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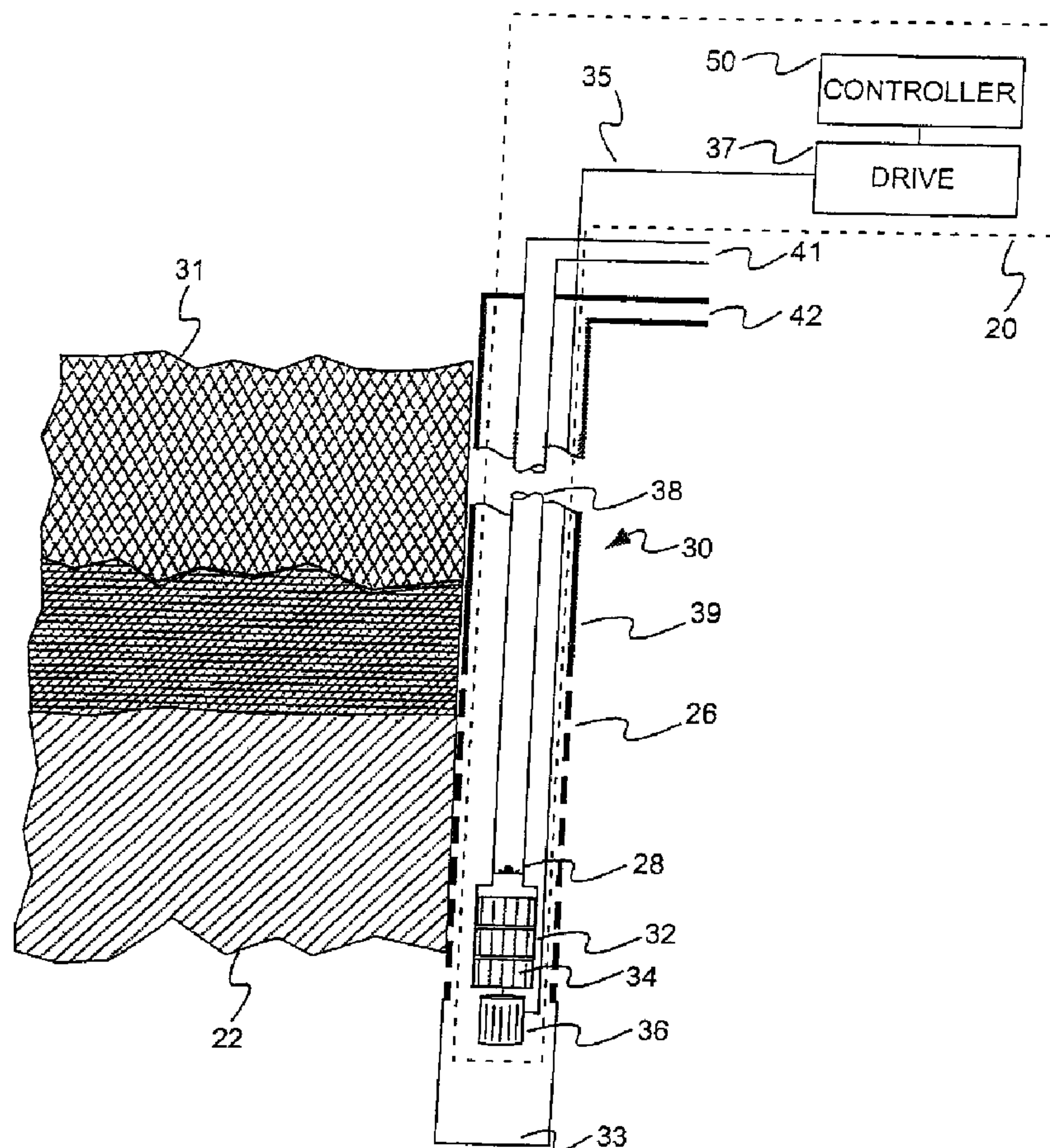
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(54) Titre : SYSTÈME DE COMMANDE DE POMPES CENTRIFUGES

(54) Title: CONTROL SYSTEM FOR CENTRIFUGAL PUMPS



(57) Abrégé/Abstract:

A control system for the operation of a centrifugal pump which may be used for production of gas and/or oil from a well. The control system includes vector feedback model to derive values of torque and speed from signals indicative of instantaneous current and



(57) **Abrégé(suite)/Abstract(continued):**

voltage drawn by the pump motor, a pump model which derives values of the fluid flow rate and the head pressure for the pump from torque and speed inputs, a pumping system model that derives from the estimated values of the pump operating parameters an estimated value of a pumping system parameter and controllers responsive to the estimated values of the pumping system parameters to control the pump to maintain fluid level at the pump input near an optimum level.

CONTROL SYSTEM FOR CENTRIFUGAL PUMPS**ABSTRACT OF THE DISCLOSURE**

A control system for the operation of a centrifugal pump which may be used for production of gas and/or oil from a well. The control system includes vector feedback model to derive values of torque and speed from signals indicative of instantaneous current and voltage drawn by the pump motor, a pump model which derives values of the fluid flow rate and the head pressure for the pump from torque and speed inputs, a pumping system model that derives from the estimated values of the pump operating parameters an estimated value of a pumping system parameter and controllers responsive to the estimated values of the pumping system parameters to control the pump to maintain fluid level at the pump input near an optimum level.

CONTROL SYSTEM FOR CENTRIFUGAL PUMPS

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BACKGROUND OF THE INVENTION

[0002] Field of the Invention -- The present
invention relates generally to pumping systems, and
more particularly, to methods for determining
operating parameters and optimizing the performance of
centrifugal pumps, which are rotationally driven and
characterized by converting mechanical energy into
hydraulic energy through centrifugal activity.

[0003] Centrifugal pumps are used for transporting
fluids at a desired flow and pressure from one
location to another, or in a recirculating system.
Examples of such applications include, but are not
limited to: oil, water or gas wells, irrigation
systems, heating and cooling systems, multiple pump
systems, wastewater treatment, municipal water
treatment and distribution systems.

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[0004] In order to protect a pump from damage or to optimize the operation of a pump, it is necessary to know and control various operating parameters of a pump. Among these are pump speed, pump torque, pump efficiency, fluid flow rate, minimum required suction head pressure, suction pressure, and discharge pressure.

[0005] Sensors are frequently used to directly measure pump operating parameters. In many applications, the placement required for the sensor or sensors is inconvenient or difficult to access and may require that the sensor(s) be exposed to a harmful environment. Also, sensors add to initial system cost and maintenance cost as well as decreasing the overall reliability of the system.

[0006] Centrifugal pumping systems are inherently nonlinear. This presents several difficulties in utilizing traditional closed-loop control algorithms, which respond only to error between the parameter value desired and the parameter value measured. Also, due to the nature of some sensors, the indication of the measured parameter suffers from a time delay, due to averaging or the like. Consequently, the non-linearity of the system response and the time lag induced by the measured values makes tuning the control loops very difficult without introducing system instability. As such, it would be advantageous to predict key pump parameters and utilize each in a feed forward control path, thereby improving controller response and stability and reducing sensed parameter time delays.

[0007] As an example, in a methane gas well, it is typically necessary to pump water off to release trapped gas from an underground formation. This

process is referred to as dewatering, where water is a byproduct of the gas production. The pump is operated to control the fluid level within the well, thereby maximizing the gas production while minimizing the energy consumption and water byproduct.

[0008] As another example, in an oil well, it is desirable to reduce the fluid level above the pump to lower the pressure in the casing, thereby increasing the flow of oil into the well and allowing increased production. This level is selected to reduce the level as much as possible while still providing sufficient suction pressure at the pump inlet. The minimum required suction head pressure of a pump is a function of its design and operating point.

[0009] Typically, centrifugal pumps are used for both oil and gas production. Generally, the fluid level is sensed with a pressure sensor inserted near the intake or suction side of the pump, typically 1000 to 5000 feet or more below the surface. These downhole sensors are expensive and suffer very high failure rates, necessitating frequent removal of the pump and connected piping to facilitate repairs.

[0010] As fluid is removed, the level within the well drops until the inflow from the formation surrounding the pump casing equals the amount of fluid being pumped out. The pump flow rate may be reduced to prevent the fluid level from dropping too far. At a given speed and flow, there is a minimum suction pressure which must be met or exceeded to prevent a condition that could be damaging to the pump.

[0011] Accordingly, it is common practice to monitor the fluid level within the well and control the operation of the pump to prevent damage. This requires the use of downhole sensors.

[0012] Downhole sensors are characterized by cost, high maintenance and reliability problems. Likewise, the need for surface flow sensors adds cost to the pump system. The elimination of a single sensor
5 improves the installation cost, maintenance cost and reliability of the system.

[0013] Also, centrifugal pumps are inefficient when operating at slow speeds and/or flows, wasting electrical power. Therefore, there is a need for a
10 method which would provide reduced flow without sacrificing overall efficiency.

[0014] Accordingly, it is an objective of the invention to provide a method for estimating the flow and pressure of a centrifugal pump without the use of
15 down hole sensors. Another objective of the invention is to provide a method for determining pump suction pressure and/or fluid levels in the pumping system using the flow and pressure of a centrifugal pump combined with other pumping system parameters.
20 Another objective of the invention is to provide a method for using closed loop control of suction pressure or fluid level to protect the pump from damage due to low or lost flow. Another objective of the invention is to provide a method for improving the
25 dynamic performance of closed loop control of the pumping system. Other objectives of the invention are to provide methods for improving the operating flow range of the pump, for using estimated and measured system parameters for diagnostics and preventive
30 maintenance, for increasing pumping system efficiency over a broad range of flow rates, and for automatically controlling the casing fluid level by adjusting the pump speed to maximize gas production from coal bed methane wells.

[0015] The apparatus of the present invention must also be of construction which is both durable and long lasting, and it should also require little or no maintenance by the user throughout its operating
5 lifetime. In order to enhance the market appeal of the apparatus of the present invention, it should also be of inexpensive construction to thereby afford it the broadest possible market. Finally, it is also an objective that all of the aforesaid advantages and
10 objectives be achieved without incurring any substantial relative disadvantage.

SUMMARY OF THE INVENTION

[0016] The disadvantages and limitations of the
15 background art discussed above are overcome by the present invention. With this invention, there is provided a method of continuously determining operational parameters of a down hole pump used in oil, water or gas production. In one embodiment,
20 wherein the pump is a centrifugal pump, the pump is rotationally driven by an AC electrical drive motor having a rotor coupled to the pump for rotating the pump element. In deep wells, it is common practice to use an AC electrical drive motor designed to operate
25 at voltages that are several times that of conventional industrial motors. This allows the motors to operate at lower currents, thereby reducing losses in the cable leading from the surface to the motor. In those cases, a step up transformer can be used at
30 the surface to boost the typical drive output voltages to those required by the motor.

[0017] The method comprises the steps of continuously measuring above ground the electrical voltages applied to the cable leading to the drive

motor to produce electrical voltage output signals;
continuously measuring above ground the electrical
currents applied to the drive motor through the cable
to produce electrical current output signals; using a
5 mathematical model of the cable and motor to derive
values of instantaneous electrical torque from the
electrical voltage output signals and the electrical
current output signals; using a mathematical model of
the cable and motor to derive values of instantaneous
10 motor velocity from the electrical voltage output
signals and the electrical current output signals; and
using mathematical pump and system models and the
instantaneous motor torque and velocity values to
calculate instantaneous values of operating parameters
15 of the centrifugal pump system. In systems using a
step up transformer, electrical voltages and currents
can be measured at the input to the step up
transformer and a mathematical model of the step up
transformer can be used to calculate the voltages and
20 currents being supplied to the cable leading to the
motor. In one embodiment, the method is used for
calculating pump flow rate, head pressure, minimum
required suction head pressure, suction pressure, and
discharge pressure. In another embodiment, used when
25 accurate calculation of pump flow rate is difficult or
impossible, the flow rate is measured above ground in
addition to determining the motor currents and motor
voltages, and the method is used to calculate head
pressure, minimum required suction head pressure,
30 suction pressure, and discharge pressure.

[0018] The invention provides a method of deriving
pump flow rate and head pressure from the drive motor
and pumping unit parameters without the need for
external instrumentation, and in particular, down hole

sensors. The self-sensing control arrangement provides nearly instantaneous readings of motor velocity and torque which can be used for both monitoring and real-time, closed-loop control of the centrifugal pump. In addition, system identification routines are used to establish parameters used in calculating performance parameters that are used in real-time closed-loop control of the operation of the centrifugal pump.

10 [0019] In one embodiment, wherein the operating parameters are pump head pressure and flow rate, the method includes the steps of using the calculated value of the flow rate at rated speed of the pump under the current operating conditions and the instantaneous value of motor speed to obtain pump efficiency and minimum required suction head pressure. The present invention includes the use of mathematical pump and system models to relate motor torque and speed to pump head pressure, flow rate and system operational parameters. In one embodiment, this is achieved by deriving an estimate of pump head pressure and flow rate from motor currents and voltage measurements which are made above ground. The results are used to control the pump to protect the pump from damage, to estimate system parameters, diagnose pumping system problems and to provide closed-loop control of the pump in order to optimize the operation of the pump. Protecting the pump includes detecting blockage, cavitation, and stuck pump. Comparisons of calculated flow estimates and surface flow measurements can detect excess pump wear, flow blockage, and tubing leaks.

[0020] The operation of a centrifugal pump is controlled to enable the pump to operate periodically,

such that the pump can achieve a broad average flow range while maintaining high efficiency. This obviates the need to replace a centrifugal pump with another pump, such as a rod beam pump, when fluid
5 level or flow in the well decreases over time. In accordance with another aspect of the invention, a check valve is used to prevent back flow during intervals in which the pump is turned off.

[0021] In accordance with a further aspect of the
10 invention, an optimizing technique is used in the production of methane gas wherein it is necessary to pump water off an underground formation to release the gas. The optimizing technique allows the fluid level in the well to be maintained near an optimum level in
15 the well and to maintain the fluid at the optimum level over time by controlling pump speed to raise or lower the fluid level as needed to maintain the maximum gas production.

[0022] This is done by measuring and/or calculating
20 fluid flow, gas flow, casing gas pressure, and fluid discharge pressure at the surface. Selected fluid levels are used to define a sweet zone. This can be done manually or using a search algorithm. The search algorithm causes the fluid level to be moved up and
25 down, searching for optimum performance. The search algorithm can be automatically repeated at preset intervals to adjust the fluid level to changing well conditions.

[0023] Uses of the self-sensing pump control system
30 also include, but are not limited to HVAC systems, multi-pump control, irrigation systems, wastewater systems, and municipal water systems.

The invention in a broad aspect pertains to a method of measuring the performance of a centrifugal pump for extracting fluid from a subterranean wellbore, the centrifugal pump being directly coupled to an electrical motor, wherein both the centrifugal pump and the electrical motor are disposed near the bottom of the wellbore, and wherein the motor receives electrical power through a motor cable extending from the motor to a point above the surface of the earth. The method comprises the steps of determining a value of speed input to the centrifugal pump, determining a value of pump flow rate, and using the value of speed input and the value of pump flow rate to calculate one or more values representing the performance of the centrifugal pump, wherein the values of speed input and pump flow rate are derived without the use of any sensor disposed within the wellbore and without having any sensing lines extending to the motor through the wellbore.

The step of determining the speed input to the centrifugal pump comprises the steps of measuring values of electrical voltages applied to the motor cable and currents drawn by the motor cable, using the values of electrical voltages applied to the motor cable and currents drawn by the motor cable to determine values of a stator voltage vector, a stator current vector and a rotor flux vector, and using the values of the stator voltage vector, the stator current vector, the rotor flux vector and a model of the motor, the model being executed by a controller, to calculate a value for the motor speed. The method may also use the value of speed input to the centrifugal pump and the value of torque input to the centrifugal pump to calculate a value for at least one of the parameters selected from the group consisting of the motor torque and the motor speed.

DESCRIPTION OF THE DRAWINGS

[0024] These and other advantages of the present invention are best understood with reference to the drawings, in which:

5 [0025] FIG. 1 is a simplified representation of a well including a centrifugal pump, the operation of which is controlled by a pump control system in accordance with the present invention;

[0026] FIG. 2 is a block diagram of the centrifugal
10 pump control system of FIG. 1;

[0027] FIG. 3 is a functional block diagram of a pump control system for the centrifugal pump of FIG. 1 when using estimated flow;

[0028] FIG. 4 is a functional block diagram of a
15 pump control system for the centrifugal pump of FIG. 1 when using measured flow;

[0029] FIG. 5 is a block diagram of an algorithm for a pump model of the centrifugal pump control system of FIG. 3;

20 [0030] FIG. 6 is a block diagram of an algorithm for a pump model of the centrifugal pump control system of FIG. 4;

[0031] FIG. 7 is a block diagram of an algorithm for a system model of the centrifugal pump control
25 system of FIGS. 3 and 4;

[0032] FIG. 8 is a block diagram of an algorithm for a fluid level feedforward controller of the centrifugal pump control system of FIGS. 3 and 4;

[0033] FIG. 9 is a block diagram of an algorithm
30 for a fluid level feedback controller of the centrifugal pump control system of FIGS. 3 and 4;

[0034] FIG. 10 is a simplified block diagram of an algorithm for a vector controller of the centrifugal pump control system of FIGS. 3 and 4;

[0035] FIGS. 11 through 13 are a set of pump specification curves for a centrifugal pump, illustrating pump power, pump head, pump efficiency and pump suction pressure required wherein each is a function of pump flow rate at rated speed;

[0036] FIG. 14 is a diagram of a typical installation of a centrifugal pump, illustrating the relationship between the pumping system parameters;

[0037] FIG. 15 is a block diagram of the controller of the pump control system of FIGS. 3 and 4; and

[0038] FIG. 16 is a set of two curves comparing the efficiency of a pumping system using duty cycle control to the efficiency of a pumping system using continuous rotary speed.

[0039] Variables used throughout the drawings have the following form: A variable with a single subscript indicates that the reference is to an actual element of the system as in T_m for the torque of the motor or a value that is known in the system and is stable as in X_p for the depth of the pump. A variable with a second subscript of 'm', as in V_{mm} for measured motor voltage, indicates that the variable is measured on a real-time basis. Similarly, a second subscript of 'e' indicates an estimated or calculated value like T_{me} for estimated motor torque; a second subscript of 'c' indicates a command like V_{mc} for motor voltage command; and a second subscript of 'f' indicates a feedforward command like U_{mf} for motor speed feedforward command. Variables in bold type, as in V_s for stator voltage, are vector values having both magnitude and direction.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0040] Referring to FIG. 1, the present invention is described with reference to an oil well 30 wherein oil is to be pumped from an underground formation 22. The well includes an outer casing 39 and an inner tube 38 that extend from ground level to as much as 1000 feet or more below ground level. The casing 39 has perforations 26 to allow the fluid in the underground formation to enter the well bore. It is to be understood that water and gas can be combined with oil and the pump can be used for other liquids. The control apparatus can also be used for pumping water only. The bottom of the tube generally terminates below the underground formations.

[0041] A centrifugal pump of the type known as an electric submersible pump (ESP) 32 is mounted at the lower end of the tube 38 and includes one or more centrifugal pump members 34 mounted inside a pump housing. The pump members are coupled to and driven by a drive motor 36 which is mounted at the lower end of the pump housing. The tube 38 has a liquid outlet 41 and the casing 39 has a gas outlet 42 at the upper end above ground level 31. An optional check valve 28 may be located on the discharge side of the pump 32 to reduce back flow of fluid when the pump is off. These elements are shown schematically in FIG. 1.

[0042] The operation of the pump 32 is controlled by a pump control system and method including a parameter estimator in accordance with the present invention. For purposes of illustration, the pump control system 20 is described with reference to an application in a pump system that includes a conventional electric submersible pump. The electric

submersible pump includes an electric drive system 37 connected to motor 36 by motor cables 35. A transformer (not shown) is sometimes used at the output of the drive to increase voltage supplied to the motor. The motor rotates the pump elements that are disposed near the bottom 33 of the well. The drive 37 receives commands from controller 50 to control its speed. The controller 50 is located above ground and contains all the sensors and sensor interface circuitry and cabling necessary to monitor the performance of the pump system.

[0043] The motor 36 can be a three-phase AC induction motor designed to be operated from line voltages in the range of 230 VAC to several thousand VAC and developing 5 to 500 horsepower or higher, depending upon the capacity and depth of the pump.

Pump Control System

[0044] Referring to FIG. 2, there is shown a simplified representation of the pump control system 20 for the pump 32. The pump control system 20 controls the operation of the pump 32. In one embodiment, the casing fluid level is estimated using pump flow rate and head pressure estimates which, in turn, can be derived from values of motor speed and torque estimates. The pump flow rate and head pressure estimates are combined with system model parameters to produce a casing fluid level estimate. In one preferred embodiment, a pump model and system model are used to produce estimated values of pump flow rate and casing fluid level for use by a pump controller in producing drive control signals for the pump 32.

[0045] Alternatively, the measured discharge flow rate of the pump 32 can be obtained using measurements from the surface flow sensor 59 and combined with the estimates produced by the pump and system models to
5 produce the casing fluid level estimate. This is particularly useful when the configuration of the pump makes it difficult to accurately calculate pump flow rate from the mechanical inputs to the pump.

[0046] While in a primary function the estimated
10 parameters are used for control, the parameters also can be used for other purposes. For example, the estimated parameters can be compared with those measured by sensors or transducers for providing diagnostics alarms. The estimated parameters may also
15 be displayed to setup, maintenance or operating personnel as an aid to adjusting or troubleshooting the system.

[0047] In one embodiment, values of flow and pressure parameters are derived using measured or
20 calculated values of instantaneous motor currents and voltages, together with pump and system parameters, without requiring down hole sensors, fluid level meters, flow sensors, etc. The flow and pressure parameters can be used to control the operation of the
25 pump 32 to optimize the operation of the system. In addition, pump performance specifications and system identification routines are used to establish parameters used in calculating performance parameters that are used in real time closed-loop control of the
30 operation of the pump.

[0048] The pump control system 20 includes transducers, such as above ground current and voltage sensors, to sense dynamic variables associated with motor load and velocity. The pump control system

further includes a controller 50, a block diagram of which is shown in FIG. 2. Above ground current sensors 51 of interface devices 140 are coupled to a sufficient number of the motor cables 35, two in the
5 case of a three phase AC motor. Above ground voltage sensors 52 are connected across the cables leading to the motor winding inputs. The current and voltage signals produced by the sensors 51 and 52 are supplied to a processing unit 54 of the controller 50 through
10 suitable input/output devices 53. The controller 50 further includes a storage unit 55 including storage devices which store programs and data files used in calculating operating parameters and producing control signals for controlling the operation of the pump
15 system. This self-sensing control arrangement provides nearly instantaneous estimates of motor velocity and torque, which can be used for both monitoring and real-time, closed-loop control of the pump. For example, in one embodiment, instantaneous
20 estimates of motor velocity and torque used for real-time, closed-loop control are provided at the rate of about 1000 times per second.

[0049] Motor currents and voltages are sensed or calculated to determine the instantaneous speed and
25 torque produced by the electric motor operating the pump. As the centrifugal pump 32 is rotated, the motor 36 is loaded. By monitoring the motor currents and voltages above ground, the calculated torque and speed produced by the motor 36, which may be below
30 ground, are used to calculate estimates of fluid flow and head pressure produced by the pump 32.

[0050] More specifically, interface devices 140 include the devices for interfacing the controller 50 with the outside world. None of these devices are

located below ground. Sensors in blocks 51 and 52 can include hardware circuits which convert and calibrate the current and voltage signals into current and flux signals. After scaling and translation, the outputs
 5 of the voltage and current sensors can be digitized by analog to digital converters in block 53. The processing unit 54 combines the scaled signals with cable and motor equivalent circuit parameters stored in the storage unit 55 to produce a precise
 10 calculation of motor torque and motor velocity. Block 59 contains an optional surface flow meter which can be used to measure the pump flow rate. Block 59 may also contain signal conditioning circuits to filter and scale the output of the flow sensor before the
 15 signal is digitized by analog to digital converters in block 53.

Pump Control

[0051] Referring to FIG. 3, which is a functional
 20 block diagram of the pump control system 20 for a pump 32 where the pump flow rate to pump power relationship allows pump flow rate to be calculated, the pump 32 is driven by a drive 37 and motor 36 to transfer fluid within a system 150. The operation of the motor 36 is
 25 controlled by the drive 37 and controller 50 which includes a pump model 60, system model 80, fluid level feedforward controller 90, fluid level feedback controller 100, motor vector controller 130 and interface devices 140.

30 [0052] More specifically, block 140, which is located above ground, can include hardware circuits which convert and calibrate the motor current signals I_m (consisting of individual phase current measurements I_{um} and I_{vm} in the case of a three phase

motor) and voltage signals V_m (consisting of individual phase voltage measurements V_{um} , V_{vm} , and V_{wm} in the case of a three phase motor) into motor current and flux signals. After scaling and translation, the outputs of the voltage and current sensors can be digitized by analog to digital converters into measured voltage signals V_{mm} and measured current signals I_{mm} . The motor vector controller 130 combines the scaled signals with cable and motor equivalent circuit parameters to produce a precise calculation of motor electrical torque T_{me} and velocity U_{me} . Automatic identification routines can be used to establish the cable and motor equivalent circuit parameters.

15 [0053] The pump model 60 calculates the values of parameters, such as pump flow rate Q_{pe} , pump head pressure H_{pe} , pump head pressure at rated speed H_{re} , minimum required suction head pressure H_{se} , pump efficiency E_{pe} , and pump safe power limit P_{le} relating to operation of the pump 32 from inputs corresponding to motor torque T_{me} and motor speed U_{me} without the need for external flow or pressure sensors. This embodiment is possible for pumps where the relationship of pump flow rate to pump power at rated speed, as shown in FIG. 13, is such that each value of power has only one unique value of pump flow rate associated with it throughout the range of pump flows to be used. Further, the system model 80 derives estimated values of the pump suction pressure P_{se} , flow head loss H_{fe} , pump discharge pressure P_{de} and the casing fluid level X_{ce} from inputs corresponding to discharge flow rate value Q_{pe} and the head pressure value H_{pe} of the pump. The fluid level feedforward controller 90 uses the pump head pressure at rated

speed value Hre, flow head loss value Hfe and
 commanded fluid level Xcc to calculate a motor speed
 feedforward command Umf. The fluid level feedback
 controller 100 compares the commanded fluid level Xcc
 5 with static and dynamic conditions of the fluid level
 value Xce to calculate a motor velocity feedback
 command Ufc. Motor velocity feedback command Ufc and
 feedforward command Umf are added in summing block 79
 to yield the motor velocity command Umc.

10 [0054] Motor vector controller 130 uses the motor
 speed command Umc to generate motor current commands
 Imc and voltage commands Vmc. Interface devices in
 block 140, which can be digital to analog converters,
 convert the current commands Imc and voltage commands
 15 Vmc into signals which can be understood by the drive
 37. These signals are shown as Ic for motor current
 commands and Vc for motor winding voltage commands.
 In installations with long cables and/or step up
 transformers, the signals Ic and Vc would be adjusted
 20 to compensate for the voltage and current changes in
 these components.

[0055] Referring to FIG. 4, which is a functional
 block diagram of the pump control system 20 for a pump
 32 where the pump flow rate is measured above ground,
 25 the pump 32 is driven by a drive 37 and motor 36 to
 transfer fluid within a system 150. The operation of
 the motor 36 is controlled by the drive 37 and
 controller 50 which includes a pump model 260, system
 model 80, fluid level feedforward controller 90, fluid
 30 level feedback controller 100, motor vector controller
 130 and interface devices 140.

[0056] More specifically, block 140, which is
 located above ground, can include hardware circuits
 which convert and calibrate the motor current signals

Im (consisting of individual phase current measurements Ium and Ivm in the case of a three phase motor) and voltage signals Vm (consisting of individual phase voltage measurements Vum, Vvm, and Vwm in the case of a three phase motor) into motor current and flux signals. After scaling and translation, the outputs of the voltage and current sensors can be digitized by analog to digital converters into measured voltage signals Vmm and measured current signals Imm. The motor vector controller 130 combines the scaled signals with cable and motor equivalent circuit parameters to produce a precise calculation of motor electrical torque Tme and velocity Ume. Automatic identification routines can be used to establish the cable and motor equivalent circuit parameters.

[0057] In this embodiment, block 140 also may contain hardware circuits which convert above ground flow rate into an electrical signal that can be digitized by analog to digital converters into the measured flow signal Qpm for use by the pump model 260 and the system model 80.

[0058] The pump model 260 calculates the values of parameters pump head pressure Hpe, pump head pressure at rated speed Hre, minimum required suction head pressure Hse, pump efficiency Epe, and pump safe power limit Ple relating to operation of the pump 32 from inputs corresponding to flow Qpm as measured by a flow sensor and motor speed Ume without the need for other external sensors. This embodiment is used for pumps where the relationship of pump flow rate to pump power at rated speed is such that there is not a unique pump flow rate for each value of pump power. Further, the system model 80 derives estimated values of the pump

suction pressure P_{se} , flow head loss H_{fe} , pump discharge pressure P_{de} and the casing fluid level X_{ce} from inputs corresponding to discharge flow rate value Q_{pm} and the head pressure value H_{pe} of the pump. The fluid level feedforward controller 90 uses the motor speed value U_{me} , flow head loss value H_{fe} and commanded fluid level X_{cc} to calculate a motor speed feedforward command U_{mf} . The fluid level feedback controller 100 compares the commanded fluid level X_{cc} with static and dynamic conditions of the fluid level value X_{ce} to calculate a motor velocity feedback command U_{fc} . Motor velocity feedback command U_{fc} and feedforward command U_{mf} are added in summing block 79 to yield the motor velocity command U_{mc} .

[0059] Motor vector controller 130 uses the motor speed command U_{mc} to generate motor current commands I_{mc} and voltage commands V_{mc} . Interface devices in block 140, which can be digital to analog converters, convert the current commands I_{mc} and voltage commands V_{mc} into signals which can be understood by the drive 37. These signals are shown as I_c for motor current commands and V_c for motor winding voltage commands. In installations with long cables and/or step up transformers, the signals I_c and V_c would be adjusted to compensate for the voltage and current changes in these components.

[0060] The controller 50 provides prescribed operating conditions for the pump and/or system. To this end, either pump model 60 or pump model 260 also can calculate the efficiency E_{pe} of the pump for use by the controller 50 in adjusting operating parameters of the pump 32 to determine the fluid level X_c needed to maximize production of gas or produced fluid and/or

the fluid level X_c needed to maximize production with a minimum power consumption.

[0061] The controller 50 (FIG. 3 and FIG. 4) uses the parameter estimates to operate the pump so as to minimize energy consumption, optimize gas flow, and maintain the fluid level to accomplish the objectives. Other inputs supplied to the controller 50 include the commanded casing fluid level X_{cc} and values representing casing pressure P_c and tubing pressure P_t (FIG. 8). Values representing casing pressure P_c and tubing pressure P_t may each be preset to approximate values as part of the system setup or, as is preferable in situations where these values are likely to vary during operation of the system, the controller 50 can use values measured by sensors mounted above ground and connected to the controller 50 through appropriate signal conditioning and interface circuitry.

[0062] The controller 50 (FIG. 3 and FIG. 4) optimizes use of electrical power as the flow delivery requirements change and can determine fluid level without using down hole sensors and, in one preferred embodiment, without using surface flow sensors. As will be shown, the control operations provided by the controller 50 include the use of the pump model 60 (FIG. 3) or pump model 260 (FIG. 4) and system model 80 (FIG. 3 or FIG. 4) to relate mechanical pump input to output flow rate and head pressure. In one embodiment (FIG. 3), this is achieved by deriving an estimate of pump flow rate from above ground measurements of motor current and voltage. In another embodiment (FIG. 4), the pump flow rate is measured using a surface flow sensor. From the flow value thus obtained, the pump head pressure, efficiency and other

pump operating parameters are determined using pump curve data. The results are used to control the pump 32 to protect it from damage and to provide closed-loop control of the pump 32 in order to optimize the operation of the pumping system. Protecting the pump 32 includes detecting blockage, cavitation, and stuck pump.

[0063] Moreover, the operation of the pump 32 can be controlled to enable it to operate periodically, such that the pump can operate efficiently at a decreased average pump flow rate. This obviates the need to replace the electric submersible pump with another pump, such as a rod beam pump, when fluid level or inflow within the well decreases over time.

[0064] Further, in accordance with the invention, the pump can be cycled between its most efficient operating speed and zero speed at a variable duty cycle to regulate average pump flow rate. Referring to FIG. 1, in cases where electric submersible pumps are being operated at a low duty cycle, such as on for twenty-five percent of the time and off for seventy-five percent of the time, a check valve 28 may be used down hole to prevent back flow of previously pumped fluid during the portion of each cycle that the pump is off. The check valve 28 can be designed to allow a small amount of leakage. This allows the fluid to slowly drain out of the tube 38 to allow maintenance operations.

30 Pump Model

[0065] Reference is now made to FIG. 5, which is a block diagram of an algorithm for the pump model 60 of the pump 32 as used in the embodiment shown in FIG. 3 where it is possible to calculate an estimate of pump

flow rate. The pump model 60 is used to calculate estimates of parameters including head pressure H_{pe} , fluid flow Q_{pe} , minimum required suction head pressure H_{se} , pump mechanical input power limit P_{le} , and pump efficiency E_{pe} . In one preferred embodiment, the calculations are carried out by the processing unit 54 (FIG. 2) under the control of software routines stored in the storage devices 55 (FIG. 2). Briefly, values of motor torque T_{me} and motor speed U_{me} are used to calculate the mechanical power input to the pump P_{pe} which is used with the motor speed value U_{me} to calculate what the flow Q_{re} would be at rated pump speed U_r . This value of Q_{re} is used with formulas derived from published pump data and pump affinity laws to solve for the pump head at rated speed H_{re} , pump efficiency E_{pe} , and minimum required suction head pressure required H_{se} . Using the value of motor speed U_{me} , the values of pump head at rated speed H_{re} and pump flow rate at rated speed Q_{re} are scaled using pump affinity laws to estimated values of pump head H_{pe} and pump flow rate Q_{pe} , respectively.

[0066] With reference to the algorithm illustrated in FIG. 5, the value for pump mechanical input power P_{pe} is obtained by multiplying the value for motor torque T_{me} by the value of motor speed U_{me} in block 61. In block 62, the mechanical input power applied to the pump, P_{pe} is multiplied by a scaling factor calculated as the cube of the ratio of the rated speed of the pump U_r to the current speed U_{me} to yield a value representing the power P_{re} which the pump would require at rated pump speed U_r . This scaling factor is derived from affinity laws for centrifugal pumps.

[0067] Block 63 derives a value of the pump flow rate Q_{re} at the rated speed with the current

conditions. This value of pump flow rate Q_{re} at rated speed is calculated as a function of power P_{re} at rated speed U_r . Pump manufacturers often provide pump curves such as the one shown in FIG. 13, which relates
5 pump mechanical input power P_p to flow Q_{re} at rated speed. Alternatively, such a curve can be generated from values of pump head as a function of flow at rated speed, pump efficiency as a function of flow at rated speed, and the fluid density. The function of
10 block 63 (FIG. 5) is derived from the data contained in the graph. One of two methods is used to derive the function of block 63 from the data in this graph. The first method is to select data points and use curve fitting techniques, which are known, to generate
15 an equation describing power as a function of flow. Solving the equation so flow is given as a function of power will provide one method of performing the calculation in block 63. One simple method is to fit the data to a second order equation. In the case of a
20 second order equation, the solution for flow is in the form of a quadratic equation which yields two solutions of flow for each value of power. In this case, block 63 must contain a means of selecting flow value Q_{re} from the two solutions. This is usually
25 easy as one of the values will be much less likely than the other, if not impossible as in a negative flow solution. The second method is to select several points on the graph to produce a look-up table of flow versus power. With such a look-up table, it is
30 relatively easy to use linear interpolation to determine values of Q_{re} between data points.

[0068] In block 64, the value for flow at rated speed, Q_{re} , is scaled by the ratio of the current speed U_{me} to the rated speed U_r to yield the pump flow

rate value Q_{pe} . This scaling factor is derived from affinity laws for centrifugal pumps.

[0069] Block 65 calculates a value of head pressure at rated speed H_{re} as a function of flow at rated speed Q_{re} . Pump manufacturers provide pump curves such as the one shown in FIG. 11, which relates pump head pressure to flow at rated speed. The function of block 65 is uses the data contained in the graph. One of two methods is used to derive the function of block 65 from the data in this graph. The first method is to select data points and use curve fitting techniques, which are known, to generate an equation describing pump head pressure as a function of flow. The second method is to select several points on the graph to produce a look-up table of pump head pressure versus flow. With such a look-up table, it is relatively easy to use linear interpolation to determine values of H_{re} between data points. In block 66, the value for pump head pressure at rated speed, H_{re} , is scaled by the square of ratio of the current speed U_{me} to the rated speed U_r to yield the pump head pressure value H_{pe} . This scaling factor is derived from affinity laws for centrifugal pumps.

[0070] The efficiency of the pump is calculated in block 67 to yield the value E_{pe} . Pump efficiency is the ratio of fluid power output divided by mechanical power input. Pump manufacturers provide pump curves such as the one shown in FIG. 12, which relates pump efficiency to pump flow rate at rated speed. The function of block 67 is derived from the data contained in the graph. One of two methods is used to derive the function of block 67 from the data in this graph. The first method is to select data points and use curve fitting techniques, which are known, to

generate an equation describing pump efficiency as a function of flow. The second method is to select several points on the graph to produce a look-up table of pump efficiency versus flow. With such a look-up
5 table, it is relatively easy to use linear interpolation to determine values of E_{pe} between data points.

[0071] An estimate of the suction head pressure required at the input of the pump, H_{se} , is calculated
10 in block 68. Pump manufacturers provide pump curves such as the one shown in FIG. 11, which relates the pump's minimum required suction head pressure H_s to pump flow rate at rated speed. The function of block 68 is derived from the data contained in the graph.
15 One of two methods is used to derive the function of block 68 from the data in this graph. The first method is to select data points and use curve fitting techniques, which are known, to generate an equation describing pump suction pressure required as a
20 function of flow. The second method is to select several points on the graph to produce a look-up table of pump suction pressure required versus pump flow rate. With such a look-up table, it is relatively easy to use linear interpolation to determine values
25 of S_{re} between data points.

[0072] A mechanical input power limit for the pump is calculated in block 69. The end of curve power level P_e as shown in FIG. 13 is scaled by the cube of the ratio of the current speed U_{me} to the rated speed
30 U_r to provide the mechanical input power limit estimate P_{le} . This scaling factor is derived from affinity laws for centrifugal pumps. The mechanical input power limit value can be used to limit the

torque and/or the speed of the pump, and thereby limit power, to levels which will not damage the pump.

[0073] Reference is now made to FIG. 6, which is a block diagram of an algorithm for the pump model 260 of the pump 32 as used in the embodiment shown in FIG. 4 where it is not possible to calculate an estimate of pump flow rate. The pump model 260 is used to calculate estimates of parameters including head pressure H_{pe} , minimum required suction head pressure H_{se} , pump mechanical input power limit P_{le} , and pump efficiency E_{pe} . In one preferred embodiment, the calculations are carried out by the processing unit 54 (FIG. 2) under the control of software routines stored in the storage devices 55 (FIG. 2). Briefly, values of measured fluid flow Q_{pm} and motor speed U_{me} are used to calculate what the flow Q_{re} would be at rated pump speed U_r . This value of flow Q_{re} is used with formulas derived from published pump data and pump affinity laws to solve for the pump head at rated speed H_{re} , pump efficiency E_{pe} , and minimum required suction head pressure required H_{se} . Using the value of motor speed U_{me} , the values of pump head at rated speed H_{re} and pump flow rate at rated speed Q_{re} are scaled using pump affinity laws to estimated values of pump head H_{pe} and pump flow rate Q_{pe} respectively.

[0074] With reference to the algorithm illustrated in FIG. 6, in block 264, the value for measured pump flow rate Q_{pm} is scaled by the ratio of the rated speed of the pump U_r to the speed of the pump U_{me} to derive an estimate of the flow of the pump at rated speed Q_{re} . This scaling factor is derived from affinity laws for centrifugal pumps.

[0075] Block 265 calculates a value of head pressure at rated speed H_{re} as a function of flow Q_{re}

at rated speed U_r . Pump manufacturers provide pump curves such as the one shown in FIG. 11, which relates pump head pressure to flow at rated speed. The function of block 265 is derived from the data
5 contained in the graph. One of two methods is used to derive the function of block 265 from the data in this graph. The first method is to select data points and use curve fitting techniques, which are known, to generate an equation describing pump head pressure as
10 a function of flow. The second method is to select several points on the graph to produce a look-up table of pump head pressure versus flow. With such a look-up table, it is relatively easy to use linear interpolation to determine values of H_{re} between data
15 points. In block 266, the value for pump head pressure at rated speed, H_{re} , is scaled by the square of the ratio of the current speed U_{me} to the rated speed U_r to yield the pump head pressure value H_{pe} . This scaling factor is derived from affinity laws for
20 centrifugal pumps.

[0076] The efficiency of the pump is calculated in block 267 to yield the value E_{pe} . Pump efficiency is the ratio of fluid power output divided by mechanical power input. Pump manufacturers provide pump curves
25 such as the one shown in FIG. 12, which relates pump efficiency to pump flow rate at rated speed. The function of block 267 is derived from the data contained in the graph. One of two methods is used to derive the function of block 267 from the data in this
30 graph. The first method is to select data points and use curve fitting techniques, which are known, to generate an equation describing pump efficiency as a function of flow. The second method is to select several points on the graph to produce a look-up table

of pump efficiency versus flow. With such a look-up table, it is relatively easy to use linear interpolation to determine values of E_p between data points.

5 [0077] An estimate of the suction head pressure required at the input of the pump, H_{se} , is calculated in block 268. Pump manufacturers provide pump curves such as the one shown in FIG. 11, which relates the pump's minimum required suction head pressure H_s to
 10 pump flow rate at rated speed. The function of block 268 is derived from the data contained in the graph. One of two methods is used to derive the function of block 68 from the data in this graph. The first method is to select data points and use curve fitting
 15 techniques, which are known, to generate an equation describing pump suction pressure required as a function of flow. The second method is to select several points on the graph to produce a look-up table of pump suction pressure required versus pump flow
 20 rate. With such a look-up table, it is relatively easy to use linear interpolation to determine values of S_{re} between data points.

[0078] A mechanical input power limit for the pump is calculated in block 269. The end of curve power
 25 level P_e as shown in FIG. 13 is scaled by the cube of the ratio of the current speed U_{me} to the rated speed U_r to provide the mechanical input power limit estimate P_{le} . This scaling factor is derived from affinity laws for centrifugal pumps. The mechanical
 30 input power limit value P_{le} can be used to limit the torque and/or the speed of the pump, and thereby limit power, to levels which will not damage the pump.

System Model

[0079] Reference is now made to FIG. 7, which is a block diagram of an algorithm for the system model 80 of the fluid system 150. The system model 80 is used to calculate estimates of system parameters including pump suction pressure P_{se} , pump discharge pressure P_{de} , head flow loss H_{fe} and casing fluid level X_{ce} . In one preferred embodiment, the calculations are carried out by the processing unit 54 (FIG. 2) under the control of software routines stored in the storage devices 55. FIG. 14 diagrammatically presents the actual reservoir system parameters used in FIG. 5 for the pump 32. P_s is the pump suction pressure, P_d is the pump discharge pressure, H_p is the pump head pressure, H_f is the flow head loss and Q_p is the pump flow rate. L_p is the length of the pump, L_t (not shown) is the length of the tubing from the pump outlet to the tubing outlet, X_p is the pump depth and X_c is the fluid level within the casing 39 (FIG. 1). P_c is the pressure within the casing and P_t is the pressure within the tubing 38. Parameter D_t is the tubing fluid specific weight, parameter D_c is the casing fluid specific weight, and parameter D_p (not shown) is the specific weight of the fluid within the pump.

[0080] Briefly, with reference to FIG. 7, a value representing pump flow rate Q_p (such as measured surface flow rate Q_{pm} or estimated pump flow rate Q_{pe}), pump head pressure estimate H_{pe} , and values of tubing pressure P_t and casing pressure P_c are combined with reservoir parameters of pump depth X_p and pump length L_p to determine pump suction pressure P_{se} and casing fluid level X_{ce} .

[0081] More specifically, the processing unit 54 responds to the value representing pump flow rate Q_p .

This value representing pump flow rate Q_p can be either the value of Q_{pe} produced by the pump model 60, as shown in FIG. 3, or the value of Q_{pm} as shown in FIG. 4 from a surface flow sensor 59 (FIG. 2). This
 5 pump flow rate value is used to calculate a tubing flow head loss estimate H_{fe} in block 81. The head loss equation for H_{fe} presented in block 81 can be derived empirically and fit to an appropriate equation or obtained from well known relationships for
 10 incompressible flow. One such relationship for flow head loss estimate H_{fe} is obtained from the Darcy-Weisbach equation:

$$(1) \quad H_{fe} = f [(L/d) (V^2/2G)]$$

15

where f is the friction factor, L is the length of the tubing, d is the inner diameter of the tubing, V is the average fluid velocity (Q/A , where Q is the fluid flow and A is the area of the tubing), and G is the
 20 gravitational constant. For laminar flow conditions ($Re < 2300$), the friction factor f is equal to $64/Re$, where Re is the Reynolds number. For turbulent flow conditions, the friction factor can be obtained using the Moody equation and a modified Colebrook equation,
 25 which will be known to one of ordinary skill in the art. For non-circular pipes, the hydraulic radius (diameter) equivalent may be used in place of the diameter in equation (1). Furthermore, in situ calibration may be employed to extract values for the
 30 friction factor f in equation (1) by system identification algorithms. Commercial programs that account for detailed hydraulic losses within the tubing are also available for calculation of fluid flow loss factors.

[0082] It should be noted that although fluid velocity V may change throughout the tubing length, the value for fluid velocity can be assumed to be constant over a given range.

5 [0083] The suction pressure P_{se} is calculated by adding the head loss H_{fe} calculated in block 81 with the pump depth X_p and subtracting the pump head pressure H_{pe} in summing block 82. The output of summing block 82 is scaled by the tubing fluid
10 specific weight D_t in block 83 and added to the value representing tubing pressure P_t in summing block 84 to yield the suction pressure P_{se} .

[0084] The pump discharge pressure P_{de} is calculated by scaling the length of the pump L_p by the
15 casing fluid specific weight D_c in block 87. The pump head pressure H_{pe} is then scaled by the pump fluid specific weight D_p in block 88 to yield the differential pressure across the pump, P_{pe} . Pump pressure P_{pe} is then added to the pump suction
20 pressure P_{se} and the negative of the output of scaling block 87 in summing block 89 to calculate the pump discharge pressure P_{de} .

[0085] The casing fluid level X_{ce} is calculated by subtracting casing pressure P_c from the suction
25 pressure P_{se} , calculated in summing block 84, in summing block 85. The result of summing block 85 is scaled by the reciprocal of the casing fluid specific weight D_c in block 86 to yield the casing fluid level X_{ce} .

30 [0086] The casing fluid specific weight D_c , pump fluid specific weight D_p , and tubing fluid specific weight D_t may differ due to different amounts and properties of dissolved gases in the fluid. At reduced pressures, dissolved gases may bubble out of

the fluid and affect the fluid density. Numerous methods are available for calculation of average fluid density as a function of fluid and gas properties which are known in the art.

5

Fluid Level Feedforward Controller

[0087] Referring to FIG. 8, there is shown a process diagram of the fluid level feedforward controller 90. The fluid level feedforward controller 90 uses flow head loss H_{fe} , pump head pressure H_{re} at rated speed and other parameters to produce a motor speed feedforward command U_{mf} to be summed with the motor speed feedback command U_{fc} in summing block 79 (FIG. 3 and FIG. 4) to produce the motor speed command U_{mc} for the motor vector controller 130. This speed signal is based on predicting the pump speed required to maintain desired pressures, flows and levels in the pumping system. Use of this controller reduces the amount of fluid level error in the fluid level feedback controller 100 (FIG. 9), allowing conservative controller tuning and faster closed loop system response.

[0088] More specifically, in scaling block 91, the value of casing pressure P_c is scaled by the inverse of the casing fluid specific weight D_c to express the result in equivalent column height (head) of casing fluid. Similarly, in scaling block 92, the value of tubing pressure P_t is scaled by the inverse of the tubing fluid specific weight D_t to express the result in equivalent column height (head) of tubing fluid. In summing block 93, the negative of the output of block 91 is added to the output of block 92, the pipe head flow loss H_{fe} , the depth of the pump X_p , and the negative of the commanded casing fluid level X_{cc} to

obtain pump head pressure command H_{pc} . The flow head loss H_{fe} is the reduction in pressure due to fluid friction as calculated in block 81 (FIG. 7). The commanded pump head H_{pc} is the pressure that the pump must produce as a result of the inputs to summing block 93. The values of casing pressure P_c and tubing pressure P_t can be measured in real time using above ground sensors in systems where they are variable or fixed for systems where they are relatively constant.

10 The values of pump depth X_p and commanded casing fluid level command X_{cc} are known.

[0089] More specifically, in block 94, the pump speed required to produce the pressure required by the head pressure command H_{pc} is calculated by multiplying the rated speed U_r by the square root of the ratio of the head pressure command H_{pc} to the head pressure at rated speed H_{re} to yield the motor speed feedforward command U_{mf} . The value of head pressure at rated speed H_{re} is calculated by block 65 of FIG. 5 or block 265 of FIG. 6 depending on the specific embodiment.

Fluid Level Feedback Controller

[0090] Reference is now made to FIG. 9, which is a block diagram of a fluid level feedback controller 100 for the motor vector controller 130. The fluid level feedback controller 100 includes a PID (proportional, integral, derivative) function that responds to errors between casing fluid level command X_{cc} and casing fluid level X_{ce} to adjust the speed command for the pump 32. Operation of the fluid level feedforward controller 90 provides a command based on the projected operation of the system. This assures that the errors to which the fluid level feedback

controller 100 must respond will only be the result of disturbances to the system.

[0091] The inputs to the fluid level feedback controller 100 include casing fluid level command X_{cc} and a casing fluid level value X_{ce} . The fluid level command X_{cc} is a known value and is subtracted from the casing fluid level value X_{ce} in block 101 to produce the error signal X_{er} for the fluid level feedback controller 100.

10 [0092] The algorithm of the fluid level feedback controller 100 uses Z-transformations to obtain values for the discrete PID controller. The term Z^{-1} (blocks 102 and 109) means that the value from the previous iteration is used during the current iteration.

15 [0093] More specifically, in summing block 101, an error signal X_{er} is produced by subtracting X_{cc} from X_{ce} . The speed command derivative error term U_{dc} is calculated by subtracting, in summing block 103, the current X_{er} value obtained in block 101 from the previous X_{er} term obtained from block 102 and multiplying by the derivative gain K_d in block 104. The speed command proportional error term U_{pc} is calculated by multiplying the proportional gain K_p in block 105 by the current X_{er} value obtained in block 20 101. The speed command integral error term U_{ic} is calculated by multiplying the integral gain K_i in block 106 by the current X_{er} value obtained in block 101 and summing this value in block 107 with the previous value of U_{ic} obtained from block 109. The 25 output of summing block 107 is passed through an output limiter, block 108, to produce the current integral error term U_{ic} . The three error terms, U_{dc} , U_{pc} and U_{ic} , are combined in summing block 110 to produce the speed command U_{fc} to be summed with the 30

motor speed feedforward command U_{mf} in summing block 79 (FIG. 3 and FIG. 4) for the motor vector controller 130.

5 Vector Controller

[0094] Reference is now made to FIG. 10, which is a simplified block diagram of the motor vector controller 130. The motor vector controller 130 contains functions for calculating the velocity error and the torque necessary to correct it, convert torque commands to motor voltage commands and current commands and calculate motor torque and speed estimates from measured values of motor voltages and motor currents.

10 [0095] In one embodiment, the stator flux is calculated from motor voltages and currents and the electromagnetic torque is directly estimated from the stator flux and stator current. More specifically, in block 131, three-phase motor voltage measurements V_{mm} and current measurements I_{mm} are converted to dq (direct/quadrature) frame signals using three to two phase conversion for ease of computation in a manner known in the art. Signals in the dq frame can be represented as individual signals or as vectors for convenience.

15 The motor vector feedback model 132 responds to motor stator voltage vector V_s and motor stator current vector I_s to calculate a measure of electrical torque T_{me} produced by the motor. In one embodiment, the operations carried out by motor vector feedback model 132 for calculating the electrical torque estimate are as follows. The stator flux vector F_s is obtained from the motor stator voltage V_s and motor stator current I_s vectors according to equation (2):

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25

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$$(2) \quad \mathbf{F_s} = (\mathbf{V_s} - \mathbf{I_s} \cdot \mathbf{R_s}) / s$$

$$(2A) \quad \mathbf{F_{ds}} = (\mathbf{V_{ds}} - \mathbf{I_{ds}} \cdot \mathbf{R_s}) / s$$

$$(2B) \quad \mathbf{F_{qs}} = (\mathbf{V_{qs}} - \mathbf{I_{qs}} \cdot \mathbf{R_s}) / s$$

5

where $\mathbf{R_s}$ is the stator resistance and s (in the denominator) is the Laplace operator for differentiation. Equations (2A) and (2B) show typical examples of the relationship between the vector notation for flux $\mathbf{F_s}$, voltage $\mathbf{V_s}$, and current $\mathbf{I_s}$ and actual d axis and q axis signals.

[0096] In one embodiment, the electrical torque $\mathbf{T_{me}}$ is estimated directly from the stator flux vector $\mathbf{F_s}$ obtained from equation (2) and the measured stator current vector $\mathbf{I_s}$ according to equation (3) or its equivalent (3A):

$$(3) \quad \mathbf{T_{me}} = \mathbf{K_u} \cdot (3/2) \cdot \mathbf{P} \cdot \mathbf{F_s} \times \mathbf{I_s}$$

$$(3A) \quad \mathbf{T_{me}} = \mathbf{K_u} \cdot (3/2) \cdot \mathbf{P} \cdot (\mathbf{F_{ds}} \cdot \mathbf{I_{qs}} - \mathbf{F_{qs}} \cdot \mathbf{I_{ds}})$$

20

where $\mathbf{P}$ is the number of motor pole pairs and $\mathbf{K_u}$ is a unit scale factor to get from MKS units to desired units.

[0097] In one embodiment, rotor velocity $\mathbf{U_{me}}$ is obtained from estimates of electrical frequency $\mathbf{U_e}$ and slip frequency $\mathbf{U_s}$. The motor vector feedback model 132 also performs this calculation using the stator voltage $\mathbf{V_s}$ and stator current $\mathbf{I_s}$ vectors. In one embodiment, the operations carried out by the motor vector feedback model 132 for calculating the motor velocity $\mathbf{U_{me}}$ are as follows. A rotor flux vector $\mathbf{F_r}$ is obtained from the measured stator voltage $\mathbf{V_s}$ and stator current $\mathbf{I_s}$ vectors along with motor stator resistance $\mathbf{R_s}$, stator inductance $\mathbf{L_s}$, magnetizing

inductance L_m , leakage inductance σL_s , and rotor inductance L_r according to equations (4) and (5); separate d axis and q axis rotor flux calculations are shown in equations (5A) and (5B) respectively:

5

$$(4) \quad \sigma L_s = L_s - L_m^2 / L_r$$

then,

$$(5) \quad F_r = (L_r / L_m) \cdot [F_s - I_s \cdot \sigma L_s]$$

$$(5A) \quad F_{dr} = (L_r / L_m) \cdot (F_{ds} - \sigma L_s \cdot I_{ds})$$

10 (5B) $F_{qr} = (L_r / L_m) \cdot (F_{qs} - \sigma L_s \cdot I_{qs})$

[0098] The slip frequency U_s can be derived from the rotor flux vector F_r , the stator current vector I_s , magnetizing inductance L_m , rotor inductance L_r ,
15 and rotor resistance R_r according to equation (6):

$$(6) \quad U_s = R_r \cdot (L_m / L_r) \cdot \frac{F_{dr} \cdot I_{qs} - F_{qr} \cdot I_{ds}}{F_{dr}^2 + F_{qr}^2}$$

20 [0099] The instantaneous excitation or electrical frequency U_e can be derived from stator flux according to equation (7):

25 (7) $U_e = \frac{F_{ds} \cdot s F_{qs} - F_{qs} \cdot s F_{ds}}{F_{ds}^2 + F_{qs}^2}$

[0100] The rotor velocity or motor velocity U_{me} can be derived from the number of motor pole pairs P the slip frequency U_s and the electrical frequency U_e
30 according to equation (8):

$$(8) \quad U_{me} = (U_e - U_s) (60) / P$$

[0101] In cases where long cable lengths or step up transformers are used, the impedances of the additional components can be added to the model of motor impedances in a method that is known.

5 [0102] The velocity controller 133 uses a PI controller (proportional, integral), PID controller (proportional, integral, derivative) or the like to compare the motor speed U_m with the motor speed command U_{mc} and produce a speed error torque command
10 T_{uc} calculated to eliminate the speed error. The speed error torque command T_{uc} is then converted to motor current commands I_{mc} and voltage commands V_{mc} in flux vector controller 134 using a method which is known.

15 [0103] Referring to FIG. 15, in one preferred embodiment, the pump control system provided by the present invention is software based and is capable of being executed in a controller 50 shown in block diagram form in FIG. 13. In one embodiment, the
20 controller 50 includes current sensors 51, voltage sensors 52, input devices 171, such as analog to digital converters, output devices 172, and a processing unit 54 having associated random access memory (RAM) and read-only memory (ROM). In one
25 embodiment, the storage devices 55 include a database 175 and software programs and files which are used in carrying out simulations of circuits and/or systems in accordance with the invention. The programs and files of the controller 50 include an operating system 176,
30 the parameter estimation engines 177 that includes the algorithms for the pump model 60 (FIG. 5) or pump model 260 (FIG. 6) and the pump system model 80 (FIG. 7), pump controller engines 178 that include the algorithms for fluid level feedforward controller 90

(FIG. 8) and the fluid level feedback controller 100 (FIG. 9), and vector controller engines 179 for the motor vector controller 130 for converting motor current and voltage measurements to torque and speed estimates and converting speed and torque feedforward commands to motor current and voltage commands, for example. The programs and files of the computer system can also include or provide storage for data. The processing unit 54 is connected through suitable input/output interfaces and internal peripheral interfaces (not shown) to the input devices, the output devices, the storage devices, etc., as is known.

15 Optimized Gas Production

[0104] The production of methane gas from coal seams can be optimized using the estimated parameters obtained by the pump controller 50 (FIG. 3 or FIG. 4) in accordance with the invention. For methane gas production, it is desirable to maintain the casing fluid level at an optimum level. A range for casing fluid level command X_{cc} is selected to define an optimal casing fluid level for extracting methane gas. This range is commonly referred to as a sweet zone.

25 [0105] In one embodiment of the present invention, the selection of the sweet zone is determined by the controller 50 (FIG. 3 or FIG. 4) that searches to find the optimum casing fluid level command X_{cc} . Since the sweet zone can change as conditions in the well change over time, it can be advantageous to program the controller 50 to perform these searches at periodic intervals or when specific conditions, such as a decrease in efficiency, are detected. In determining the sweet zone, the centrifugal pump intake pressure

Ps or casing fluid level X_c is controlled. The centrifugal pump 32 is controlled by the fluid level feedforward controller 90 and the fluid level feedback controller 100 to cause the casing fluid level X_c to be adjusted until maximum gas production is obtained. The casing fluid level command X_{cc} is set to a predetermined start value. The methane gas flow through outlet 42 at the surface is measured. The casing fluid level command is then repeatedly incremented to progressively lower values. The methane gas production is measured at each new level to determine the value of casing fluid level X_c at which maximum gas production is obtained. The point of optimum performance is called the sweet spot. The sweet zone is the range of casing fluid level above and below the sweet spot within which the gas production decrease is acceptable. However, the selection of the sweet zone can be done manually by taking readings.

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Improved Pump Energy Efficiency and Operating Range

[0106] One method to optimize the pump control when operated at low flow and/or efficiency, is to operate using a duty cycle mode to produce the required average flow rate while still operating the centrifugal pump at its most efficient and optimal flow rate point Q_o . In this duty cycle mode, the volume of fluid to be removed from the casing can be determined using the fluid inflow rate Q_i when the casing fluid level X_c is near the desired level. A fluid level tolerance band is defined around the desired fluid level, within which the fluid level is allowed to vary. The volume V_b of the fluid level tolerance band is calculated from the projected area

between the tubing, casing and pump body and the prescribed length of the tolerance band. This volume is used with the fluid inflow rate Q_i to determine the pump off time period T_{off} . When the centrifugal pump is on, the value for casing fluid level X_c is calculated and the fluid level in the casing is reduced to the lower level of the fluid level tolerance band, when the pump is again turned off. The fluid inflow rate Q_i is calculated by dividing the fluid level tolerance band volume V_b by the on time period T_{on} used to empty the band, then subtracting the result from the optimal pump flow rate Q_o used to empty the band. The on-off duty cycle varies automatically to adjust for changing well inflow characteristics. This variable duty cycle continues with the centrifugal pump operating at its maximum efficiency over a range of average pump flow rates varying from almost zero to the flow associated with full time operation at the most efficient speed. Use of the duty cycle mode also increases the range of controllable pump average flow by using the ratio of on time, T_{on} , multiplied by optimal flow rate, Q_o , divided by total cycle time ($T_{on} + T_{off}$) rather than the centrifugal pump speed to adjust average flow. This also avoids the problem of erratic flow associated with operating the pump at very low speeds. This duty cycle method can produce significant energy savings at reduced average flow rates as shown in FIG. 16. As can be seen in FIG. 16, the efficiency of the example pump using continuous operation decreases rapidly below about 7.5 gallons per minute (GPM), while the efficiency of the same pump operated using the duty cycle method remains at near optimum efficiency over the full range of average flow.

[0107] Pump system efficiency is determined by the ratio of the fluid power output to the mechanical or electrical power input. When operated to maximize efficiency, the controller turns the centrifugal pump off when the centrifugal pump starts operating in an inefficient range. In addition, the centrifugal pump is turned off if a pump off condition casing level at the pump intake is detected by a loss of measured flow.

10 [0108] For systems with widely varying flow demands, multiple centrifugal pumps, each driven by a separate motor, may be connected in parallel and staged (added or shed) to supply the required capacity and to maximize overall efficiency. The decision for

15 staging multiple centrifugal pumps is generally based on the maximum operating efficiency or capacity of the centrifugal pump or combination of centrifugal pumps. As such, when a system of centrifugal pumps is operating beyond its maximum efficiency point or

20 capacity and another centrifugal pump is available, a centrifugal pump is added when the efficiency of the new combination of centrifugal pumps exceeds the current operating efficiency. Conversely, when multiple centrifugal pumps are operating in parallel

25 and the flow is below the combined maximum efficiency point, a centrifugal pump is shed when the resulting combination of centrifugal pumps have a better efficiency. These cross-over points can be calculated directly from the efficiency data for each centrifugal

30 pump in the system, whether the additional centrifugal pumps are variable speed or fixed speed.

Pump and Pump System Protection

[0109] One method of protecting the centrifugal pump and system components is to use sensors to measure the performance of the system above ground and compare this measurement to a calculated performance value. If the two values differ by a threshold amount, a fault sequence is initiated which may include such steps as activating an audio or visual alarm for the operator, activating an alarm signal to a separate supervisory controller or turning off the centrifugal pump. In one embodiment, a sensor is used to measure the flow in the tubing at the surface Q_{pm} and compare it with the calculated value Q_{pe} . If the actual flow Q_{pm} is too low relative to the calculated flow Q_{pe} , this could be an indication of a fault such as a tubing leak, where not all of the flow through the centrifugal pump is getting to the measurement point.

[0110] Another method of protecting the pump is to prevent excessive mechanical power input. In one embodiment, the mechanical power input to the pump is calculated by multiplying the speed U_{me} by the torque T_{me} . The result is compared to the mechanical input power limit P_{le} calculated by the pump model (FIG. 5 or FIG. 6). If the limit P_{le} is exceeded, the torque and speed are reduced to protect the pump.

[0111] Although exemplary embodiments of the present invention have been shown and described with reference to particular embodiments and applications thereof, it will be apparent to those having ordinary skill in the art that a number of changes, modifications, or alterations to the invention as described herein may be made, none of which depart from the spirit or scope of the present invention.

All such changes, modifications, and alterations should therefore be seen as being within the scope of the present invention.

What is claimed is:

1. A method for controlling the operational performance of a centrifugal pump for extracting fluid from a subterranean wellbore, said centrifugal pump being directly coupled to an electrical motor, wherein both the centrifugal pump and the electrical motor are disposed near the bottom of the wellbore, and wherein said motor receives electrical power through a motor cable extending from the motor to a point above the surface of the earth, the method comprising the steps of:

- a) measuring the performance of the centrifugal pump comprising the steps of:
 - (i) determining a value of speed input to the centrifugal pump comprising the steps of:
 - measuring values of electrical voltages applied to the motor cable and currents drawn by the motor cable;
 - using the values of electrical voltages applied to the motor cable and currents drawn by the motor cable to determine values of a stator voltage vector, a stator current vector and a rotor flux vector;
 - using the values of the stator voltage vector, the stator current vector, the rotor flux vector and a model of the motor, the model being executed by a controller, to calculate a value for the motor speed; and
 - (ii) determining a value of pump flow rate;
 - (iii) using the value of speed input and the value of pump flow rate to calculate one or more values representing the performance of the centrifugal pump, wherein the values of speed input and pump flow rate are derived without the use of any sensor disposed within the wellbore and without having any sensing lines extending to the motor through the wellbore; and
- b) controlling the operational performance of the centrifugal pump based on the one or more calculated values of pump performance to enhance the efficiency of pump operation or prevent damage to the centrifugal pump.

2. The method of claim 1, wherein the values representing the performance of the centrifugal pump are values for one or more parameters selected from the group consisting of pump minimum required suction head pressure, pump head pressure, pump head pressure at rated speed, pump mechanical input power limit, and pump efficiency.

3. The method of claim 1, further comprising the steps of:

using at or above ground sensors to determine measured centrifugal pump performance values for one or more of the calculated centrifugal pump performance values;

comparing the measured centrifugal pump performance values determined by the sensors with the corresponding calculated centrifugal pump performance values; and

generating a fault sequence if the difference between corresponding values exceeds an allowable limit.

4. A method for controlling the performance of a centrifugal pump for extracting fluid from a subterranean wellbore, said centrifugal pump being directly coupled to an electrical motor, wherein both the centrifugal pump and the electrical motor are disposed near the bottom of the wellbore, and wherein said motor receives electrical power through a motor cable extending from the motor to a point above the surface of the earth, the method comprising the steps of:

(a) measuring the performance of the centrifugal pump comprising the steps of:

(i) determining a value of speed input to the centrifugal pump;

(ii) determining a value of torque input to the centrifugal pump, wherein the steps of determining the torque and speed inputs to the centrifugal pump comprises the steps of:

measuring values of electrical voltages applied to the motor cable and currents drawn by the motor cable;

using the values of electrical voltages applied to the motor cable and currents drawn by the motor cable to determine values of a stator voltage vector, a stator current vector and a rotor flux vector; and

using the values of the stator voltage vector, the stator current vector, the rotor flux vector and a model of the motor, the model being executed by a controller, to calculate a value for at least one of the parameters selected from the group consisting of the motor torque and the motor speed.

- (iii) using the value of speed input and the value of torque input to calculate one or more values representing the performance of the centrifugal pump, wherein the values of speed input and torque input are calculated without the use of any sensor disposed within the wellbore and without having any sensing lines extending to the motor through the wellbore; and
- (b) controlling the operational performance of the centrifugal pump based on the one or more calculated values of pump performance to enhance the efficiency of pump operation or prevent damage to the centrifugal pump.

5. The method of claim 4, wherein the values representing the performance of the centrifugal pump are values for one or more parameters selected from the group consisting of pump flow rate, pump minimum required suction head pressure, pump head pressure, pump head pressure at rated speed, pump mechanical input power limit, and pump efficiency.

6. The method of claim 4, further comprising the steps of:

using at or above ground sensors to determine measured centrifugal pump performance values for one or more of the calculated centrifugal pump performance values;

comparing the measured centrifugal pump performance values determined by the sensors with the corresponding calculated centrifugal pump performance values; and

generating a fault sequence if the difference between corresponding values exceeds an allowable limit.

7. A method for controlling operational performance of a subterranean well fluid system wherein a centrifugal pump is used for extracting fluid from said subterranean well, wherein said centrifugal pump is directly coupled to an electrical motor, wherein both the centrifugal pump and the electrical motor are disposed near the bottom of the wellbore, and wherein said motor receives electrical power through a motor cable extending from the motor to a point above the surface of the earth, the method comprising the steps of:

- (a) measuring the performance of the centrifugal pump comprising the steps of:
 - (i) determining a value of speed input to the centrifugal pump, wherein the step of determining the speed input to the centrifugal pump comprises the steps of:
 - measuring values of electrical voltages applied to the motor cable and currents drawn by the motor cable;
 - using the values of electrical voltages applied to the motor cable and currents drawn by the motor cable to determine values of a stator voltage vector, a stator current vector and a rotor flux vector; and
 - using the values of the stator voltage vector, the stator current vector, the rotor flux vector and a model of the motor, the model being executed by a controller, to calculate a value for the motor speed.
 - (ii) determining a value of pump flow rate;
 - (iii) using the value of speed input and the value of pump flow rate to calculate one or more values representing the performance of the centrifugal pump, wherein the values of speed input and pump flow rate are derived without the use of any sensor disposed within the wellbore and without having any sensing lines extending to the motor through the wellbore; and
- (b) controlling the operational performance of the well fluid system by controlling the operational performance of the centrifugal pump based on the calculated values of pump performance to enhance the efficiency of the well fluid system or prevent damage to the centrifugal pump.

8. The method of claim 7, wherein the values representing the performance of the fluid system are one or more values selected from the group consisting of pump suction pressure, pump discharge pressure, flow head loss and fluid level.

9. The method of claim 7, further comprising the steps of:

using at or above ground sensors to determine measured fluid system performance values for one or more of the calculated fluid system performance values comparing each measured fluid system performance value with the corresponding calculated fluid system performance value; and

generating a fault sequence if the difference between corresponding values exceeds an allowable limit.

10. A method for controlling operational performance of a subterranean well fluid system wherein a centrifugal pump is used for extracting fluid from said subterranean well, wherein said centrifugal pump is directly coupled to an electrical motor, wherein both the centrifugal pump and the electrical motor are disposed near the bottom of the wellbore, and wherein said motor receives electrical power through a motor cable extending from the motor to a point above the surface of the earth, the method comprising the steps of:

(a) measuring the performance of the centrifugal pump comprising:

- (i) determining a value of speed input to the centrifugal pump;
- (ii) determining a value of torque input to the centrifugal pump, the steps of determining the torque and speed inputs to the centrifugal pump comprising the steps of:

measuring values of electrical voltages applied to the motor cable and currents drawn by the motor cable;

using the values of electrical voltages applied to the motor cable and currents drawn by the motor cable to determine values of a stator voltage vector, a stator current vector and a rotor flux vector;

using the values of the stator voltage vector, the stator current vector, the rotor flux vector and a model of the motor, the model being executed by a controller, to calculate a value for at least one of the parameters selected from the group consisting of the motor torque and the motor speed; and

- (iii) using the value of speed input and the value of torque input to calculate one or more values representing the performance of the centrifugal pump, and using the values representing the performance of the centrifugal pump to calculate values representing the performance of the fluid system, wherein the values of speed input and torque input are calculated without the use of any sensors disposed within the wellbore and without having any sensing lines extending to the motor through the wellbore; and
- (b) controlling the operational performance of the well fluid system by controlling the operational performance of the centrifugal pump based on the calculated values of pump performance to enhance the efficiency of the well fluid system or prevent damage to the centrifugal pump.

11. The method of claim 10, wherein the values representing the performance of the fluid system are one or more values selected from the group consisting of pump suction pressure, pump discharge pressure, flow head loss and fluid level.

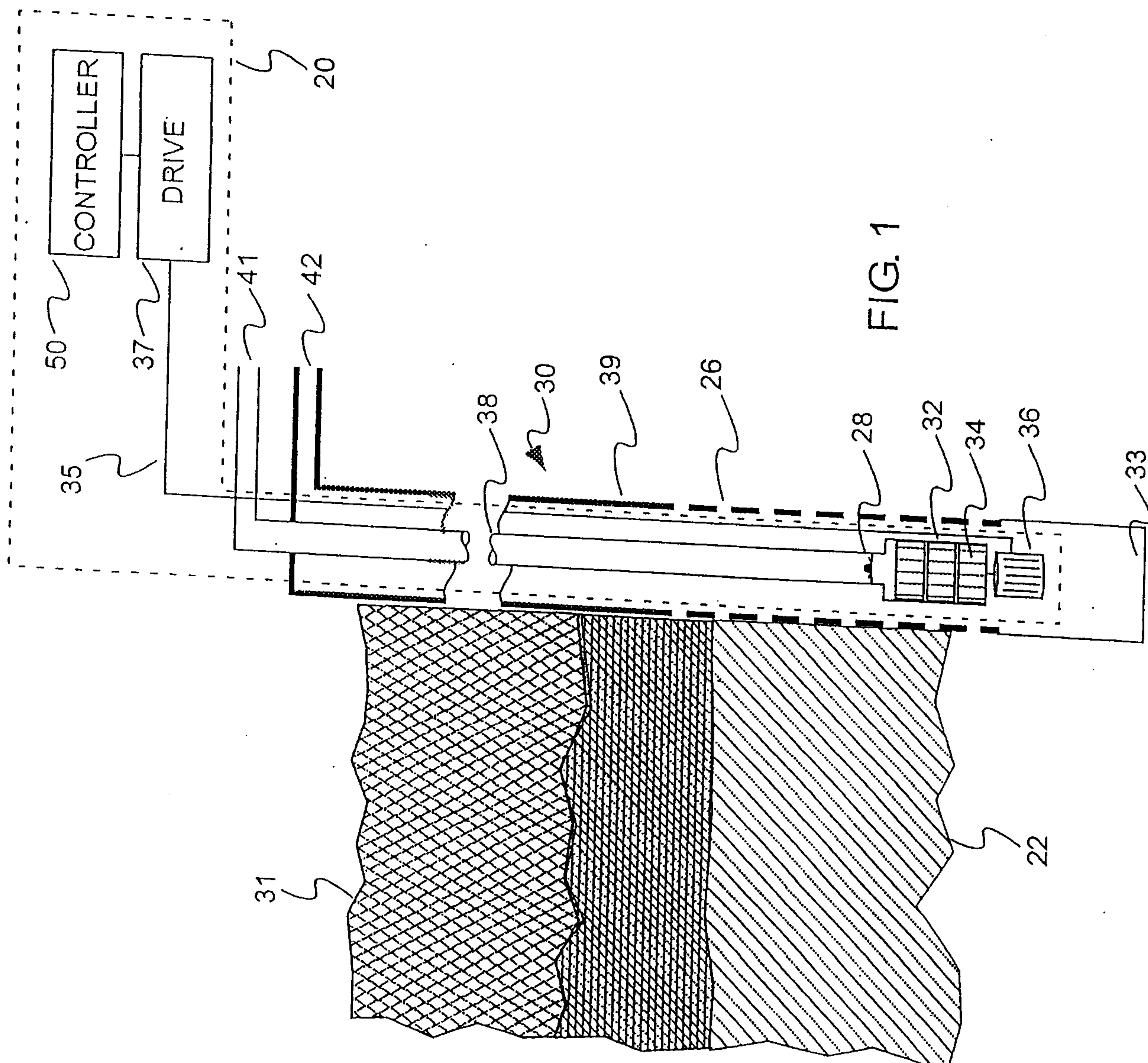
12. The method of claim 10, further comprising the steps of:

using at or above ground sensors to determine measured fluid system performance values for one or more of the calculated fluid system performance values;

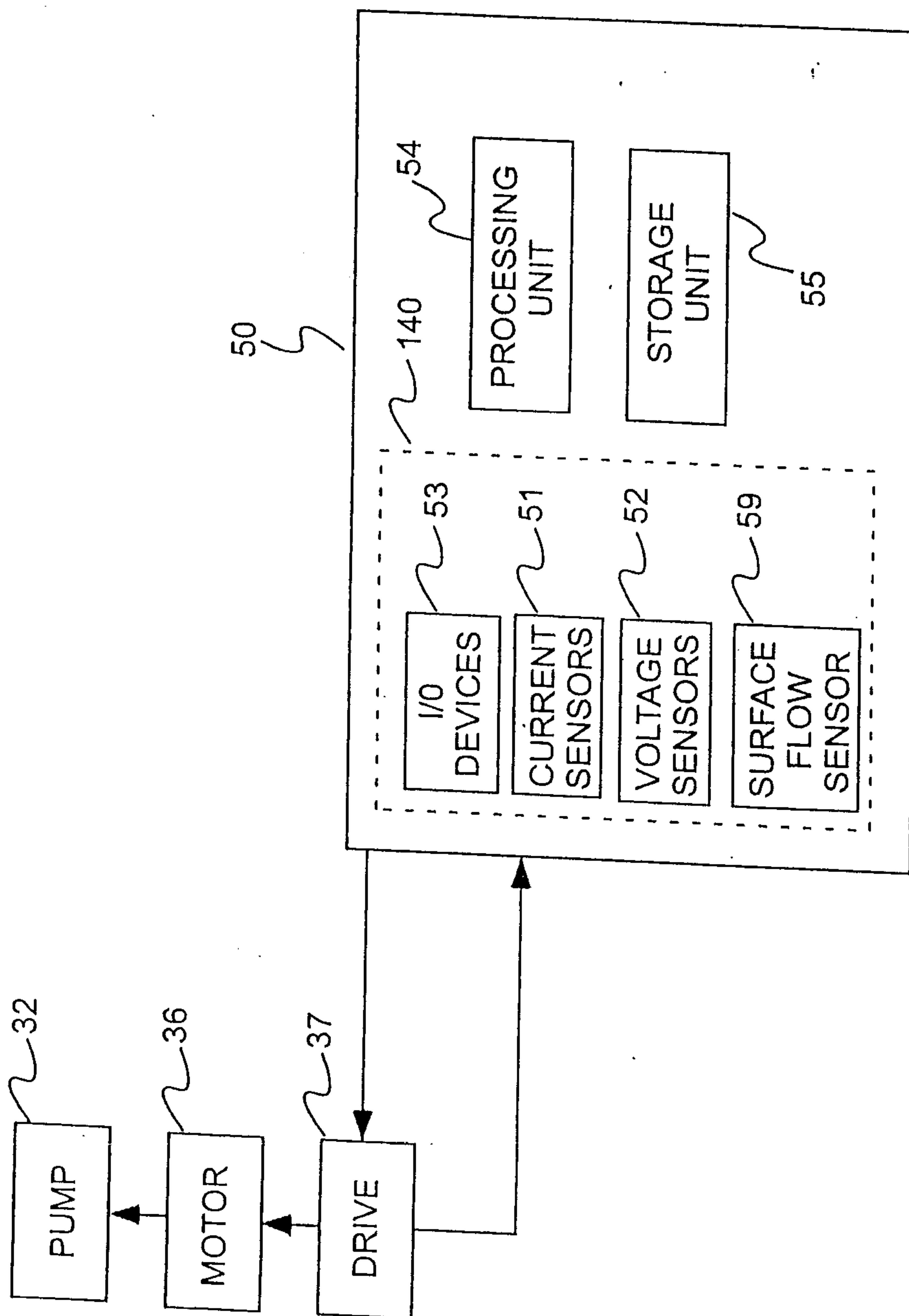
comparing each measured fluid system performance value with the corresponding calculated fluid system performance value; and

generating a fault sequence if the difference between corresponding values exceeds an allowable limit.

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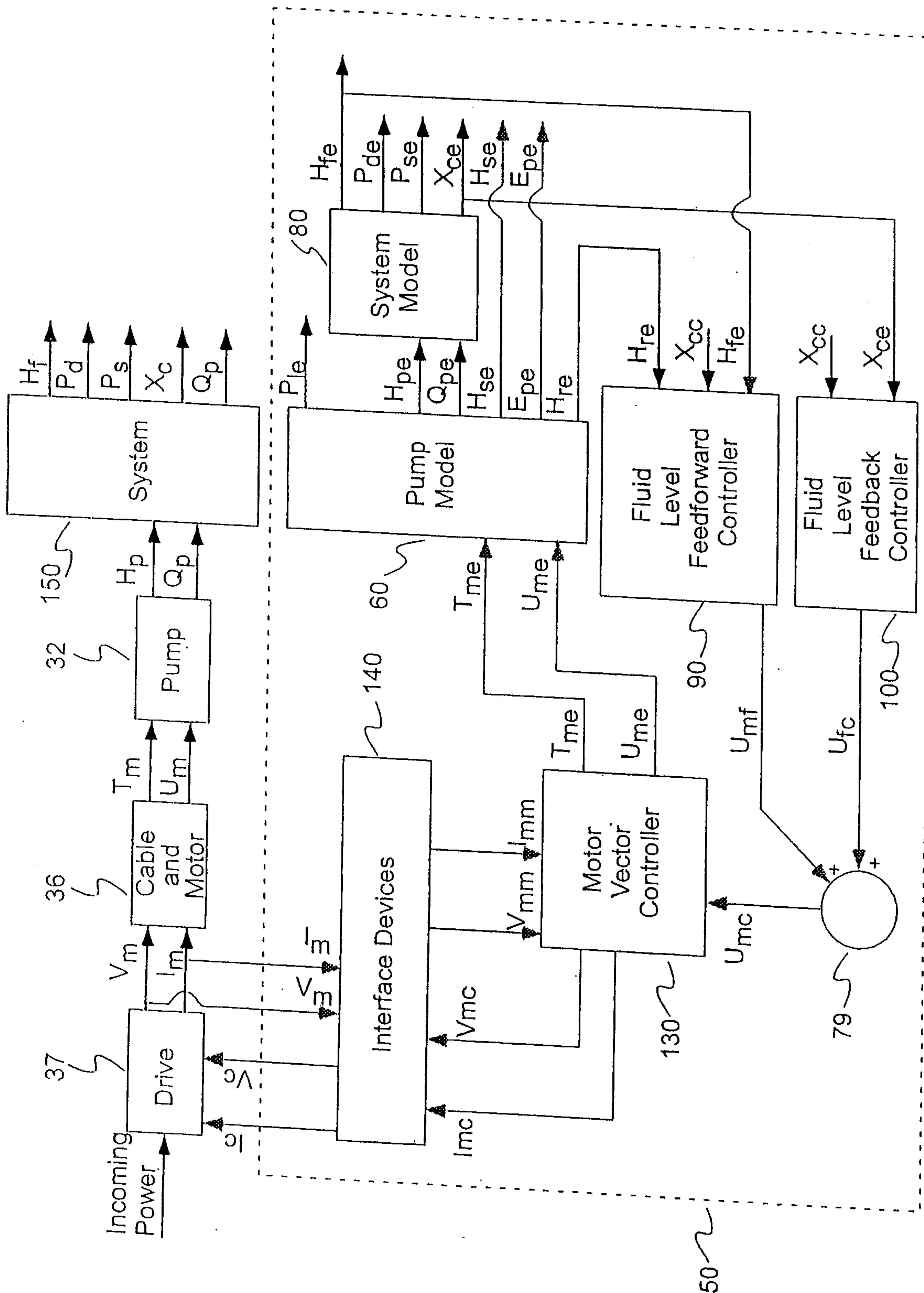
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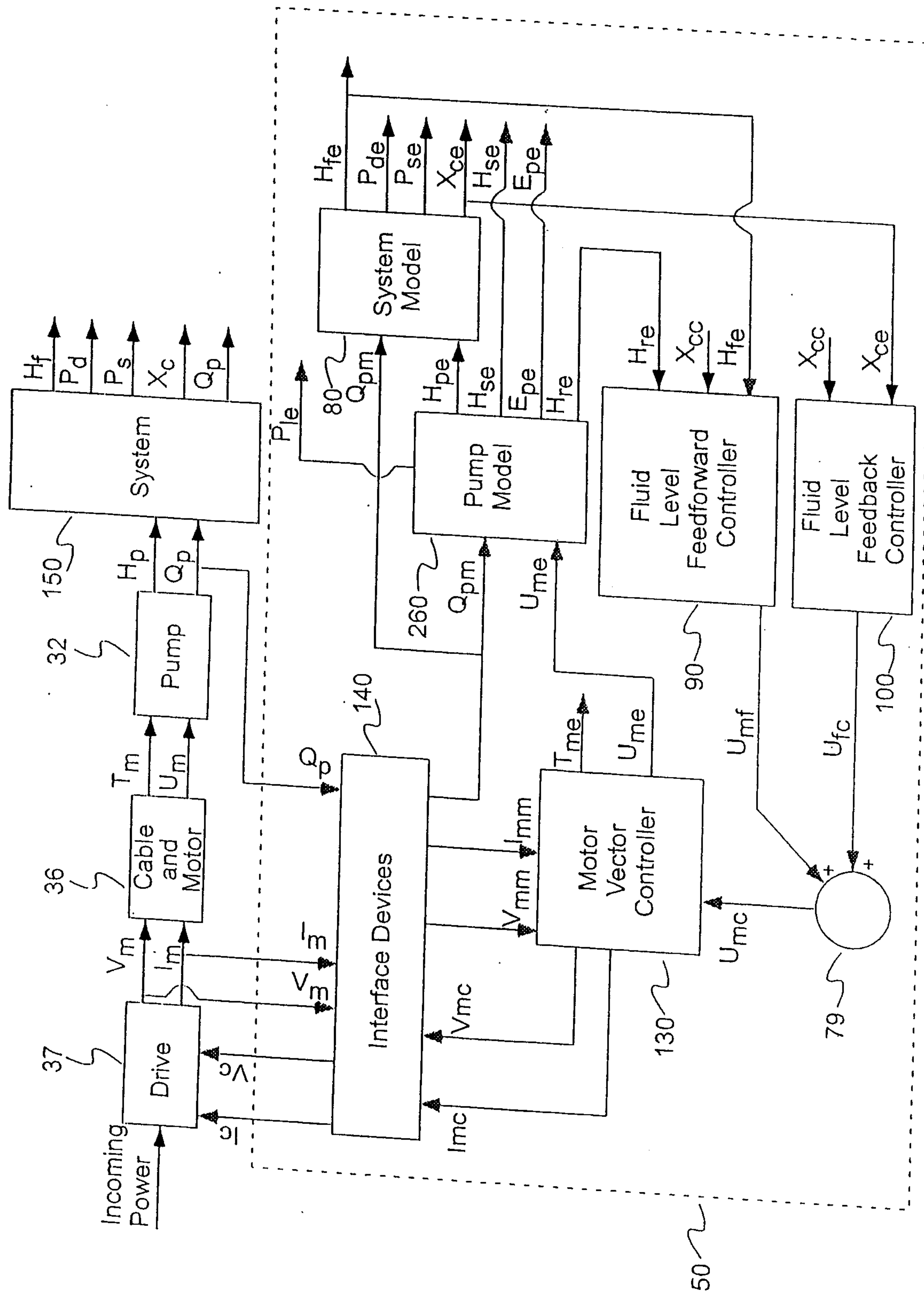
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FIG. 2

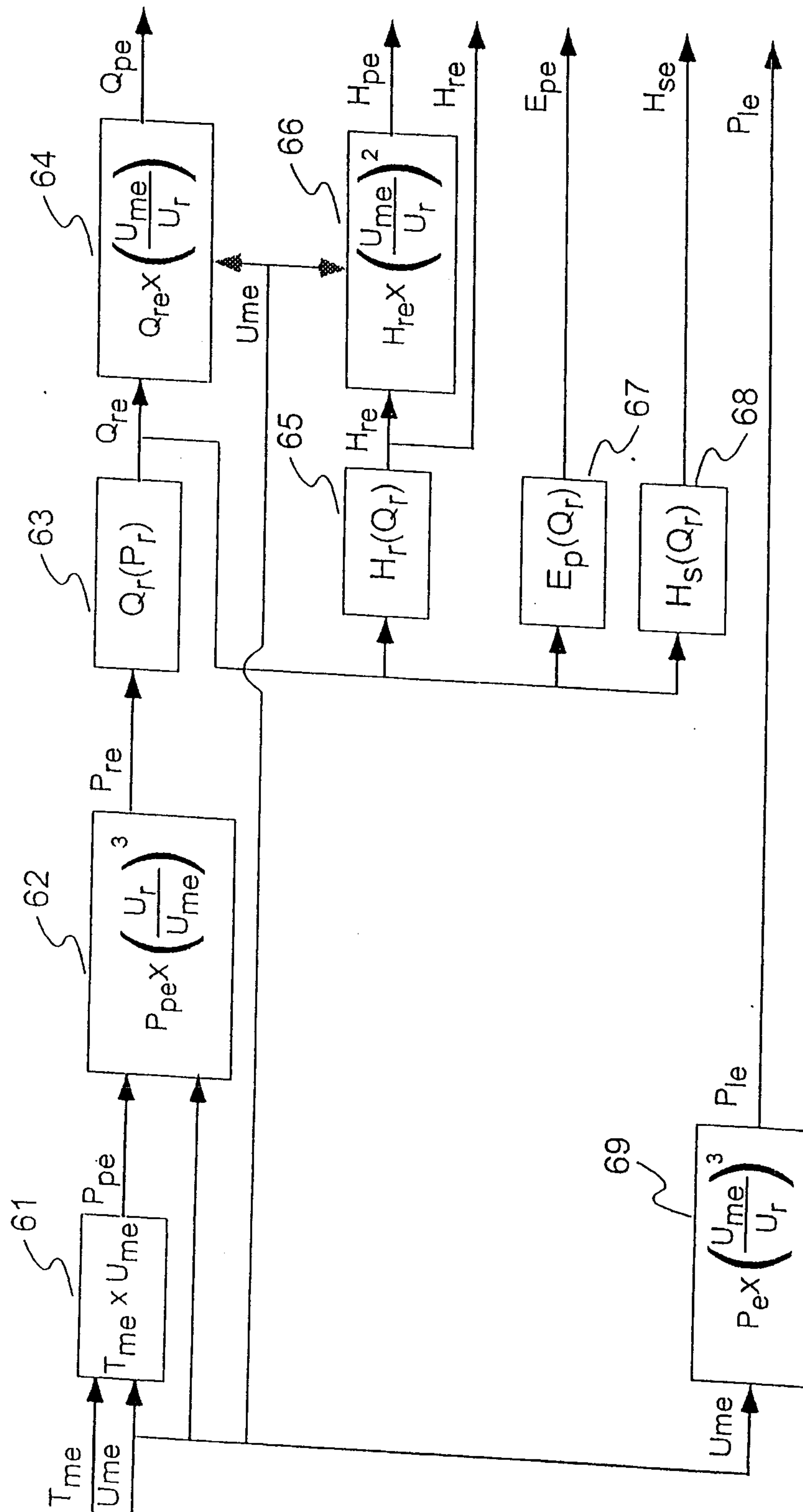
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FIG. 3

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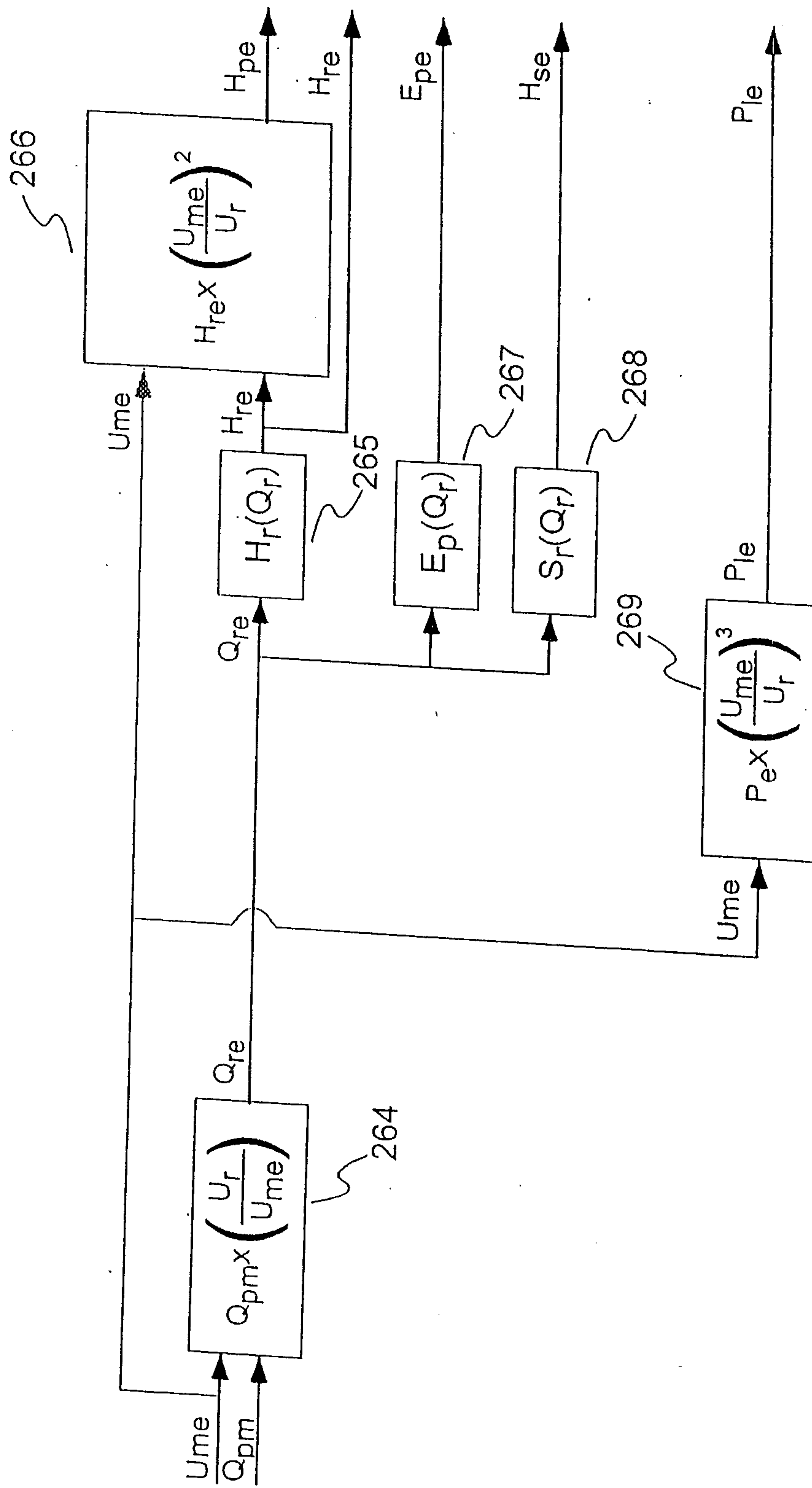
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FIG. 4

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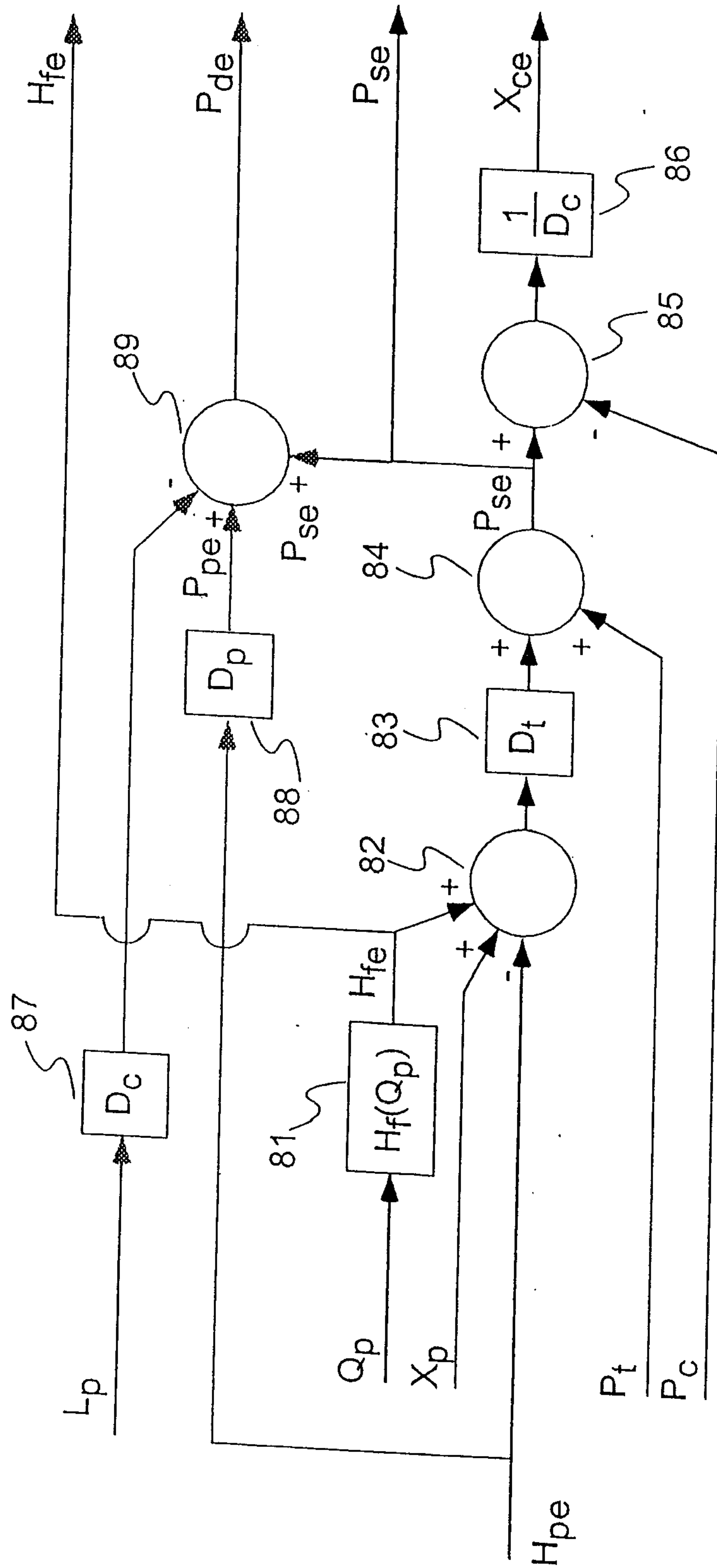
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FIG. 5

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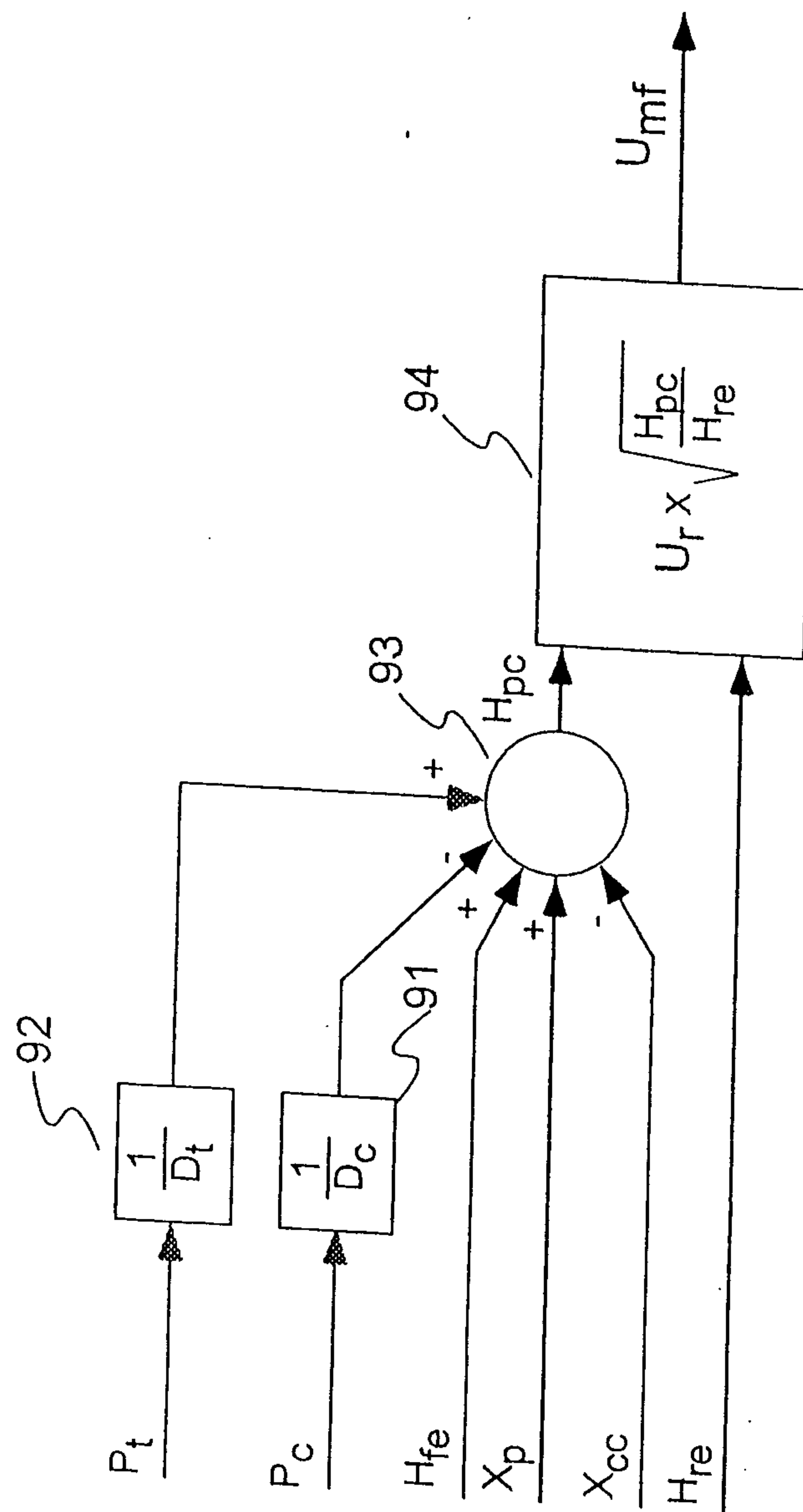
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FIG. 6

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FIG. 7

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FIG. 8

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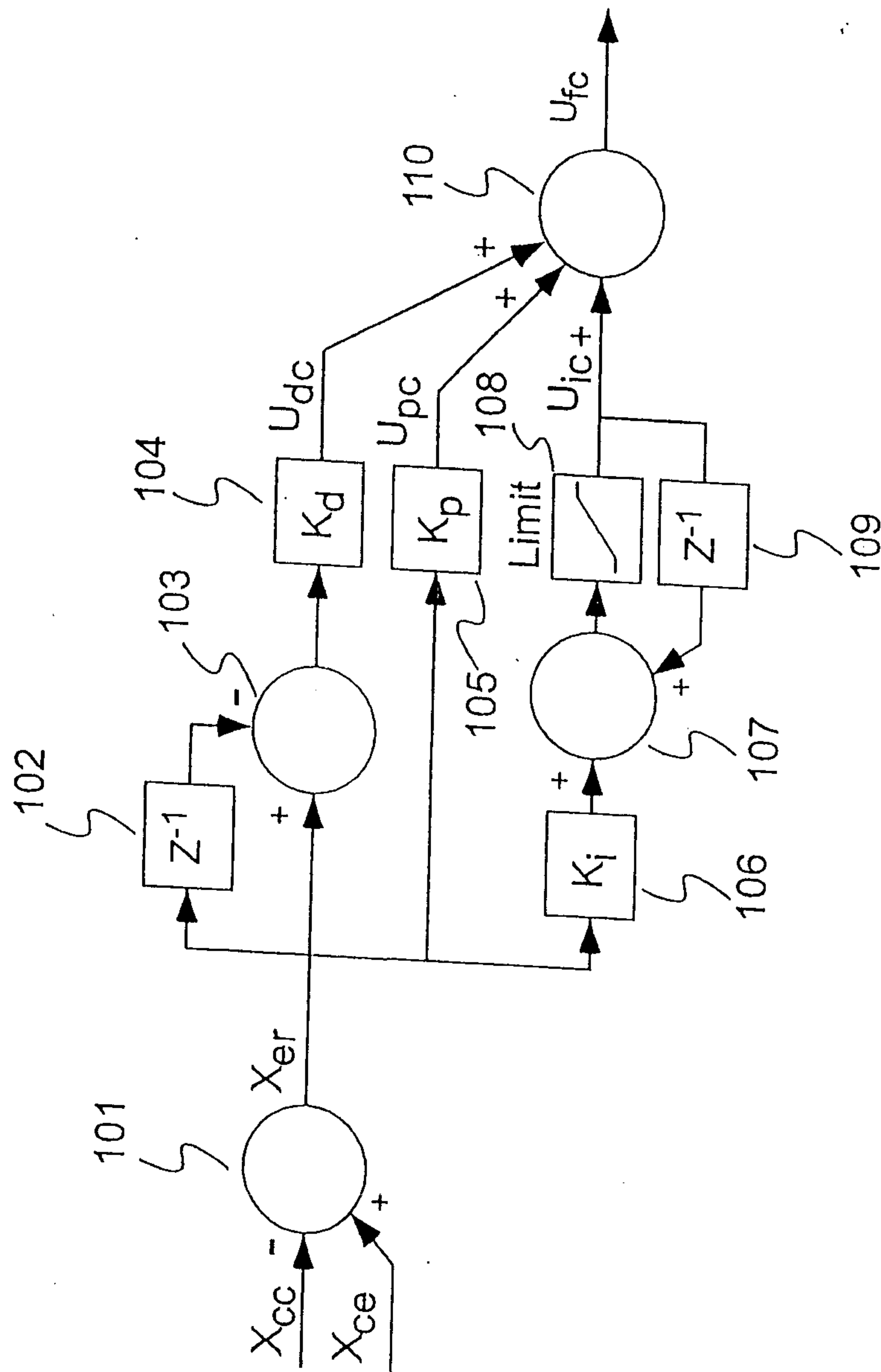
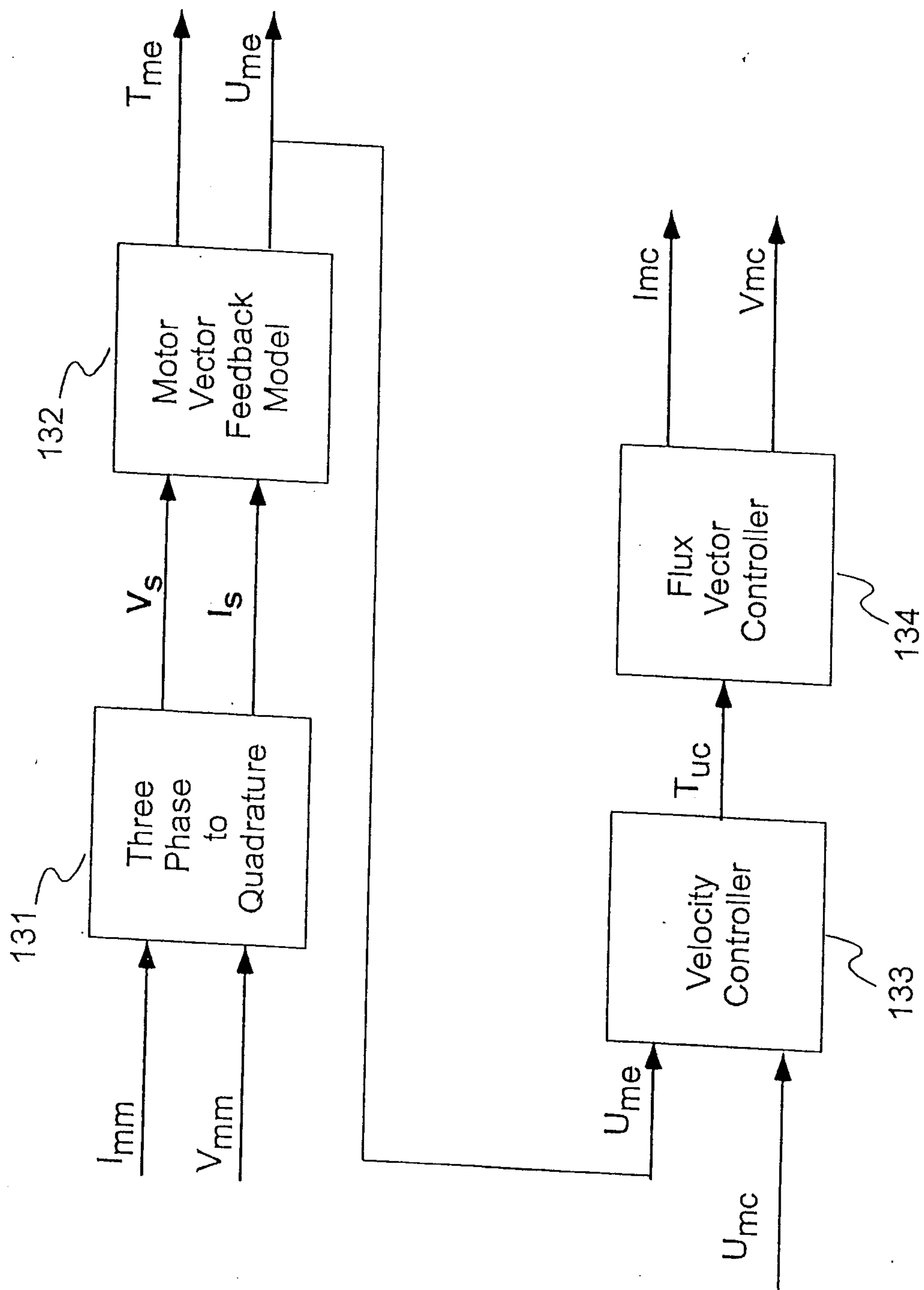
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FIG. 9

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FIG. 10

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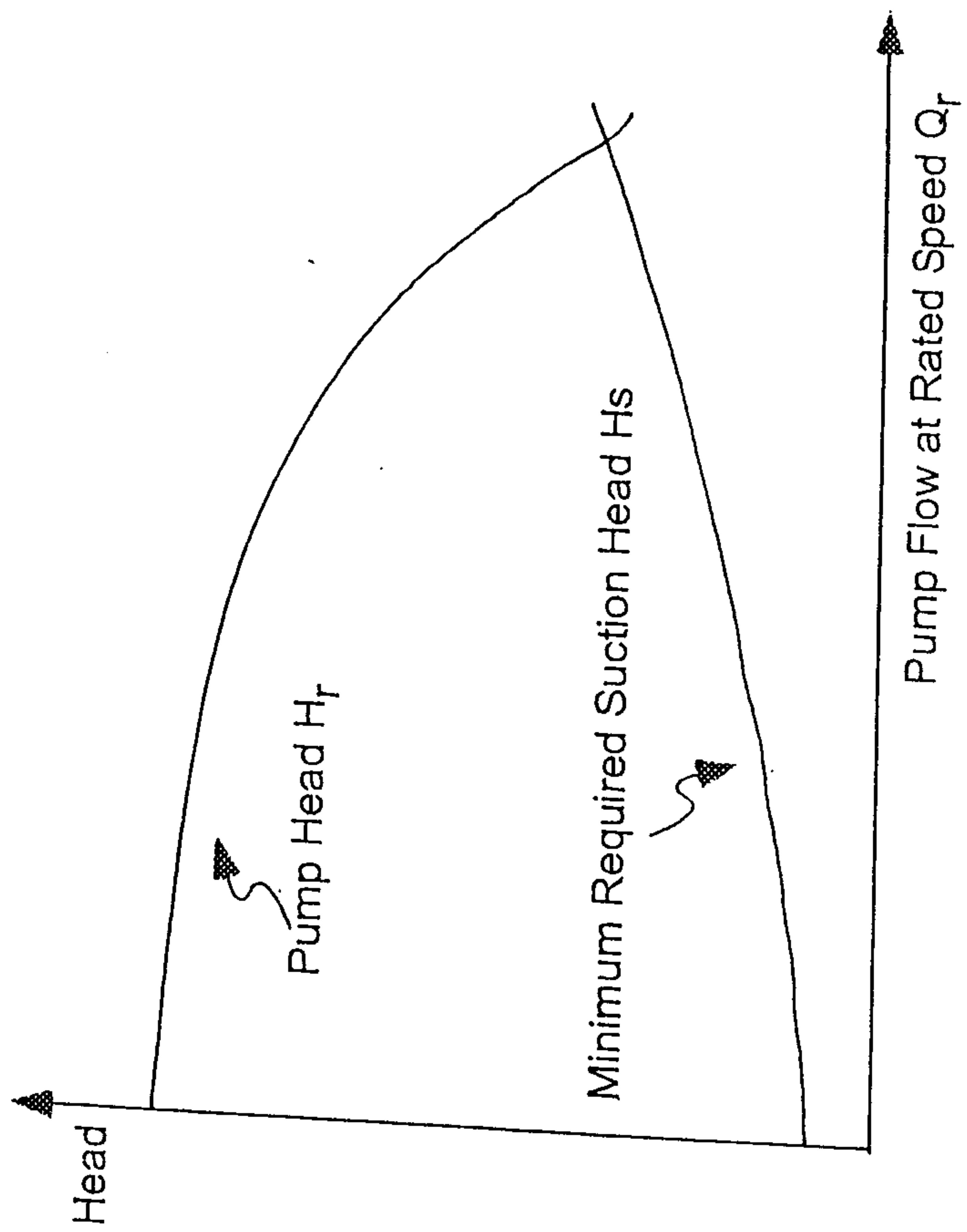


FIG. 11

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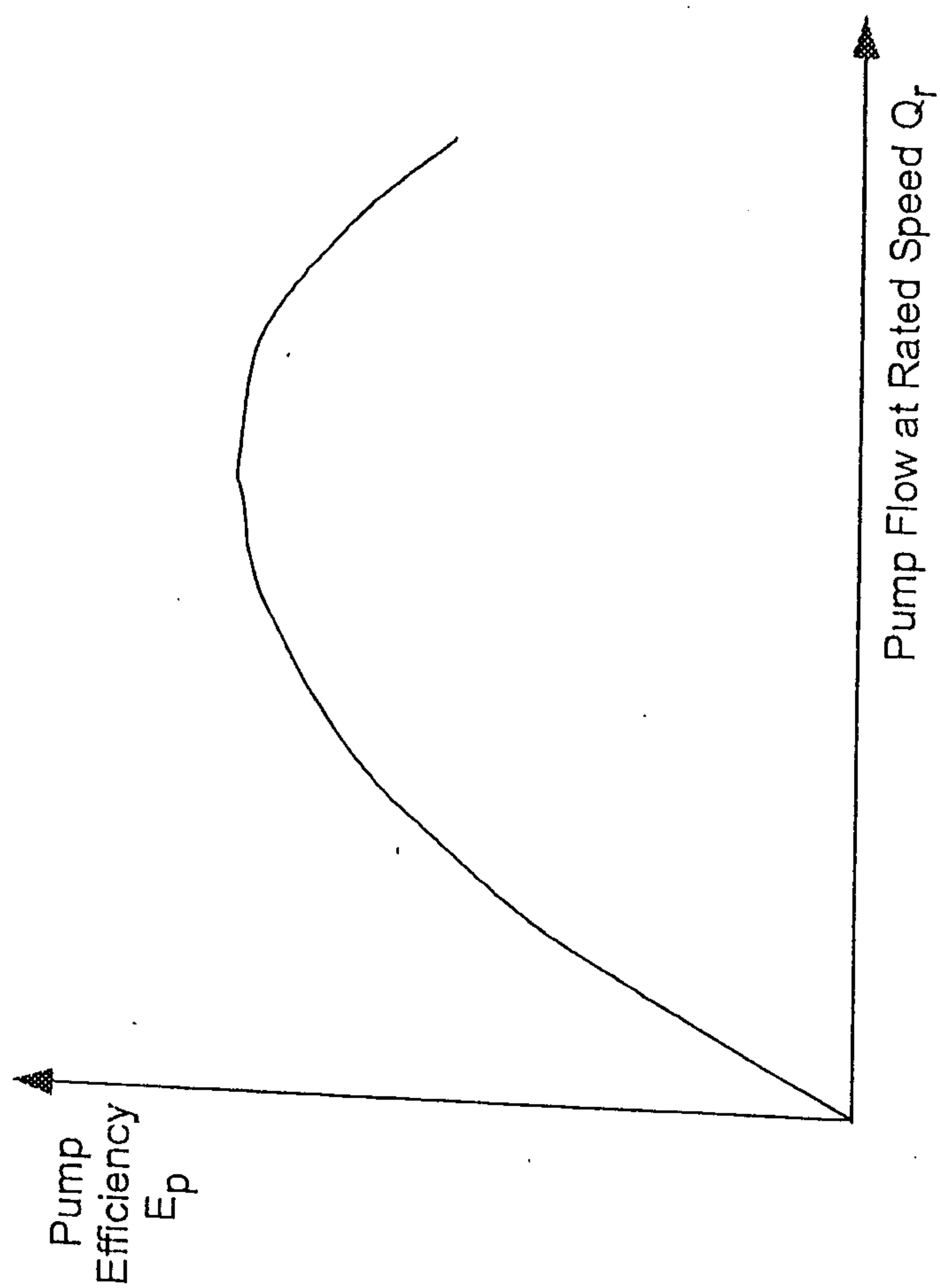


FIG. 12

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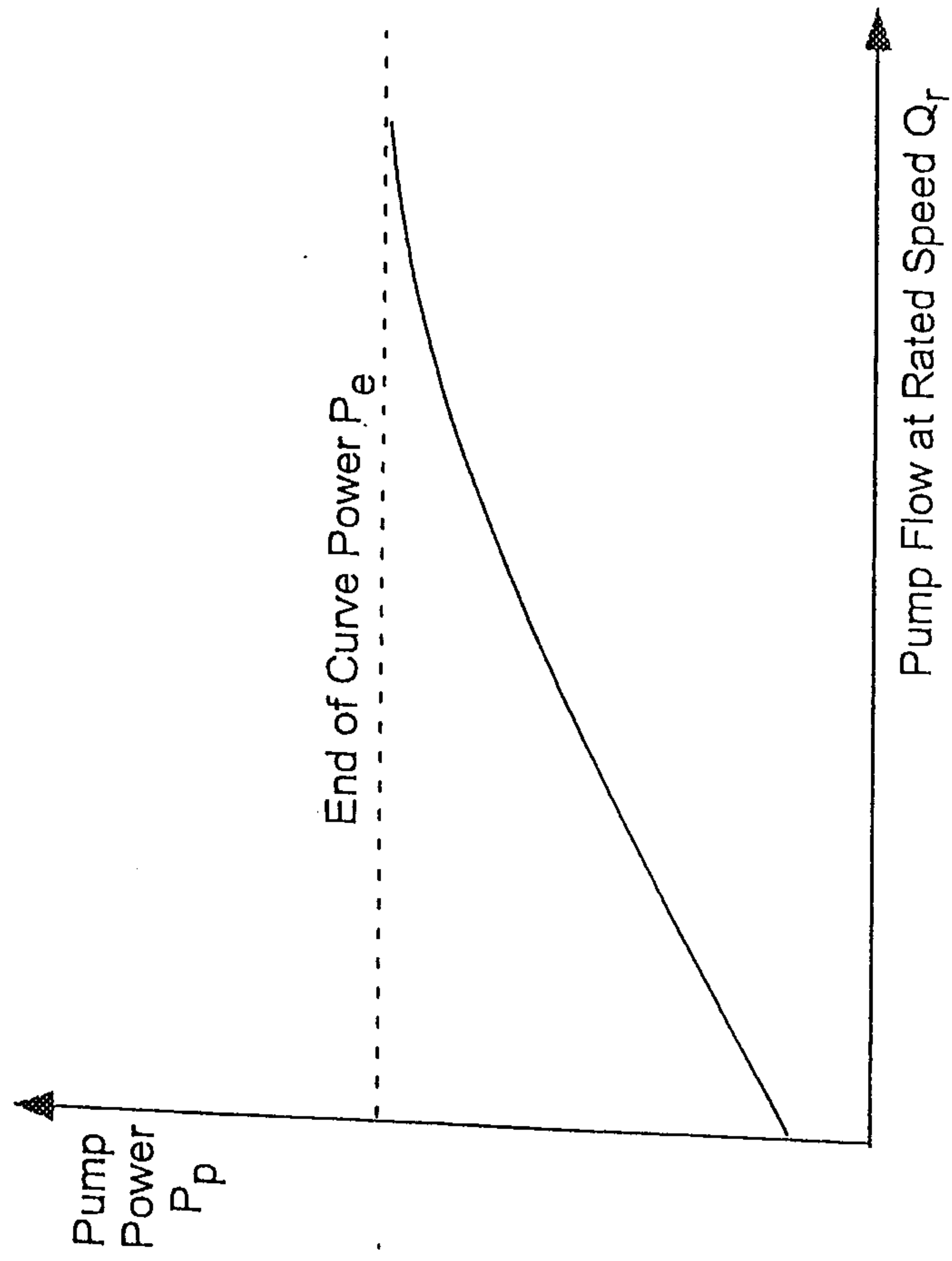
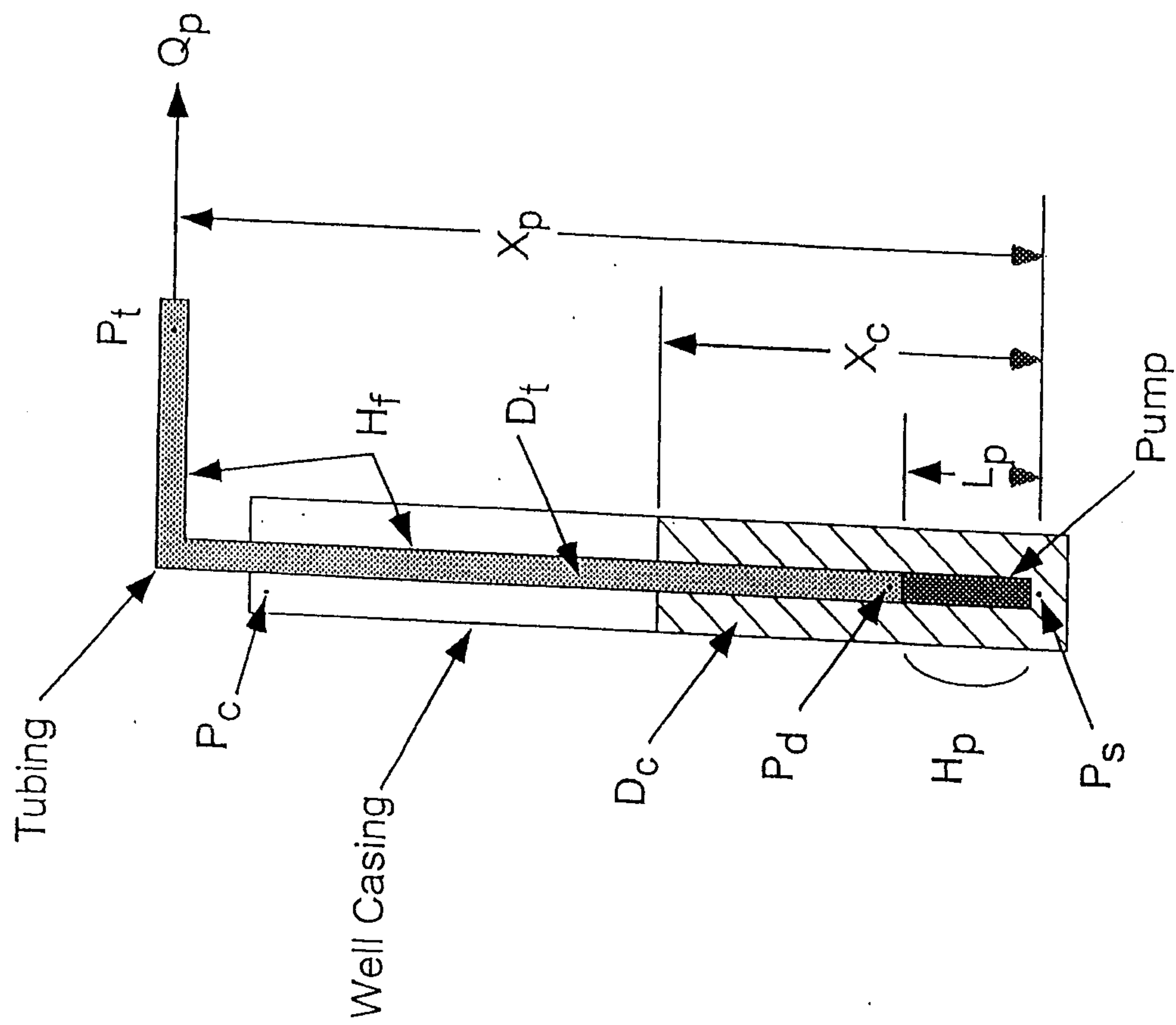


FIG. 13

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FIG. 14

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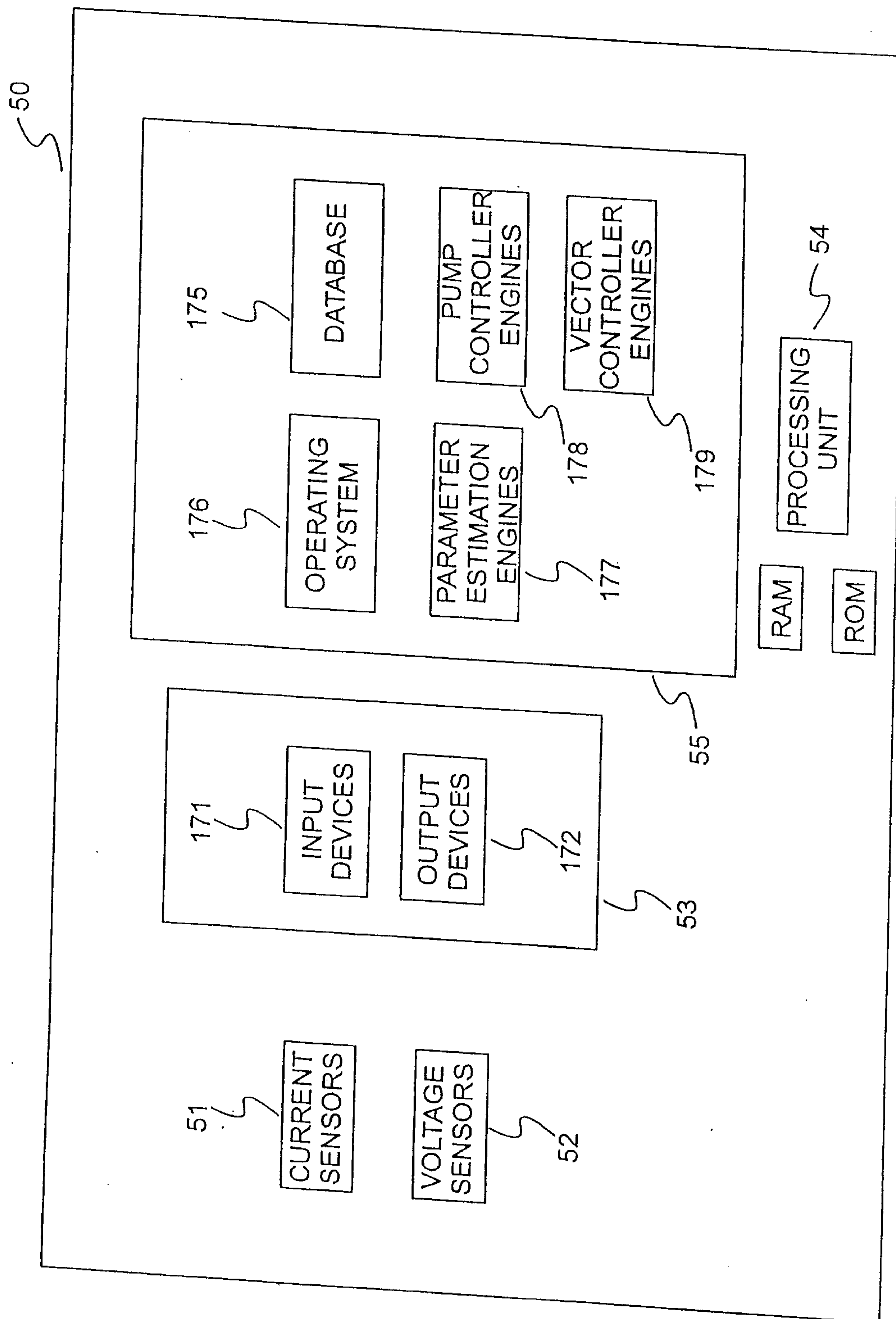


FIG. 15

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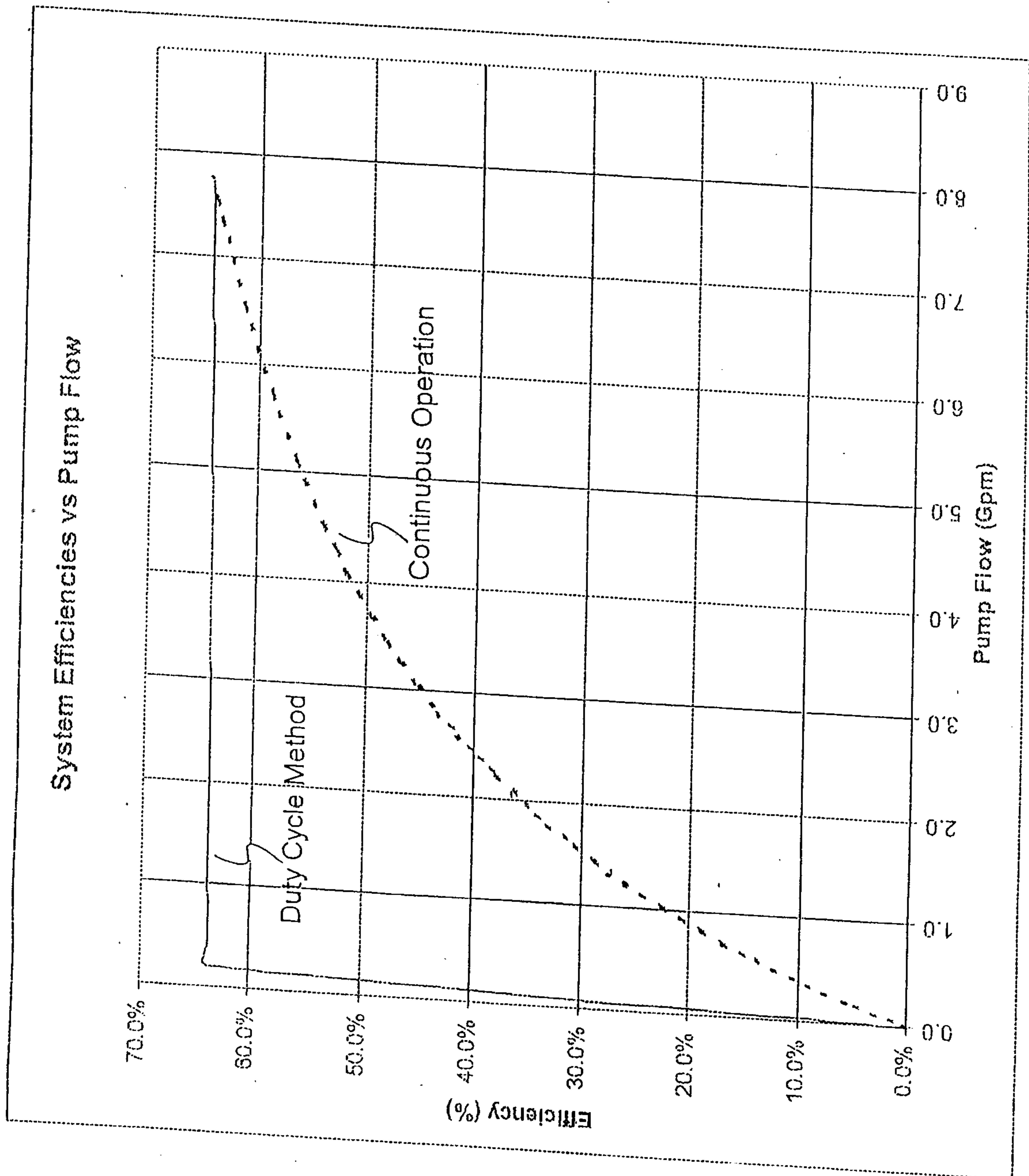


FIG. 16

