 has a tapered bore 255. Motor 20 has a locking keyed shaft 24 which interfaces with a  
11 complementary shaped portion of tapered bore 255. Specifically, as shown in FIG. 14, motor  
12 shaft 24 is configured to have a key channel 256 that receives a complementary shaped portion  
13 of fan hub 16. Tapered bushing 257 is fastened to motor shaft 24 with set screw 258 so as to  
14 prevent movement of tapered bushing 257. The height H indicates the correct height at which  
15 the fan blades 18 should be located (see FIG. 13) within fan stack 14. The height H indicates the  
16 uppermost point of the narrow portion of fan stack 14. This is the correct height at which the fan  
17 blades 18 should be located in order for the fan assembly 12 to operate properly and efficiently.  
18 An optional adapter plate 260 can be used to accurately position the fan blades 18 at the correct  
19 height H (see FIGS. 13 and 14). Retrofitting motor 20 and adapter plate 260, as required, and  
20 correcting fan height can actually increase airflow through the cooling tower by setting the fan  
21 assembly 12 at the correct height H. Adapter plate 260 is positioned between ladder  
22 frame/torque tube 262 and motor 20 such that motor 20 is seated upon and connected to adapter  
23 plate 260. Motor 20 is connected to a ladder frame or torque tube or other suitable metal frame

1 that extends over the central opening in the fan deck 250. Motor 20 is designed such that only  
2 four bolts are needed to connect motor 20 to the existing ladder frame or torque tube. As shown  
3 in FIG. 12B, motor housing 21 has four holes 264A, 264B, 264C and 264D extending  
4 therethrough to receive four mounting bolts. Adapter plate 260 is designed with corresponding  
5 through-holes that receive the aforementioned four bolts. The four bolts extend through  
6 corresponding openings 264A, 264B, 264C and 264D through the corresponding openings in  
7 adapter plate 260 and through corresponding openings in the ladder frame or torque tube. Thus,  
8 by design, the architecture of motor 20 is designed to be a drop-in replacement for all prior art  
9 gearboxes (see FIG. 1) and maintains or corrects fan height in the fan stack 14 without structural  
10 modifications to the cooling tower or existing ladder frame or torque tubes. Such a feature and  
11 advantage is possible because motor 20 is designed to have a weight that is the same or less than  
12 the prior art gearbox system it replaces. The mounting configuration of motor 20 (see FIG. 12B)  
13 allows motor 20 to be mounted to existing interfaces on existing structural ladder frames and  
14 torque tubes and operate within the fan stack meeting Area Classification for Class 1, Div. 2,  
15 Groups B, C, D. Therefore, new or additional ladder frames and torque tubes are not required  
16 when replacing a prior art gearbox system with motor 20. Since motor 20 has a weight that is the  
17 same or less than the prior art gearbox it replaces, motor 20 maintains the same weight  
18 distribution on the existing ladder frame or torque tube 262. Motor 20 is connected to fan hub 16  
19 in the same way as a prior art gearbox is connected to fan hub 16. The only components needed  
20 to install motor 20 are: (a) motor 20 having power cable 105 wired thereto as described in the  
21 foregoing description, wherein the other end of power cable 105 is adapted to be electrically  
22 connected to motor disconnect junction box 106, (b) the four bolts that are inserted into through-  
23 holes 264A, 264B, 264C and 264D in motor casing or housing 21, (c) cable 110 having one

1 terminated at a quick-disconnect adapter 108, and the other end adapted to be electrically  
2 connected to communication data junction box 111 (d) power cable 107 which is adapted to be  
3 electrically connected to motor disconnect junction box 106 and VFD device 22. Power cables  
4 105 and 107 were described in the foregoing description. As a result of the design of motor 20,  
5 the process of replacing a prior art drive system with motor 20 is simple, expedient, requires  
6 relatively less crane hours, and requires relatively less skilled labor than required to install and  
7 align the complex, prior art gearboxes, shafts and couplings. In a preferred embodiment, motor  
8 20 includes lifting lugs or hooks 270 that are rigidly connected to or integrally formed with  
9 motor housing 21. These lifting lugs 270 are located at predetermined locations on motor  
10 housing 21 so that motor 20 is balanced when being lifted by a crane during the installation  
11 process. Motor 20 and its mounting interfaces have been specifically designed for Thrust, Pitch,  
12 Yaw, reverse loads and fan weight (dead load).

13 Thus, motor 20 is specifically designed to fit within the installation envelope of an  
14 existing, prior art gearbox and maintain or correct the fan height in the fan stack. In one  
15 embodiment, the weight of motor 20 is less than or equal to the weight of the currently-used  
16 motor-shaft-gearbox drive system. In a preferred embodiment of the invention, the weight of  
17 motor 20 does not exceed 2500 lbs. In one embodiment, motor 20 has a weight of approximately  
18 2350 lbs. Motor shaft 24 has been specifically designed to match existing interfaces with fan-  
19 hub shaft diameter size, profile and keyway. Motor 20 can rotate all hubs and attaching fans  
20 regardless of direction, blade length, fan solidity, blade profile, blade dimension, blade pitch,  
21 blade torque, and fan speed.

22 It is to be understood that motor 20 may be used with other models or types of cooling  
23 tower fans. For example, motor 20 may be used with any of the commercially available 4000

1 Series Tuft-Lite Fans manufactured by Hudson Products, Corporation of Houston, Texas. In an  
2 alternate embodiment, motor 20 is connected to a fan that is configured without a hub structure.  
3 Such fans are known as whisper-quiet fans or single-piece wide chord fans. When single-piece  
4 wide chord fans are used, rotatable motor shaft 24 is directly bolted or connected to the fan. One  
5 commercially available whisper-quiet fan is the PT2 Cooling Tower Whisper Quiet Fan  
6 manufactured by Baltimore Aircoil Company of Jessup, Maryland.

7 Motor 20 is designed to withstand the harsh chemical attack, poor water quality, mineral  
8 deposits and pH attack, biological growth, and humid environment without contaminating the  
9 lubrication system or degrading the integrity of motor 20. Motor 20 operates within the fan stack  
10 and does not require additional cooling ducts or flow scoops.

11 For a new installation (i.e. newly constructed cooling tower), the installation of motor 20  
12 does not require ladder frames and torque tubes as do prior art gearbox systems. The elimination  
13 of ladder frames and torque tubes provides a simpler structure at a reduced installation costs.  
14 The elimination of the ladder frame and torque tubes significantly reduces obstruction and  
15 blockage from the support structure thereby reducing airflow loss. The elimination of ladder  
16 frames and torque tubes also reduce fan pressure loss and turbulence. The installation of motor  
17 20 therefore is greatly simplified and eliminates multiple components, tedious alignments, and  
18 also reduces installation time, manpower and the level of skill of the personnel installing motor  
19 20. The electrical power is simply connected at motor junction box 106. The present invention  
20 eliminates shaft penetration through the fan stack thereby improving fan performance by  
21 reducing airflow loss and fan pressure loss.

22 As described in the foregoing description, cable 105 is terminated or prewired at motor  
23 20 during the assembly of motor 20. Such a configuration simplifies the installation of motor 20.

1 Otherwise, confined-space entry training and permits would be required for an electrician to  
2 enter the cell to install cable 105 to motor 20. Furthermore, terminating cable 105 to motor 20  
3 during the manufacturing process provides improved reliability and sealing of motor 20 since the  
4 cable 105 is assembled and terminated at motor 20 under clean conditions, with proper lighting  
5 and under process and quality control. If motor 20 is configured as a three-phase motor, then  
6 cable 105 is comprised of three wires and these three wires are to be connected to the internal  
7 wiring within motor disconnect junction box 106.

#### 8 Test Results

9 The system of the present invention was implemented with a wet-cooling tower  
10 system. Extensive Beta Testing was conducted on the system with particular  
11 attention being directed to vibrations and vibration analysis. FIG. 11A is a  
12 bearing vibration report, in graph form, which resulted from a beta test of the  
13 system of the present invention. FIG. 11B is the same bearing vibration report of  
14 FIG. 11A and shows a prior art (i.e. gearbox) trip value of 0.024G. FIG. 11C is a  
15 vibration severity graph showing the level of vibrations generated by the system  
16 of the present invention. These test results reveal motor 20 and its drive system  
17 operate significantly smoother than the prior art gearbox systems thereby  
18 producing a significantly lower vibration signature. Such smooth operation is due  
19 to the unique bearing architecture of motor 20. The average operating range of  
20 the motor 20 is 0.002G with peaks of  $\pm 0.005G$  as opposed to the average prior art  
21 gearbox trip value of 0.024G.  
22

23 The aforementioned smooth operation of motor 20 and its drive system allows accurate  
24 control, supervision, monitoring and system-health management because the variable process  
25 control system of the present invention is more robust. On the other hand, prior art gear-train  
26 meshes (i.e. motor, shaft, couplings and subsequent multiple gear-train signatures) have multiple  
27 vibration signatures and resultant cross-frequency noise that are difficult to identify and manage  
28 effectively. Motor 20 increases airflow through a cooling tower by converting more of the  
29 applied electrical energy into airflow because it eliminates the losses of the prior art gearbox  
30 systems and is significantly more efficient than the prior art gearbox systems.

1           A common prior art technique employed by many operators of cooling towers is to  
2   increase water flow into the cooling towers in order to improve condenser performance. FIG. 17  
3   shows a graph of approximated condenser performance. However, the added stress of the  
4   increased water flow causes damage to the cooling tower components and actually reduces  
5   cooling performance of the tower (L/G ratio). In some cases, it can lead to catastrophic failure  
6   such as the collapse of a cooling tower at one of Shell Chemical's olefins units at Deer Park,  
7   Texas (see Chemical Week, July 17, 2002, page 14). However, with the variable process control  
8   system of the present invention, increasing water flow is totally unnecessary because the cooling  
9   tower design parameters are programmed into both DAQ device 200 and industrial computer  
10   300. Specifically, in the variable process control system of the present invention, the cooling  
11   tower pumps and auxiliary systems are networked with the fans to provide additional control,  
12   supervision and monitoring to prevent flooding of the tower and dangerous off-performance  
13   operation. In such an embodiment, the pumps are hardwired to DAQ device 200 so that DAQ  
14   device 200 controls the operation of the fan, motor and pumps. In such an embodiment, pump-  
15   water volume is monitored as a way to prevent the collapse of the tower under the weight of the  
16   water. Such monitoring and operation of the pumps will improve part-load cooling performance  
17   of the tower as the L/G ratio is maximized for all load and environmental conditions. Such  
18   monitoring and operation will also prevent flooding and further reduce energy consumption. The  
19   flow rate through the pumps is a function of process demand or the process of a component, such  
20   as the condenser process. In a preferred embodiment, the variable process control system of the  
21   present invention uses variable speed pumps. In an alternate embodiment, variable frequency  
22   drive devices, similar to VFD device 22, are used to control the variable speed pumps in order to  
23   further improve part-load performance. In a further embodiment, the cooling tower variable

1 speed pumps are driven by permanent magnet motors that have the same or similar  
2 characteristics as motor 20.

3 Thus, the present invention can:

- 4 1) operate the fan at a constant speed;
- 5 2) vary the speed of the fan to maintain a constant basin temperature as the  
6 environmental and process demand conditions change;
- 7 3) use current wet-bulb temperature and environmental stress and past process demand  
8 and past environmental stress to anticipate changes in fan speed, and ramp fan speed  
9 up or ramp fan speed down in accordance with a sine wave (see FIG. 9) in order to  
10 meet cooling demand and save energy with relatively smaller and less frequent  
11 changes in fan speed;
- 12 4) vary the speed of the fan to maintain a constant basin temperature as environmental  
13 stress and process demands change AND maintain pre-defined heat exchanger and  
14 turbine back-pressure set-points in the industrial process in order to maintain turbine  
15 back-pressure and avoid heat exchanger fouling;
- 16 5) vary the speed of the fan and the speed of the variable speed pumps to maintain a  
17 constant basin temperature as environmental stress and process demands change  
18 AND maintain pre-defined heat exchanger and turbine back-pressure set-points in the  
19 industrial process in order to maintain turbine back-pressure and avoid heat  
20 exchanger fouling;
- 21 6) vary the speed of the fan to maintain a constant basin temperature as environmental  
22 stress and process conditions change AND maintain pre-defined heat exchanger and

1 turbine back-pressure set-points in the industrial process in order to maintain turbine  
2 back-pressure and avoid heat exchanger fouling AND prevent freezing of the cooling  
3 tower by either reducing fan speed or operating the fan in reverse;

4 7) vary the speed of the fan to change basin temperature as environmental stress and  
5 process conditions change AND maintain pre-defined heat exchanger and turbine  
6 back-pressure set-points in the industrial process in order to maintain turbine back-  
7 pressure and avoid heat exchanger fouling AND prevent freezing of the cooling tower  
8 by either reducing fan speed or operating the fan in reverse; and

9 8) vary the speed of the fan and the speed of the variable speed pumps to change the  
10 basin temperature as environmental stress and process conditions change AND  
11 maintain turbine back-pressure and avoid heat exchanger fouling AND prevent  
12 freezing of the cooling tower by either reducing fan speed or operating the fan in  
13 reverse.

14 Referring to FIG. 26, there is shown a schematic diagram of the variable process control  
15 system and motor 20 of the present invention used with a wet-cooling tower that is part of an  
16 industrial process. In this embodiment, the variable process control system includes a plurality  
17 of variable speed pumps. Each variable speed pump comprises a permanent magnet motor that  
18 has the same operational characteristics as permanent magnet motor 20. Wet-cooling tower 1700  
19 comprises tower structure 1702, fan deck 1704, fan stack 1706 and collection basin 1708.  
20 Cooling tower 1700 includes fan 1710 and permanent magnet motor 20 which drives fan 1710.  
21 Fan 1710 has the same structure and function as fan 12 which was described in the foregoing  
22 description. Cooling tower 1700 includes inlet for receiving make-up water 1712. The portion

1 of cooling tower 1700 that contains the fill material, which is well known in the art, is not shown  
2 in FIG. 26 in order to simplify the drawing. Collection basin 1708 collects water cooled by fan  
3 1710. Variable speed pumps pump the cooled water from collection basin 1708, to condenser  
4 1714, and then to process 1716 wherein the cooled water is used in an industrial process. It is to  
5 be understood that condenser 1714 is being used as an example and a similar device, such as a  
6 heat exchanger, can be used as well. The condenser temperature set-point is typically set by the  
7 operators through the Distributed Control System 315 (see FIG. 3) via signal 1717. The  
8 industrial process may be petroleum refining, turbine operation, crude cracker, etc. The variable  
9 speed pumps also pump the heated water from process 1716 back to condenser 1714 and then  
10 back to cooling tower 1700 wherein the heated water is cooled by fan 1710. Cooled water  
11 exiting collection basin 1708 is pumped by variable speed pump 1722 to condenser 1714.  
12 Variable speed pump 1722 further includes an instrumentation module which outputs pump  
13 status data signals 1726 that represent the flow rate, pressure and temperature of water flowing  
14 through variable speed pump 1722 and into condenser 1714. Data signals 1726 are inputted into  
15 DAQ device 200. This feature will be discussed in the ensuing description. Water exiting  
16 condenser 1714 is pumped to process 1716 by variable speed pump 1730. Variable speed pump  
17 1730 includes an instrumentation module that outputs pump status data signals 1734 that  
18 represent the flow rate, pressure and temperature of water flowing through variable speed pump  
19 1730. Water leaving process 1716 is pumped back to condenser by 1714 by variable speed  
20 pump 1738. Variable speed pump 1738 includes an instrumentation module which outputs pump  
21 status data signals 1742 that represent the flow rate, pressure and temperature of water flowing  
22 through variable speed pump 1738. The water exiting condenser 1714 is pumped back to  
23 cooling tower 1700 by variable speed pump 1752. Variable speed pump 1752 further includes

1 an instrumentation module that outputs pump status data signals 1756 that represent the flow  
2 rate, pressure and temperature of water flowing through variable speed pump 1752.

3 VFD device 22 comprises a plurality of Variable Frequency Devices. Specifically, VFD  
4 device 22 comprises VFD devices 23A, 23B, 23C, 23D and 23E. VFD device 23A outputs  
5 power over power cable 107. Power cables 107 and 105 are connected to junction box 106.  
6 Power cable 105 delivers the power signals to motor 20. Power cables 105 and 107 and junction  
7 box 106 were discussed in the foregoing description. VFD device 23B outputs power signal  
8 1724 for controlling the permanent magnet motor of the variable speed pump 1722. VFD device  
9 23C outputs power signal 1732 for controlling the permanent magnet motor of the variable speed  
10 pump 1730. VFD device 23D outputs power signal 1740 for controlling the permanent magnet  
11 motor of the variable speed pump 1738. VFD device 23E outputs power signal 1754 for  
12 controlling the permanent magnet motor of the variable speed pump 1752. DAQ device 200 is in  
13 electronic signal communication with VFD devices 23A, 23B, 23C, 23D and 23E. DAQ device  
14 200 is programmed to control each VFD device 23A, 23B, 23C, 23D and 23E individually and  
15 independently. All variable speed pump output data signals 1726, 1734, 1742 and 1756 from the  
16 variable speed pumps 1722, 1730, 1738 and 1752, respectively, are inputted into DAQ device  
17 200. DAQ device 200 processes these signals to determine the process load and thermal load.  
18 DAQ device 200 determines the thermal load by calculating the differences between the  
19 temperature of the water leaving the collection basin and the temperature of the water returning  
20 to the cooling tower. DAQ device 200 determines process demand by processing the flow-rates  
21 and pressure at the variable speed pumps. Once DAQ device 200 determines the thermal load  
22 and process load, it determines whether the rotational speed of the fan 1710 is sufficient to meet  
23 the process load. If the current rotational speed of the fan is not sufficient, DAQ device 200

1 develops a fan speed curve that will meet the thermal demand and process demand. As  
2 described in the foregoing description, DAQ device 200 uses Cooling Tower Thermal Capacity,  
3 current thermal demand, current process demand, current environmental stress, and historical  
4 data, such as historic process and thermal demand and historic environmental stress to generate a  
5 fan speed curve.

6 As shown in FIG. 26, DAQ device 200 also receives the temperature and vibration sensor  
7 signals that were discussed in the foregoing description. Typically, the basin temperature set-  
8 point is based on the condenser temperature set-point which is usually set by the plant operators.  
9 DAQ device 200 determines if the collection basin temperature meets the basin temperature set-  
10 point. If the collection basin temperature is above or below the basin temperature set-point, then  
11 DAQ device 200 adjusts the rotational speed of motor 20 in accordance with a revised or updated  
12 fan speed curve. Therefore, DAQ device 200 processes all sensor signals and data signals from  
13 variable speed pumps 1722, 1730, 1738 and 1752. DAQ device 200 is programmed to utilize the  
14 processed signals to determine if the speed of the variable speed pumps should be adjusted in  
15 order to increase cooling capacity for increased process load, adjust the flow rate of water into  
16 the tower, prevent condenser fouling, maintain vacuum back-pressure, or adjust the flow-rate and  
17 pressure at the pumps for plant-part load conditions in order to conserve energy. If speed  
18 adjustment of the variable speed pumps is required, DAQ device 200 generates control signals  
19 that are routed over data bus 202 for input to VFD devices 23B, 23C, 23D and 23E. In response,  
20 these VFD devices 23B, 23C, 23D and 23E generate power signals 1724, 1732, 1740 and 1754,  
21 respectively, for controlling the permanent magnet motors of variable speed pumps 1722, 1730,  
22 1738 and 1752, respectively. DAQ device 200 controls each VFD devices 23A, 23B, 23C, 23D  
23 and 23E independently. Thus, DAQ device 200 can increase the speed of one variable speed

1 pump while simultaneously decreasing the speed of another variable speed pump and adjusting  
2 the speed of the fan 1710.

3 In an alternate embodiment of the invention, all variable speed pump output data signals  
4 1726, 1734, 1742 and 1756 are not inputted into DAQ device 200 but instead, are inputted into  
5 industrial computer 300 (see FIG. 3) which processes the pump output data signals and then  
6 outputs pump control signals directly to the VFD devices 23B, 23C, 23D and 23E.

7 Each instrumentation module of each variable speed pump includes sensors for  
8 measuring motor and pump vibrations and temperatures. The signals outputted by these sensors  
9 are inputted to DAQ device 200 for processing.

10 It is to be understood that instrumentation of than the aforesaid instrumentation modules  
11 may be used to provide the pump status signals. The electrical power source for powering all  
12 electrical components and instruments shown in FIG. 26 is not shown in order to simplify the  
13 drawing. Furthermore, all power and signal junction boxes are not shown in order to simplify  
14 the drawing.

15 Furthermore, the DAQ device 200 and industrial computer 300 enable the health  
16 monitoring of Cooling Tower Thermal Capacity, energy consumption and cooling tower  
17 operation as a way to manage energy and thereby further enhance cooling performance,  
18 troubleshooting and planning for additional upgrades and modifications.

19 The Federal Clean Air Act and subsequent legislation will require monitoring of  
20 emissions from cooling towers of all types (Wet Cooling, Air and HVAC). Air and hazardous  
21 gas monitors can be integrated into the motor housing 21 as Line Replaceable Units to sense  
22 leaks in the system. The Line Replaceable Units (LRU) are mounted and sealed into the motor  
23 in a manner similar to the (LRU) vibration sensors described in the foregoing description. The

1 LRU's will use power and data communication resources available to other components of the  
2 variable process control system. Hazardous gas monitors can also be located at various locations  
3 in the cooling tower fan stack and air-flow stream. Such monitors can be electronically  
4 integrated with DAQ device 200. The monitors provide improved safety with 100% monitoring  
5 of dangerous gases and also provide the capability to trace the source of the gas (e.g. leaking  
6 condenser, heat exchanger, etc.). Such a feature can prevent catastrophic events.

7 In response to the data provided by the sensors, DAQ device 200 generates appropriate  
8 signals to control operation of motor 20, and hence fan assembly 12. Thus, the variable process  
9 control system of the present invention employs feedback control of motor 20 and monitors all  
10 operation and performance data in real-time. As a result, the operation of motor 20 and fan  
11 assembly 12 will vary in response to changes in operating conditions, process demand,  
12 environmental conditions and the condition of subsystem components. The continuous  
13 monitoring feature provide by the feedback loops of the variable process control system of the  
14 present invention, shown in FIG. 3, is critical to efficient operation of the cooling tower and the  
15 prevention of failure of and damage to the cooling tower and the components of the system of  
16 the present invention. As a result of continuously monitoring the parameters of motor 20 that  
17 directly relate to the tower airflow, operating relationships can be determined and monitored for  
18 each particular cooling tower design in order to monitor motor health, cooling tower health,  
19 Cooling Tower Thermal Capacity, provide supervision, trigger inspections and trigger  
20 maintenance actions. For example, in the system of the present invention, the horsepower (HP)  
21 of motor 20 is related to airflow across fan 12. Thus, if the fill material of the tower is clogged,  
22 the airflow will be reduced. This means that motor 20 and fan assembly 12 must operate longer  
23 and under greater strain in order to attain the desired basin temperature. The temperature within

1 the interior of motor casing 21 and stator 32 increases and the motor RPM starts to decrease.  
2 The aforementioned sensors measure all of these operating conditions and provide DAQ device  
3 200 with data that represents these operating conditions. The feedback loops continuously  
4 monitor system resonant vibrations that occur and vary over time and initiate operational  
5 changes in response to the resonant vibrations thereby providing adaptive vibration control. If  
6 resonant vibrations occur at a certain motor speed, then the feedback loops cause that particular  
7 motor speed (i.e. RPM) to be locked out. When a motor speed is locked out, it means that the  
8 motor 20 will not be operated at that particular speed. If the vibration signature is relatively  
9 high, which may indicate changes in the fan blade structure, ice build-up or a potential  
10 catastrophic blade failure, the feedback loops will cause the system to shut down (i.e. shut down  
11 motor 20). If a vibration signature corresponds to stored data representing icing conditions (i.e.  
12 temperature, wind and fan speed), then DAQ device 200 will automatically initiate the De-Icing  
13 Mode of operation. Thus, the feedback loops, sensors, pump status signals, and DAQ device 200  
14 cooperate to:

- 15 a) measure vibrations at the bearings of motor 20;
- 16 b) measure temperature at the stator of motor 20;
- 17 c) measure temperature within motor casing 21;
- 18 d) measure environmental temperatures near motor 20 and fan assembly 12;
- 19 e) determine process demand;
- 20 f) measure the temperature of the water in the cooling tower collection basin;
- 21 g) identify high vibrations which are the characteristics of “blade-out” or equivalent  
22 and immediately decelerate the fan to zero (0) RPM and hold the fan from  
23 windmilling, and immediately alert the operators using the known alert systems

(e.g. email, text or DCS alert);

h) lock out particular motor speed (or speeds) that create resonance;

i) identify icing conditions and automatically initiate the De-Icing Mode of operation and alert operators and personnel via e-mail, text or DCS alert; and

j) route the basin-water temperature data to other portions of the industrial process so as to provide real-time cooling feedback information that can be used to make other adjustments in the overall industrial process.

In a preferred embodiment, the variable process control system of the present invention further comprises at least one on-sight camera 480 that is located at a predetermined location. Camera 480 is in electrical signal communication with communication data junction box 111 and outputs a video signal that is fed to DAQ device 200. The video signals are then routed to display screens that are being monitored by operations personnel. In a preferred embodiment, the video signals are routed to industrial computer 300 and host server 310. The on-sight camera 480 monitors certain locations of the cooling tower to ensure authorized operation. For example, the camera can be positioned to monitor motor 20, the cooling tower, the fan, etc. for unauthorized entry of persons, deformation of or damage to system components, or to confirm certain conditions such as icing. In a preferred embodiment, there is a plurality of on-sight cameras.

Industrial computer 300 is in data communication with data base 301 for storing (1) historical data, (2) operational characteristics of subsystems and components, and (3) actual, real-time performance and environmental data. Industrial computer 300 is programmed to use this data to optimize energy utilization by motor 20 and other system components, generate trends, predict performance, predict maintenance, and monitor the operational costs and

1 efficiency of the system of the present invention. Industrial computer 300 uses historical data, as  
2 a function of date and time, wherein such historical data includes but is not limited to (1) weather  
3 data such as dry bulb temperature, wet bulb temperature, wind speed and direction, and  
4 barometric temperature, (2) cooling tower water inlet temperature from the process (e.g. cracking  
5 crude), (3) cooling tower water outlet temperature return to process, (4) fan speed, (5) cooling  
6 tower plenum pressure at fan inlet, (6) vibration at bearings, (7) all motor temperatures, (8)  
7 cooling tower water flow rate and pump flow-rates, (9) basin temperature, (10) process demand  
8 for particular months, seasons and times of day, (11) variations in process demand for different  
9 products, e.g. light crude, heavy crude, etc., (12) previous maintenance events, and (13) library  
10 of vibration signatures, (14) cooling tower design, (15) fan map, (16) fan pitch and (17) Cooling  
11 Tower Thermal Capacity.

12 Industrial computer 300 also stores the operational characteristics of subsystems or  
13 components which include (1) fan pitch and balancing at commissioning, (2) known motor  
14 characteristics at commissioning such as current, voltage and RPM ratings, typical performance  
15 curves, and effects of temperature variations on motor performance, (3) variation in performance  
16 of components or subsystem over time or between maintenance events, (4) known operating  
17 characteristics of variable frequency drive (VFD), (5) operating characteristics of accelerometers  
18 including accuracy and performance over temperature range, and (6) cooling tower performance  
19 curves and (7) fan speed curve. Actual real-time performance and environmental data are  
20 measured by the sensors of the system of the present invention and include:

21 1) weather, temperature, humidity, wind speed and wind direction;

22 2) temperature readings of motor interior, motor casing, basin liquids, air flow generated  
23 by fan, variable frequency drive, and data acquisition device;

- 1           3) motor bearing accelerometer output signals representing particular vibrations (to
- 2           determine fan pitch, fan balance and fan integrity);
- 3           4) plenum pressure at fan inlet;
- 4           5) pump flow-rates which indicate real-time variations in process demand;
- 5           6) motor current (amp) draw and motor voltage;
- 6           7) motor RPM (fan speed);
- 7           8) motor torque (fan torque);
- 8           9) motor power factor;
- 9           10) motor horsepower, motor power consumption and efficiency;
- 10          11) exception reporting (trips and alarms);
- 11          12) system energy consumption; and
- 12          13) instrumentation health.

13          Industrial computer 300 processes the actual real-time performance and environmental  
14 data and then correlates such data to the stored historical data and the data representing the  
15 operational characteristics of subsystems and components in order to perform the following  
16 tasks: (1) recognize new performance trends, (2) determine deviation from previous trends and  
17 design curves and related operating tolerance band, (3) determine system power consumption  
18 and related energy expense, (4) determine system efficiency, (5) development of proactive and  
19 predictive maintenance events, (6) provide information as to how maintenance intervals can be  
20 maximized, (7) generate new fan speed curves for particular scenarios, and (8) highlight areas  
21 wherein management and operation can be improved. VFD device 22 provides DAQ device 200  
22 with data signals representing motor speed, motor current, motor torque, and power factor. DAQ  
23 device 200 provides this data to industrial computer 300. As described in the foregoing

1 description, industrial computer 300 is programmed with design fan map data and cooling tower  
2 thermal design data. Thus, for a given thermal load (temperature of water in from process,  
3 temperature of water out from process and flow, etc.) and a given day (dry bulb temp, wet bulb  
4 temp, barometric pressure, wind speed and direction, etc.), the present invention predicts design  
5 fan speed from the tower performance curve and the fan map and then compares the design fan  
6 speed to operating performance. The design of each tower is unique and therefore the  
7 programming of each tower is unique. The programming of all towers includes the operational  
8 characteristic that a tower clogged with fill would require the motor to run faster and longer and  
9 would be captured by trending. Fan inlet pressure sensors are in electronic signal  
10 communication with DAQ device 200 and provide data representing airflow. Since industrial  
11 computer 300 determines operating tolerances based on trending data, the operation of the fan 12  
12 at higher speeds may trigger an inspection. This is totally contrary to prior art fan drive systems  
13 wherein the operators do not know when there are deviations in operational performance when  
14 tower fill becomes clogged.

15 Industrial computer 300 is programmed to compare the signals of the vibration sensors  
16 400, 402, 404 and 406 on motor the bearing housings 50 and 52 as a way to filter environmental  
17 noise. In a preferred embodiment, industrial computer 300 is programmed so that certain  
18 vibration frequencies are maintained or held for a predetermined amount of time before any  
19 reactive measures are taken. Certain vibration frequencies indicate different failure modes and  
20 require a corresponding reaction measure. The consistent and tight banding of the vibration  
21 signature of motor 20 allows for greater control and supervision because changes in the system  
22 of the present invention can be isolated and analyzed immediately thereby allowing for  
23 corrective action. Isolated vibration spikes in the system of the present invention can be

1 analyzed instantaneously for amplitude, duration, etc. Opposing motor bearing signatures can be  
2 compared to minimize and eliminate trips due to environmental vibrations without impacting  
3 safety and operation (false trip). As described in the foregoing description, industrial computer  
4 300 is also programmed with operational characteristics of the wet-cooling tower and ACHE.  
5 For example, industrial computer 300 has data stored therein which represents the aerodynamic  
6 characteristics of the fill material in the cooling tower. The processor of industrial computer 300  
7 implements algorithms that generate compensation factors based on these aerodynamic  
8 characteristics. These compensation factors are programmed into the operation software for each  
9 particular cooling tower. Thus, the positive or negative aerodynamic characteristics of the fill  
10 material of a particular wet-cooling tower or ACHE are used in programming the operation of  
11 each wet-cooling tower or ACHE. As described in the foregoing description, industrial  
12 computer 300 is programmed with the historical weather data for the particular geographical  
13 location in which the wet-cooling tower or ACHE is located. Industrial computer 300 is also  
14 programmed with historical demand trend which provides information that is used in predicting  
15 high-process demand and low-process demand periods. Since industrial computer 300 and DAQ  
16 device 200 are programmed with the cooling tower thermal design data that is unique to each  
17 tower including the fan map, each cooling tower can be designed to have its own unique set of  
18 logic depending on its geographical location, design (e.g. counter-flow, cross flow, ACHE,  
19 HVAC) and service (e.g. power plant, refinery, commercial cooling, etc.). When these  
20 characteristics are programmed into industrial computer 300, these characteristics are combined  
21 with sufficient operational data and trending data to establish an operational curve tolerance band  
22 for that particular cooling tower. This enables cooling tower operators to predict demand based  
23 upon historical operational characteristics and optimize the fan for energy savings by using

1 subtle speed changes as opposed to dramatic speed changes to save energy.

2 A significant feature of the present invention is that the air flow through the cooling  
3 tower is controlled via the variable speed fan to meet thermal demand and optimize energy  
4 efficiency of the system. DAQ device 200 generates motor-speed control signals that are based  
5 on several factors including cooling tower basin temperature, historical trending of weather  
6 conditions, process cooling demand, time of day, current weather conditions such as temperature  
7 and relative humidity, cooling tower velocity requirements, prevention of icing of the tower by  
8 reducing fan speed, and de-icing of the tower using reverse rotation of the fan. Thus, the system  
9 of the present invention can anticipate cooling demand and schedule the fan (or fans) to optimize  
10 energy savings (ramp up or ramp down) while meeting thermal demand. The system of the  
11 present invention is adaptive and thus learns the cooling demand by historical trending (as a  
12 function of date and time).

13 The speed of the fan or fans may be increased or decreased as a result of any one of  
14 several factors. For example, the speed of the fan or fans may be decreased or increased  
15 depending upon signals provided by the basin water temperature sensor. In another example, the  
16 speed of the fan or fans may be increased or decreased as a result of variable process demand  
17 wherein the operator or programmable Distributed Control System (DCS) 315 generates a signal  
18 indicating process-specific cooling needs such as the need for more cooling to maintain or lower  
19 turbine backpressure. In a further example, the speed of the fan or fans may be increased or  
20 decreased by raising the basin temperature if the plant is operating at part-load production. Fan  
21 speed can also be raised in "compensation mode" if a cell is lost in a multiple-cell tower in order  
22 to overcome the cooling loss. Since motor 20 provides more torque than a comparable prior art  
23 induction motor, motor 20 can operate with increased fan pitch providing required design airflow

1 at slower speeds. Since most 100% speed applications operate at the maximum fan speed of  
2 12,000 fpm to 14,000 fpm maximum tip speed depending upon the fan design, the lower speeds  
3 of motor 20 provide an airflow buffer that can be used for hot day production, compensation  
4 mode and future cooling performance.

5 A particular geographical location may have very hot summers and very cold winters. In  
6 such a case, the variable process control system operates the fan in the "hot-day" mode of  
7 operation on very hot summer days in order to meet the maximum thermal load at 100%. When  
8 the maximum thermal load diminishes, the speed of the fan is then optimized at lower fan speeds  
9 for energy optimization. The fan will operate in this energy optimization mode during the cooler  
10 months in order to optimize energy consumption, which may include turning fan cells off. Since  
11 the torque of motor 20 is constant, the shifting of fan speed between maximum operation and  
12 energy optimization is without regard to fan pitch. The constant, high-torque characteristics of  
13 motor 20 allow the fan to be re-tasked for (true) variable speed duty. Thus, the variable process  
14 control system of the present invention operates in a manner totally opposite to that of prior art  
15 fan drive systems wherein an induction motor drives the fan at 100% speed, typically between  
16 12,000 and 14,000 ft/min tip speed, and wherein the fan remains at constant speed and its pitch is  
17 limited by the torque limitations of the induction motor. In order to provide the required torque,  
18 the size of the prior art induction motor would have to be significantly increased, but this would  
19 dramatically increase the weight of the motor. On the other hand, in the present invention,  
20 permanent magnet motor 20 is able to drive the fan at slower speeds with increased fan pitch  
21 without exceeding the fan tip speed limitation of 12,000 feet/minute. Slower fan speed also  
22 allows for quieter operation since fan noise is a direct function of speed. Motor 20 allows 100%  
23 design air flow to be set below the maximum fan tip speed. This feature allows for a design

1 buffer to be built into the variable process control system of the present invention to allow for  
2 additional cooling capacity in emergency situations such as the compensation mode (for multi-  
3 cell systems) or extremely hot days or for increased process\_demand such as cracking heavier  
4 crude. The constant torque of motor 20 also means that part-load operation is possible without  
5 the limitations and drawbacks of prior art fan drive systems that use a gearbox and induction  
6 motor. In such prior art systems, part-load torque may not be sufficient to return the fan to 100%  
7 speed and would typically require a larger induction motor with increased part-load torque.

8 Motor 20 converts relatively more “amperes to air” than prior art gearbox systems.  
9 Specifically, during actual comparison testing of a cooling system using motor 20 and a cooling  
10 system using a prior art gearbox system, motor 20 is at least 10% more efficient than prior art  
11 gearbox systems. During testing, at 100% fan speed and design pitch, a power-sight meter  
12 indicated the prior art gearbox system demanded 50 kW whereas motor 20 demanded 45 kW.  
13 Almost all existing towers are cooling limited. Since motor 20 is a drop-in replacement for prior  
14 art gearboxes, motor 20 will have an immediate impact on cooling performance and production.

15 The system and method of the present invention is applicable to multi-cell cooling  
16 apparatuses. For example, a wet-cooling tower may comprise a plurality of cells wherein each  
17 cell has a fan, fan stack, etc. Similarly, a multi-cell cooling apparatus may also comprise a  
18 plurality of ACHEs, HVACs or chillers (wet or dry, regardless of mounting arrangement).

19 Referring to FIGS. 15A, 15B and 15C, there is multi-cell cooling apparatus 600 which utilizes  
20 the variable process control\_system of the present invention. Multi-cell cooling apparatus 600  
21 comprises a plurality of cells 602. Each cell 602 comprises fan assembly 12 and fan stack 14.  
22 Fan assembly 12 operates within fan stack 14 as described in the foregoing description. Each  
23 cell 602 further comprises permanent magnet motor 20. In this embodiment, the system of the

1 present invention includes Motor Control Center (MCC) 630. A Motor Control Center (MCC)  
2 typically serves more than motor or fan cell. The Motor Control Center is typically located  
3 outside of the Class One, Division Two area on the ground, at least ten feet from the cooling  
4 tower. The Motor Control Center is in a walk-in structure that houses VFD device 22, DAQ  
5 device 200, industrial computer 300, power electronics and Switchgear. The Motor Control  
6 Center is air-conditioned to cool the electronics. The Motor Control Center is typically a walk-in  
7 metal building that houses the DAQ device, the Variable Frequency Drives, the industrial  
8 computer 300 and the power electronics. MCC 630 comprises a plurality of Variable Frequency  
9 Drive (VFD) devices 650. Each VFD device 650 functions in the same manner as VFD device  
10 22 described in the forgoing description. Each VFD device 650 controls a corresponding motor  
11 20. Thus, each motor 20 is controlled individually and independent of the other motors 20 in the  
12 multi-cell cooling apparatus 600. MCC 630 further comprises a single Data Acquisition (DAQ)  
13 device 660 which is in data signal communication with all of the VFD devices 650 and all  
14 sensors (e.g. motor, temperature, vibration, pump-flow, etc.) in each cell. These sensors were  
15 previously described in the foregoing description. DAQ device 660 controls the VFD devices  
16 650 in the same manner as DAQ device 200 controls VFD device 22 which was previously  
17 described in the foregoing description. DAQ device 660 is also in data signal communication  
18 with industrial computer 300 via data bus 670. Industrial computer 300 is in data signal  
19 communication with database 301. Both industrial computer 300 and database 301 were  
20 previously described in the foregoing description. As shown in FIG. 15A, there are a plurality of  
21 communication data junction boxes 634 which receive the signals outputted by the sensors (e.g.  
22 temperature, pressure, vibration). Each communication data junction box 634 is in data signal  
23 communication with DAQ device 660. Each communication data junction box 634 has the same

1 function and purpose as communication data junction box 111 described in the foregoing  
2 description. The power signals outputted by the VFD devices 650 are routed to motor disconnect  
3 junction boxes 636 which are located outside of fan stack 14. Each motor disconnect junction  
4 box 636 has the same configuration, purpose and function as motor disconnect junction box 106  
5 previously described in the foregoing description. Since there is a dedicated VFD device 650 for  
6 each motor 20, each cell 602 is operated independently from the other cells 602. Thus, this  
7 embodiment of the present invention is configured to provide individual and autonomous control  
8 of each cell 602. This means that DAQ device 660 can operate each fan at different variable  
9 speeds at part-load based on process demand, demand trend, air-flow characteristics of each  
10 tower (or fill material) and environmental stress. Such operation optimizes energy savings while  
11 meeting variable thermal loading. Such a configuration improves energy efficiency and cooling  
12 performance. For example, if all fans are operating at minimum speed, typically 80%, and  
13 process demand is low, DAQ device 660 is programmed to output signals to one or more VFD  
14 devices 650 to shut off the corresponding fans 12. DAQ device 660 implements a compensation  
15 mode of operation if one of the cells 602 is not capable of maximum operation, or malfunctions  
16 or is taken off line. Specifically, if one cell 602 is lost through malfunction or damage or taken  
17 off line, DAQ device 660 controls the remaining cells 602 so these cells compensate for the loss  
18 of cooling resulting from the loss of that cell. End wall cells are not as effective as cells in the  
19 middle of the tower and therefore, the end wall cells may be shut off earlier in hot weather or  
20 may need to run longer in cold weather. In accordance with the invention, the fan speed of each  
21 cell 602 increases and decreases throughout the course of a cooling day in a pattern generally  
22 similar to a sine wave as shown in FIG. 9. DAQ device 660 can be programmed so that when  
23 the basin temperature set-point is not met (in the case of a wet-cooling tower), DAQ device 660

1 issues signals to the VFD devices 650 to increase fan speed based on a predictive schedule of  
2 speed increments based on (a) part-load based on process demand, (b) demand trend, (c) air flow  
3 characteristics of each tower (or fill material) and (d) environmental stress without returning fan  
4 speed to 100%. This operational scheme reduces energy consumption by the cell and preserves  
5 the operational life of the equipment. This is contrary to prior art reactive cooling schedules  
6 which quickly increase the fans to 100% fan speed if the basin temperature set-point is not met.

7 The system and method of the present invention provides infinite variable fan speed  
8 based on thermal load, process demand, historical trending, energy optimization schedules, and  
9 environmental conditions (e.g. weather, geographical location, time of day, time of year, etc.).

10 The present invention provides supervisory control based on continuous monitoring of  
11 vibrations, temperature, pump flow rate and motor speed. The present invention uses historical  
12 trending data to execute current fan operation and predicting future fan operation and  
13 maintenance. The system provides automatic de-icing of the fan without input from the operator.

14 De-icing cooling towers using permanent magnet motor 20 is relatively easier, safer and  
15 less expensive than de-icing cooling towers using prior art gearbox fan drive systems. The  
16 capability of motor 20 to operate the fans at slower speeds in colder weather reduces icing.

17 Motor 20 has no restrictions or limitations in reverse rotation and can therefore provide the heat  
18 retention required to de-ice a tower in winter. DAQ device 200 is configured to program the  
19 operation of motor 20 to implement de-icing based on outside temperature, wind speed and  
20 direction, wet bulb temperature, and cooling tower inlet/outlet and flow rate. All parameters are  
21 used to develop a program of operation that is tailored made for the particular and unique  
22 characteristics of each cooling tower, the cooling tower's location and environment stress.

23 Permanent magnet motor 20 provides constant high torque thereby allowing the fan to

1 operate at a relatively slower speed with greater pitch to satisfy required air-flow while reducing  
2 acoustic noise (acoustic noise is a function of fan speed) with additional airflow built into the  
3 system for other functions. This is not possible with prior art fan drive systems that use a single-  
4 speed gear-box and induction motor that drives the fan at 100% speed at the maximum tower  
5 thermal condition for 100% of the time. Unlike prior art fan drive systems, motor 20 is capable  
6 of infinite variable speed in both directions. Motor 20 is configured to provide infinite variable  
7 speed up to 100% speed with constant torque but without the duration restrictions of prior art fan  
8 drive systems that relate to induction motor torque at part-load, drive train resonance, torque load  
9 relative to pitch, and induction motor cooling restrictions.

10 The infinite variable speed of motor 20 in both directions allows the fan to match the  
11 thermal loading to the environmental stress. This means more air for hot-day cooling and less air  
12 to reduce tower icing. The infinite variable speed in reverse without duration limitations enables  
13 de-icing of the tower. Motor 20 provides high, constant torque in both directions and high,  
14 constant torque adjustment which allows for greater fan pitch at slower fan speeds. These  
15 important features allow for a built-in fan-speed buffer for emergency power and greater  
16 variation in diurnal environments and seasonal changes without re-pitching the fan. Thus, the  
17 infinite variable speed adjustment aspect of the present invention allows for built-in cooling  
18 expansion (greater flow) and built-in expansion without changing a motor and gear box as  
19 required in prior art fan drive systems. The present invention provides unrestricted variable  
20 speed service in either direction to meet ever changing environmental stress and process demand  
21 that results in improved cooling, safety and reduced overhead. All parameters are used to  
22 develop a unique programmed, operation for each cooling tower design, the cooling tower's  
23 geographical location and the corresponding environmental stress. DAQ device 200 operates

1 motor 20 (and thus fan 12) in a part-load mode of operation that provides cooling with energy  
2 optimization and then automatically shifts operation to a full-load mode that provides relatively  
3 more variable process control which is required to crack heavier crude. Once the process  
4 demand decreases, DAQ device 200 shifts operation of motor 20 back to part-load.

5 Due to the fan hub interface, the motor shaft 24 is relatively large resulting in a relatively  
6 large bearing design. Combined with the slow speed of the application, the bearing system is  
7 only 20% loaded, thereby providing an L10 life of 875,000 hours. The 20% loading and unique  
8 bearing design of motor 20 provides high fidelity of vibration signatures and consistent narrow  
9 vibration band signatures well below the current trip setting values to allow for improved  
10 monitoring via historical trending and improved health monitoring via vibration signatures  
11 beyond the operating tolerance. The bearing system of motor 20 enables motor 20 to rotate all  
12 fan hubs and fan diameters at all speeds and torques in both directions and is specifically  
13 designed for thrust loads, reverse loads, yaw loads, fan dead weight, etc.

14 The variable process control system of the present invention determines Cooling Tower  
15 Thermal Capacity so as to enable operators to identify proactive service, maintenance and  
16 cooling improvements and expansions. The present invention provides the ability to monitor,  
17 control, supervise and automate the cooling tower subsystems so as to manage performance and  
18 improve safety and longevity of these subsystems. The system of the present invention is  
19 integrated directly into an existing refinery Distributed Control System (DCS) so as to allow  
20 operators to monitor, modify, update and override the variable process control system in real  
21 time. Operators can use the plant DCS 315 to send data signals to the variable process control  
22 system of the present invention to automatically increase cooling for cracking crude or to prevent  
23 auxiliary system fouling or any other process. As shown by the foregoing description, for a given

1 fan performance curve, a cooling tower can be operated to provide maximum cooling as a  
2 function of fan pitch and speed. Fan speed can be reduced if basin temperature set-point is met.  
3 The present invention provides accurate cooling control with variable speed motor 20 as a  
4 function of environmental stress (e.g. cooling and icing), variable process control (i.e. part load  
5 or more cooling for cracking crude, etc.) and product quality such as light end recovery with  
6 more air-per-amp for existing installations. The variable process control system of the present  
7 invention allows operators to monitor cooling performance in real time thereby providing the  
8 opportunity to improve splits and production and identify service and maintenance requirements  
9 to maintain cooling performance and production throughput. Furthermore, the data acquired by  
10 the system of the present invention is utilized to trend cooling performance of the cooling tower  
11 which results in predictive maintenance that can be planned before outages occur as opposed to  
12 reactive maintenance that results in downtime and loss of production. The unique dual-bearing  
13 design of motor 20, the placement of accelerometers, velocity probes and displacement probes  
14 on each of these bearings, and the vibration analysis algorithms implemented by industrial  
15 computer 300 allow significant improvements in fan vibration monitoring and provides an  
16 effective trim balancing system to remove the fan dynamic couple. The trim balance feature  
17 removes the fan dynamic couple which reduces structural fatigue on the cooling tower.

18 The present invention eliminates many components and machinery used in prior art fan  
19 drive systems such as gearboxes, shafts and couplings, two-speed motors, gearbox sprag clutches  
20 to prevent reverse operation, electric and gerotor lube pumps for gearboxes and vibration cut-off  
21 switches. Consequently, the present invention also eliminates the maintenance procedures  
22 related to the aforesaid prior art components, e.g. pre-seasonal re-pitching, oil changes and  
23 related maintenance. The present invention allows monitoring and automation of the operation

1 of the cooling tower subsystems to enable management of performance and improvement in  
2 component longevity. The present invention allows continuous monitoring and management of  
3 the permanent magnet motor 20, the fan and the cooling tower itself. The present invention  
4 allows for rapid replacement of a prior art fan drive system with motor 20, without specialized  
5 craft labor, for mission critical industries minimizing production loss. The system of the present  
6 invention provides an autonomous de-icing function to de-ice and/or prevent icing of the cooling  
7 tower.

8         The system of the present invention is significantly more reliable than prior art systems  
9 because the present invention eliminates many components, corresponding complexities and  
10 problems related to prior art systems. For example, prior art gearboxes and corresponding drive  
11 trains are not designed for the harsh environment of cooling towers but were initially attractive  
12 because of their relatively lower initial cost. However, in the long run, these prior art fan drive  
13 systems have resulted in high Life-Cycle costs due to continuous maintenance and service  
14 expense (e.g. oil changes, shaft alignments, etc.), equipment failure (across-the-line start  
15 damage), application of heavy duty components, poor reliability, lost production and high energy  
16 consumption.

17         The data collected by DAQ device 200, which includes motor voltage, current, power  
18 factor, horsepower and time is used to calculate energy consumption. In addition, voltage and  
19 current instrumentation are applied to the system to measure energy consumption. The energy  
20 consumption data can be used in corporate energy management programs to monitor off-  
21 performance operation of a cooling tower. The energy consumption data can also be used to  
22 identify rebates from energy savings or to apply for utility rebates, or to determine carbon credits  
23 based upon energy savings. The system of the present invention also generates timely reports for

1 corporate energy coordinators on a schedule or upon demand. The data provided by DAQ device  
2 200 and the post-processing of such data by industrial computer 300 enables cooling  
3 performance management of the entire system whether it be a wet-cooling tower, air-cooled heat  
4 exchanger (ACHE), HVAC systems, chillers, etc. Specifically, the data and reports generated by  
5 DAQ device 200 and industrial computer 300 enable operators to monitor energy consumption  
6 and cooling performance. The aforesaid data and reports also provide information as to  
7 predictive maintenance (i.e. when maintenance of cooling tower components will be required)  
8 and proactive maintenance (i.e. maintenance to prevent a possible breakdown). Industrial  
9 computer 300 records data pertaining to fan energy consumption and thus, generates fan energy  
10 consumption trends. Industrial computer 300 implements computer programs and algorithms  
11 that compare the performance of the cooling tower to the energy consumption of the cooling  
12 tower in order to provide a cost analysis of the cooling tower. This is an important feature since  
13 an end user spends more money operating a poor performing tower (i.e. lower flow means more  
14 fan energy consumption and production loss) than a tower than is in proper operating condition.  
15 Industrial computer 300 implements an algorithm to express the fan energy consumption as a  
16 function of the tower performance which can be used in annual energy analysis reports by  
17 engineers and energy analysts to determine if the tower is being properly maintained and  
18 operated. Energy analysis reports can be used to achieve energy rebates from utilities and for  
19 making operational improvement analysis, etc. With respect to large capital asset planning and  
20 utilization cost, a relation is derived by the following formula:

$$N = (\text{Cooling Tower Thermal Capacity}) / (\text{Cooling Tower Energy Consumption})$$

23 wherein the quotient "N" represents a relative number that can be used to determine if a cooling  
24 tower is operating properly or if it has deteriorated or if it is being incorrectly operated.

1 Deterioration and incorrect operation of the cooling tower can lead to safety issues such as  
2 catastrophic failure, poor cooling performance, excessive energy consumption, poor efficiency  
3 and reduced production.

4 The present invention provides accurate cooling control with variable speed motor 20 as  
5 a function of environmental stress (cooling and icing), variable process control (part load or  
6 more cooling for cracking, etc.) and product quality such as light end recovery with more air-per-  
7 amp for existing installations. The present invention also provides automatic adjustment of fan  
8 speed as a function of cooling demand (process loading), environmental stress and energy  
9 efficiency and provides adaptive vibration monitoring of the fan to prevent failure due to fan  
10 imbalance and system resonance. The present invention allows the fans to be infinitely pitched  
11 due to constant, high torque. The built-in vibration monitoring system provides a simple and  
12 cost effective trim balance to eliminate fan dynamic couple and subsequent structural wear and  
13 tear. The variable process control system of the present invention reduces maintenance to  
14 auxiliary equipment, maintains proper turbine back pressure and prevents fouling of the  
15 condensers. Motor 20 provides constant torque that drives the fan at lower speed to achieve  
16 design airflow at a greater fan pitch thereby reducing fan noise which typically increases at  
17 higher fan speeds (noise is a function of fan speed). The present invention reduces energy  
18 consumption and does not contribute to global warming. The high-torque, permanent magnet  
19 motor 20 expands the operational range of the fan to meet ever changing process load changes  
20 and environmental conditions by providing high, constant torque for full fan pitch capability.  
21 This enables increased airflow for existing installations, provides unrestricted variable speed for  
22 energy savings and reduction of ice formation, and allows reverse operation of the fan for  
23 retaining heat in the cooling tower for de-icing.

1           Although the previous description describes how motor 20 and the corresponding system  
2 components (e.g. VFD 22, DAQ device 200, etc.) may be used to retrofit an existing cooling  
3 tower that used a prior art fan drive system, it is to be understood that the present invention can  
4 be used in newly constructed cooling towers, regardless of the materials used to construct such  
5 new cooling towers, e.g. wood, steel, concrete, FRP or combinations thereof.

6           The present invention is also applicable to steel mills and glass processing, as well as any  
7 other process wherein the control of cooling water is critical. Temperature control of the water is  
8 crucial for cooling the steel and glass product to obtain the correct material composition. The  
9 capability of the present invention to provide constant basin water temperature is directly  
10 applicable to steel mill operation, glass processing and resulting product quality and capacity.  
11 The capability of the permanent magnet motor 20 and fan 12 to operate in reverse without  
12 limitation allows more heat to be retained in the process water on cold days. This would be  
13 accomplished by slowing the fan 12 or operating the fan 12 in reverse in order to retain more  
14 heat in the tower and thus, more heat in the process water in the basin. The variable process  
15 control feature of the system of the present invention can deliver infinite temperature variation  
16 on demand to the process as required to support production and improve control and quality of  
17 the product.

18           While the foregoing description is exemplary of the present invention, those of ordinary  
19 skill in the relevant arts will recognize the many variations, alterations, modifications,  
20 substitutions and the like are readily possible, especially in light of this description, the  
21 accompanying drawings and the claims drawn hereto. In any case, because the scope of the  
22 invention is much broader than any particular embodiment, the foregoing detailed description

- 1 should not be construed as a limitation of the present invention, which is limited only by the
- 2 claims appended hereto.

## CLAIMS:

What we claim is:

1. A method for operating a cooling tower having a fan for cooling liquids used in an industrial process, comprising:

utilizing a direct-drive, variable speed permanent magnet motor to rotate the fan;

utilizing a plurality of variable speed pumps to pump the liquids from the cooling tower to the industrial process and then back to the cooling tower, wherein each variable speed pump comprises a permanent magnet motor and sensor devices for outputting pump status signals;

utilizing a variable process control system that comprises a plurality of programmable motor controllers, each of which providing power signals to a corresponding permanent magnet motor and outputting motor status signals that represent the speed and torque of each permanent magnet motor, the variable process control system further comprising a computer system in electronic communication with the programmable motor controllers and the pump status signals, wherein the computer system comprises a data storage resource for storing data representing operational characteristics of the permanent magnet motors and the programmable motor controllers, a fan speed curve, cooling tower design parameters, environmental stress,

fan aerodynamic properties including fan pitch, fan balance data, and fan vibration signatures;

measuring the flow rate of liquids flowing through the variable speed pumps;

processing the measured flow rate to determine the process demand;

measuring the plenum pressure; and

utilizing the computer system to process the determined process demand, the measured plenum pressure, the fan pitch and the rotational speed and torque of the fan to determine to determine mass airflow produced by the fan.

2. The method according to claim 1 wherein the step of utilizing the computer system to process the determined process demand further comprises determining if the mass airflow produced by the fan is sufficient to meet the determined process demand.
3. The method according to claim 2 further comprising the step of using a programmable motor controller to increase the speed of the permanent magnet motor that drives the fan in order to increase mass airflow if the current mass airflow is not sufficient to meet the determined process demand.
4. The method according to claim 2 wherein cooling tower includes a collection basin for

receiving liquids cooled by the fan and a condenser that is in the flow of liquids from the collection basin to the industrial process and in the flow of liquids from the industrial process to the cooling tower, and wherein the method further comprising the steps of:

receiving a condenser temperature set-point;

utilizing the computer system to determine a collection basin temperature that is based on the received condenser temperature set-point; and

utilizing the programmable motor controllers to output motor control signals to all permanent magnet motors that will adjust the fan rotational speed and the flow of liquids through the variable speed pumps in order to maintain the actual collection basin temperature at a temperature that is substantially the same as the determined collection basin temperature.

5. The method according to claim 4 further comprising the step of continuously measuring the actual collection basin temperature.

6. The method according to claim 5 further comprising the step of utilizing the computer system to process the measured actual collection basin temperature.

7. The method according to claim 4 wherein the step of utilizing the computer system to determine a collection basin temperature comprises the step of calculating the collection basin

temperature.

8. The method according to claim 4 wherein the data storage device has stored therein historical process demand data and historical environmental stress data, the method further comprising the steps of:

utilizing the computer system to process the current process demand data and environmental stress data and the historical process demand data and environmental stress data with a Runge-Kutter algorithm to generate a fan speed curve that defines fan speed over a predetermined amount of time wherein variations in fan speed occur in relatively small increments over the predetermined amount of time; and

utilizing the programmable motor controllers to control the speed of the direct-drive variable speed permanent magnet motor in accordance with the generated fan speed curve.

9. The method according to claim 8 further comprising the step of utilizing the programmable motor controllers to control the speed of the permanent magnet motors of the variable speed pumps in accordance with the rotation speeds defined by the generated fan speed curve.

10. The method according to claim 8 wherein the predetermined amount of time is twenty four hours.

11. The method according to claim 8 wherein the fan speed curve is substantially similar to a sinewave.

12. The method according to claim 1 wherein the direct-drive, variable speed motor, permanent magnet motor comprises a housing having an interior, a stator and rotor within the interior and bearings within the interior, the method further comprising the steps of:

measuring the temperature of the motor housing;

determining if the measured temperature of the motor housing exceeds a motor housing temperature threshold; and

utilizing the computer system to generate an alert signal if the measured motor housing temperature exceeds the motor housing temperature threshold.

13. The method according to claim 12 further comprising the steps of routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

14. The method according to claim 12 further comprising the steps of:

measuring the temperatures of the interior and the stator;

determining if the measured temperature of the stator exceeds a predetermined stator

temperature threshold;

determining if the measured temperature of the interior exceeds a predetermined interior temperature threshold;

utilizing the computer system to generate an alert signal if the measured interior temperature exceeds the interior threshold temperature or if the measure stator temperature exceeds the stator threshold temperature.

15. The method according to claim 14 further comprising the steps of routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

16. The method according to claim 12 further comprising the steps of:

measuring the temperatures of the bearings;

determining if the measured temperature of the bearings exceeds a predetermined bearing temperature threshold;

utilizing the computer system to generate an alert signal if the measured bearing temperature exceeds the bearing threshold temperature.

17. The method according to claim 16 further comprising the steps of routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

18. The method according to claim 12 further comprising the steps of:

measuring vibrations at the motor;

utilizing the computer system to process the measured vibrations and determine if the measured vibrations match any of the stored reference vibration signatures; and

generating an alert signal if the measured vibrations match any of the stored reference vibration signatures.

19. The method according to claim 18 wherein the step of utilizing the computer system to process the measured vibrations further comprises the step of processing the measured vibrations with a Fast Fourier Transform.

20. The method according to claim 18 wherein the step of measuring the vibrations at the motor comprise the step of measuring the vibrations at the motor housing.

21. The method according to claim 18 wherein the step of measuring the vibrations at the motor comprise the step of measuring the vibrations at the bearings.

22. The method according to claim 18 wherein the stored reference vibration signatures include predetermined vibration signatures that correspond to impending failure of the fan or the direct-drive, variable speed, permanent magnet motor, and wherein the method further comprises the steps of:

utilizing the computer system to determine if the measured vibrations match any of the predetermined vibration signatures; and

generating an alert signal if the measured vibrations match any of the predetermined vibration signatures.

23. The method according to claim 22 further comprising the step of generating a motor control signal to a programmable motor controller to cease providing power signals to the direct-drive variable speed, permanent magnet motor so as to allow the direct-drive variable speed, permanent magnet motor to coast to 0.0 RPM if it is determined that the measured vibrations match any of the predetermined vibration signatures.

24. The method according to claim 23 further comprising the step of holding the motor at 0.0 RPM.

25. The method according to claim 22 further comprising the step of generating a motor control signal to a programmable motor controller to ramp down the speed of the direct-drive variable speed, permanent magnet motor to 0.0 RPM in accordance with a predetermined

negative ramp rate.

26. The method according to claim 25 further comprising the step of holding the motor at 0.0 RPM.

27. The method according to claim 22 further comprising the steps:

determining if the measured vibration results from a resonant motor speed of the direct-drive variable speed permanent magnet motor if it has previously been determined that the measured vibration does not match any of the stored reference vibrations; and

programming the programmable motor controller which powers the direct-drive, variable speed permanent magnet motor to skip over the motor speed that is the same as the resonant speed.

28. The method according to claim 25 further comprising the step of storing in the data storage device the measured vibration that corresponds to the resonant motor speed.

29. A method for operating a fan in a cooling tower wherein the fan cools liquids used in an industrial process, the method comprising the steps of:

utilizing a direct-drive variable speed motor, permanent magnet motor to rotate the fan at a rotational speed;

utilizing a variable process control system comprising a programmable motor controller for providing power signals to the variable speed motor, permanent magnet motor, programmable motor controller having a data storage resource for storing a predetermined motor deceleration operation curve that decelerates the motor in accordance with a predetermined negative ramp rate; and

providing power signals to the direct-drive variable speed motor, permanent magnet motor that correspond to the predetermined motor deceleration operation curve to decrease the motor speed to 0.0 RPM.

30. The method according to claim 29 further comprising the step of holding the motor at 0.0 RPM:

31. The method according to claim 30 further comprising the step locking the motor shaft to prevent rotation thereof.

32. The method according to claim 29 wherein the cooling tower includes a collection basin for receiving liquids cooled by the fan and a condenser that is in the flow of liquids from the collection basin to the industrial process and in the flow of liquids from the industrial process to the cooling tower, and wherein each programmable motor controller has a data storage resource for storing the predetermined motor deceleration operation curve having a predetermined negative ramp rate, and wherein the method further comprises the steps of:

utilizing a plurality of variable speed pumps to (i) pump the liquids from the collection basin to the condenser, (ii) pump liquids from the condenser to the industrial process, (iii) pump liquids from the industrial process back to the condenser, and (iv) pump liquids from the condenser to the cooling tower, each variable speed pump comprising a permanent magnet motor; and

providing power signals, in accordance with the predetermined motor deceleration operation curve, to the permanent magnet motors of the variable speed pumps so as to decrease the speed of the permanent magnet motors of the pumps to 0.0 RPM.

34. A method for de-icing a cooling tower having a fan that cools liquids in an industrial process, the method comprising the steps of:

utilizing a direct-drive variable speed permanent magnet motor to rotate the fan at a rotational speed;

utilizing a variable process control system that comprises a programmable motor controller for providing power signals to the direct-drive variable speed permanent magnet motor to effect either forward or reverse operation of the motor, the variable process control system further comprising a computer system in communication with the programmable motor controller, the computer system having a data storage resource for storing (i) cooling tower design parameters, and (ii) historical environmental

stress data corresponding to the geographical location of the cooling tower;

providing current environmental stress data to the computer system;

processing the current environmental stress data, the cooling tower design parameters and the historical environmental stress data to determining if a de-icing should be implemented; and

providing power signals to the direct-drive variable speed permanent magnet motor to effect reverse operation of the permanent magnet motor so as to effect reverse operation of the fan if the processing of the current environmental stress data, the cooling tower design parameters and the historical environmental stress data to determine that de-icing is to be implemented.

35. The method according to claim 34 further comprising the step of maintaining reverse rotation of the permanent magnet motor for a predetermined amount of time.

36. A method for operating a fan in a cooling tower comprising the steps of:

utilizing a direct-drive variable speed motor, permanent magnet motor to rotate the fan;

utilizing a variable process control system comprising a computer system and a programmable motor controller in electronic signal communication with the computer

system, wherein the programmable motor controller provides power signals to the variable speed motor, permanent magnet motor that accelerate or decelerate the rotational speed of the permanent magnet motor and wherein the programmable motor controller outputs signals for input to the computer system which represent the speed of the permanent magnet motor; and

utilizing the programmable motor controller to detect the rotational speed of the permanent magnet motor and whether the permanent magnet motor is operating in a forward or reverse direction.

37. The method according to claim 36 further comprising the steps of accelerating the motor rotational speed to a desired motor speed in within a first time duration if the detected motor rotational speed was 0.0 RPM.

38. The method according to claim 36 wherein if it is detected than the motor is rotating in reverse, then the method further comprises the steps of:

using a first rate of acceleration to cause deceleration of the motor rotational speed to 0.0 RPM; and

accelerating the motor rotational speed to a first determined rotational speed in a second time duration that is less than the first time duration.

39. The method according to claim 36 wherein if it is detected than the motor is rotating in the forward direction, then the method further comprises the step of using the first rate of acceleration to accelerate the motor rotational speed to the first determined rotational speed in a time duration that is less than the first time duration.

40. The method according to claim 39 wherein if it is detected that the motor rotational speed is greater than the first predetermined rotational speed, then method further comprises the step of using a first rate of deceleration to decelerate the motor rotational speed to the first predetermined rotational speed.

41. A variable process control system for a cooling tower having a fan that cools liquid used in an industrial process, the variable process control system comprising:

a variable speed permanent magnet motor having a rotatable shaft connected to the fan to rotate the fan;

a plurality of variable speed pumps to pump the liquids from the cooling tower to the industrial process and then back to the cooling tower, wherein each variable speed pump comprises a permanent magnet motor and sensor devices for providing pump status signals;

a plurality of programmable motor controllers, each of which providing power signals to a corresponding permanent magnet motor and outputting motor status signals that

represent the speed and torque of each permanent magnet motor;

sensor devices for measuring the flow rate of liquids flowing through the variable speed pumps and measuring plenum pressure;

a computer system in electronic communication with the programmable motor controllers and the pump status signals, the computer system includes a data storage resource for storing reference data representing operational characteristics of the permanent magnet motors and the programmable motor controllers, at least one fan speed curve, cooling tower design parameters, environmental stress, fan aerodynamic properties including fan pitch, fan balance data, and fan vibration signatures, wherein the computer system is programmed to process the measured flow rate to determine the process demand and then process determined process demand, the measured plenum pressure, the fan pitch and the rotational speed and torque of the fan to determine to determine mass airflow produced by the fan.

42. The variable process control system according to claim 1 wherein the computer system comprises:

a data acquisition and signal processing device; and

an industrial computer in communication with the data acquisition and signal processing device.

43. The variable process control system according to claim 41 wherein the computer system is programmed to determine if the mass airflow produced by the fan is sufficient to meet the determined process demand.

44. The variable process control system according to claim 42 wherein the computer system is programmed to automatically issue control signals to the programmable motor controller corresponding to the permanent magnet motor that drives the fan to increase the rotational speed of the fan if the current mass airflow is not sufficient to meet the determined process demand.

45. The variable process control system according to claim 41 wherein cooling tower includes a collection basin for receiving liquids cooled by the fan and wherein a condenser is in the flow of liquids from the collection basin to the industrial process and in the flow of liquids from the industrial process to the cooling tower, the variable process control system further comprising:

means for providing a condenser temperature set-point to the computer system; and

wherein the computer system is further programmed to calculate a collection basin

temperature that is based on the provided condenser temperature set-point and

generate motor control signals for input to the programmable motor controllers to

adjust the speed of the permanent magnet motors so as to adjust the fan rotational

speed and the flow of liquids through the variable speed pumps in order to maintain

the actual collection basin temperature at a temperature that is substantially the same as the determined collection basin temperature.

46. The variable process control system according to claim 45 further comprising at least one temperature sensor in communication with the computer system for continuously measuring the actual collection basin temperature.

47. The variable process control system according to claim 46 wherein the computer system is further programmed to process the measured actual collection basin temperature.

48. The variable process control system according to claim 46 wherein computer system is programmed to calculate the collection basin temperature.

49. The variable process control system according to claim 41 wherein the data storage resource has stored therein historical process demand data and historical environmental stress data, the computer system being further programmed to:

process the current process demand data and environmental stress data and the historical process demand data and environmental stress data with a Runge-Kutter algorithm to generate a fan speed curve that defines fan speed over a predetermined amount of time wherein variations in fan speed occur in relatively small increments over the predetermined amount of time; and

generate control signals for the programmable motor controllers to control the speed of the direct-drive variable speed permanent magnet motor in accordance with the generated fan speed curve.

50. The variable process control system according to claim 49 wherein the computer system is further programmed to generate control signals to the programmable motor controllers to control the rotational speed of the permanent magnet motors of the variable speed pumps in accordance with the rotational speeds defined by the generated fan speed curve.

51. The variable process control system according to claim 41 wherein the direct-drive, variable speed motor, permanent magnet motor comprises a housing having an interior, a stator and rotor within the interior and bearings within the interior.

52. The variable process control system according to claim 51 further comprising at least one sensor for measuring the temperature of the motor housing, and wherein the computer system is programmed to determine if the measured temperature of the motor housing exceeds a motor housing temperature threshold, and generate an alert signal if the measured motor housing temperature exceeds the motor housing temperature threshold.

53. The variable process control system according to claim 52 further comprising means for routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

54. The variable process control system according to claim 51 further comprising at least one sensor device for measuring the temperatures of the interior and the stator, and wherein the computer system is programmed to determine if the measured temperature of the stator exceeds a predetermined stator temperature threshold, determine if the measured temperature of the interior exceeds a predetermined interior temperature threshold and generate an alert signal if the measured interior temperature exceeds the interior threshold temperature or if the measure stator temperature exceeds the stator threshold temperature.

55. The variable process control system according to claim 54 further comprising means for routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

56. The variable process control system according to claim 55 further comprising sensors for measuring the temperatures of the bearings, and wherein the computer system is programmed to determine if the measured temperature of the bearings exceeds a predetermined bearing temperature threshold, and generate an alert signal if the measured bearing temperature exceeds the bearing threshold temperature.

57. The variable process control system according to claim 56 further comprising means for routing the alert signal to a plant distributed control system in order to alert the operators of the industrial process.

58. The variable process control system according to claim 51 further comprising sensors for measuring vibrations at the motor, and wherein the computer system is programmed to process the measured vibrations and determine if the measured vibrations match any of the stored reference vibration signatures, and generate an alert signal if the measured vibrations match any of the stored reference vibration signatures.

59. The variable process control system according to claim 58 wherein the computer system is programmed to process the measured vibrations further comprises the step of processing the measured vibrations with a Fast Fourier Transform.

60. The variable process control system according to claim 58 wherein the sensors measure the vibrations at the motor housing.

61. The variable process control system according to claim 58 wherein the sensors measure vibrations at the bearings.

62. The variable process control system according to claim 58 wherein the stored reference vibration signatures include predetermined vibration signatures that correspond to impending failure of the fan or the direct-drive, variable speed, permanent magnet motor, and wherein the computer system is programmed to determine if the measured vibrations match any of the predetermined vibration signatures, and generate an alert signal if the measured vibrations match any of the predetermined vibration signatures.

63. A high torque, low speed permanent magnet motor, comprising:
- a motor housing;
  - a stator within the housing;
  - a rotor within the housing;
  - a shaft connected to the rotor which rotates with the rotor; and
  - a bearing system comprising a pair of radial bearings that locate and support the shaft relative to the motor housing, the pair of radial bearings comprising a cylindrical roller bearing and a tapered roller output bearing.
64. The high torque, low speed permanent magnet motor according to claim 63 wherein the bearing system further comprises a spherical thrust bearing which provides only axial locating forces.
65. The high torque, low speed permanent magnet motor according to claim 63 wherein the shaft penetrates and extends from the motor housing, the high torque, low speed permanent magnet motor further comprising a sealing system to seal the area where the shaft penetrates the motor housing, the sealing system comprising:
- a double radial lip seal; and
  - an Inpro™ seal mounted immediately outboard of the double radial lip seal.
66. The high torque, low speed permanent magnet motor according to claim 63 wherein the

motor housing has no more than four longitudinally extending channels in the peripheral portion of the motor housing for receiving mounting bolts.

67. The high torque, low speed permanent magnet motor according to claim 63 further comprising a quick-disconnect connector connected to the exterior of the motor housing, the quick-disconnect connector having signal connection section located within the interior of the motor housing.

68. The high torque, low speed permanent magnet motor according to claim 67 further comprising a plurality of temperature and vibration sensors wired to the signal connection section of the quick-disconnect connector.