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Borgstadt et al.(10) **Pub. No.: US 2009/0053072 A1**(43) **Pub. Date: Feb. 26, 2009**(54) **INTEGRATED "ONE PUMP" CONTROL OF PUMPING EQUIPMENT****Publication Classification**(51) **Int. Cl.****F04B 49/00**

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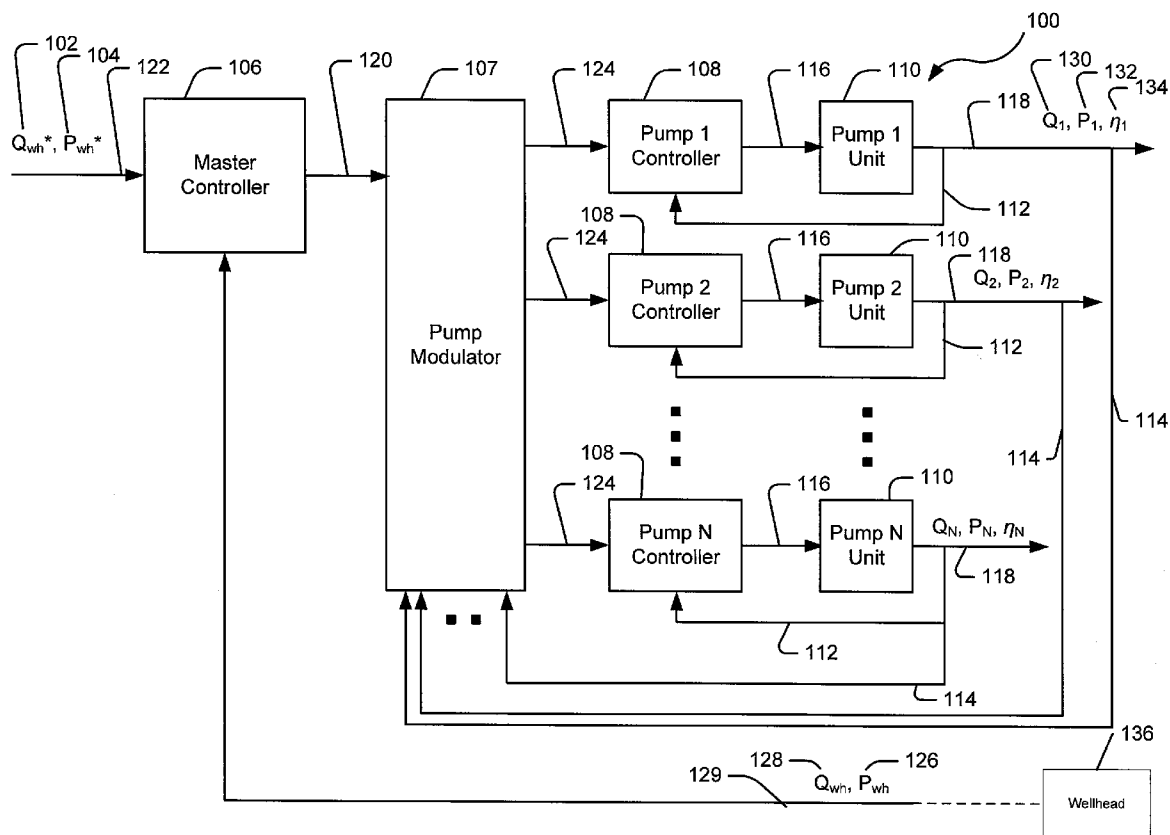
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ABSTRACT

Methods and systems for improving the efficiency of a pumping process by controlling the operation of the pumps involved based on certain parameters characterizing the pump. A pump unit is coupled to a pump controller which is in turn, coupled to a pump modulator. A master controller drives the pump modulator based on a desired output parameter for the system. The pump modulator then drives each pump unit through its corresponding pump controller in a manner for the system to achieve optimal performance.

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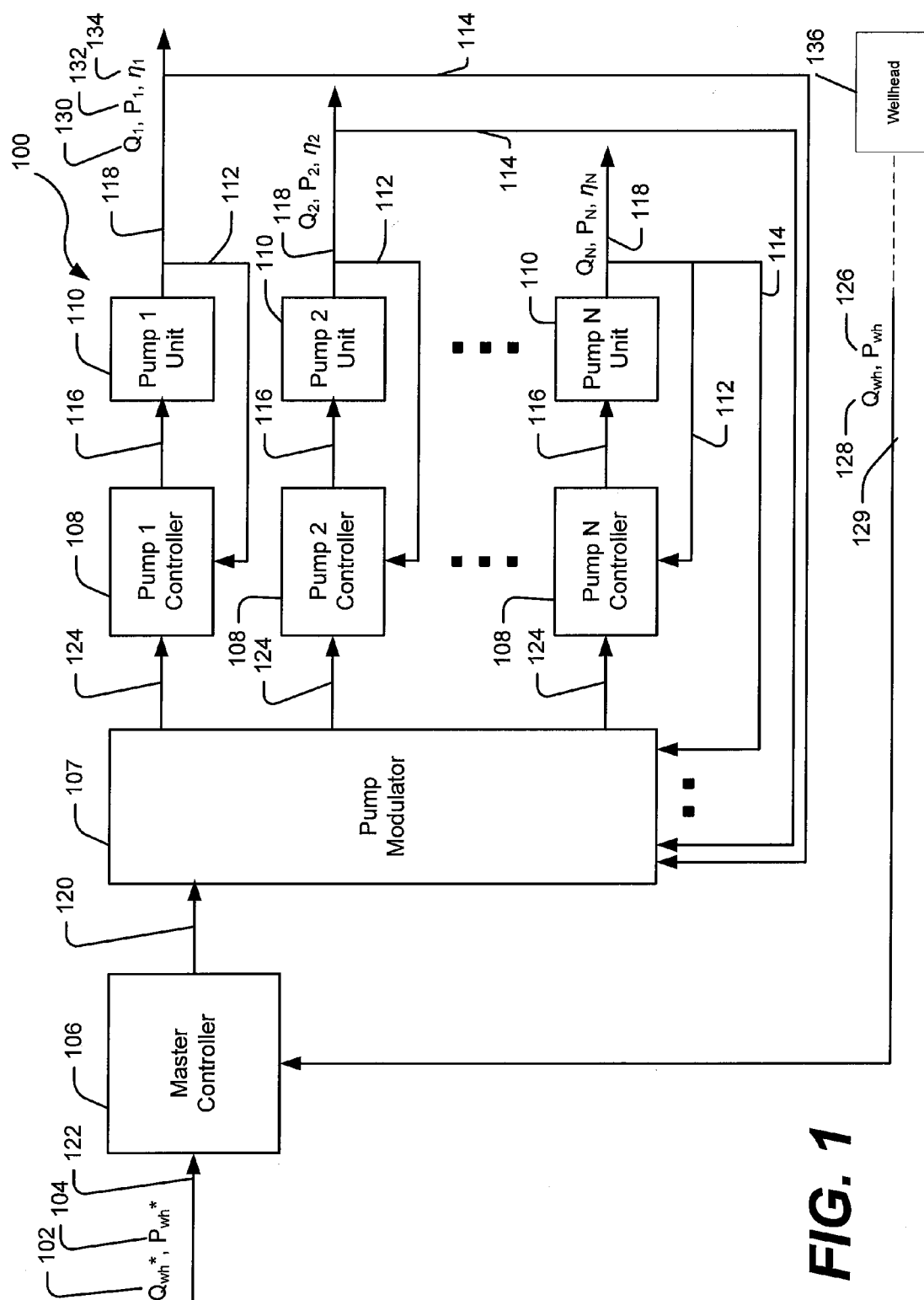


FIG. 1

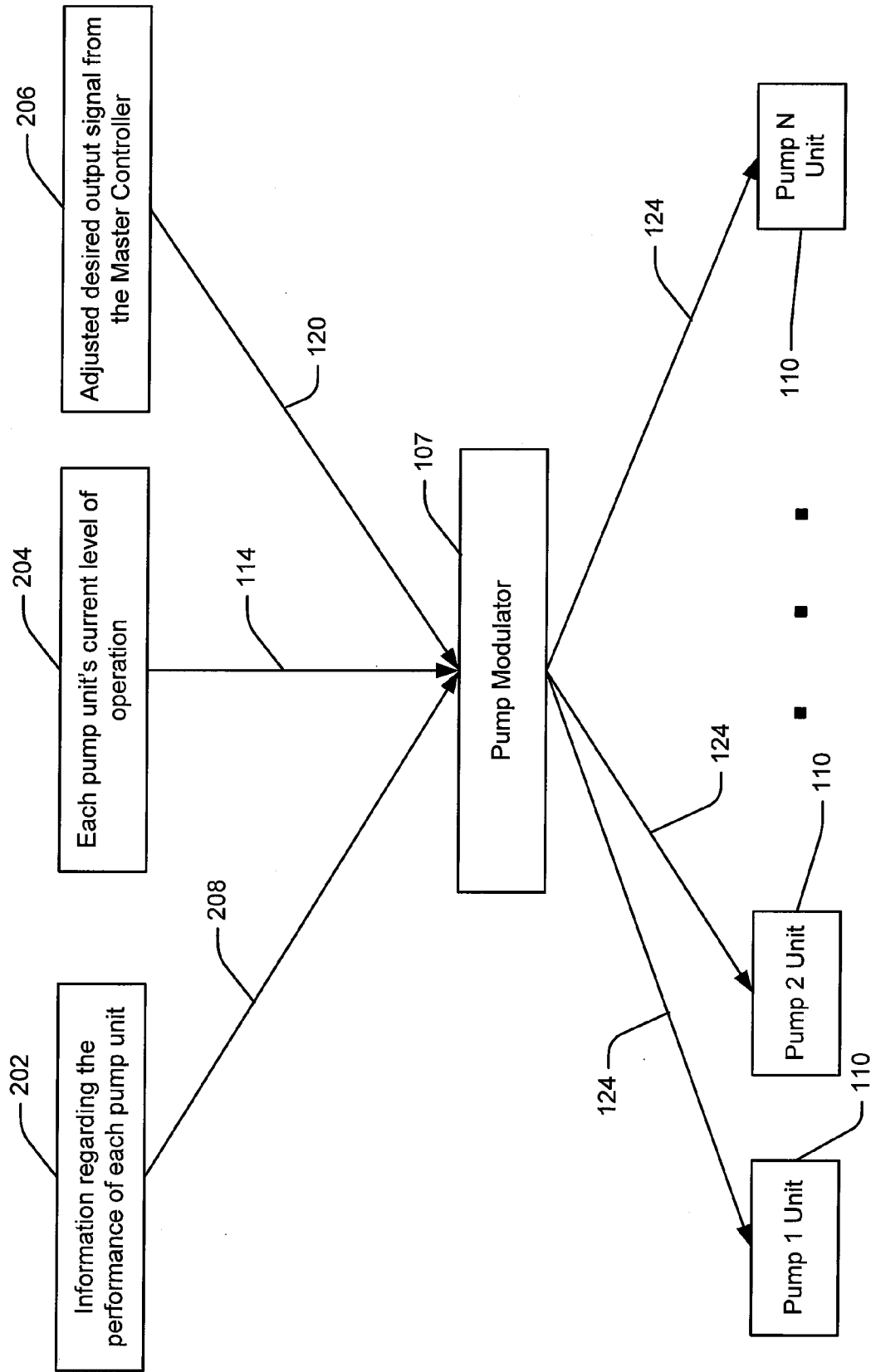


FIG. 2

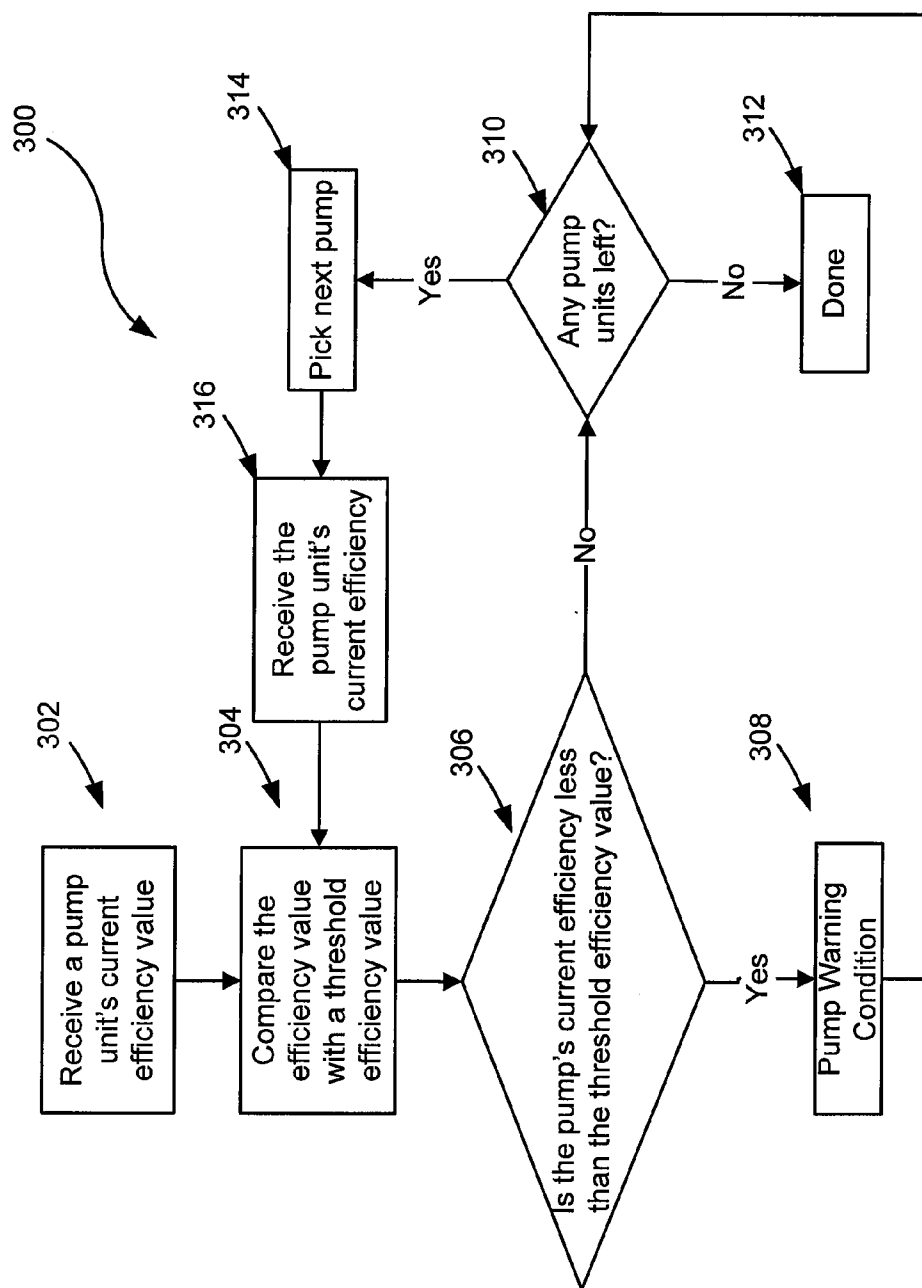


FIG. 3

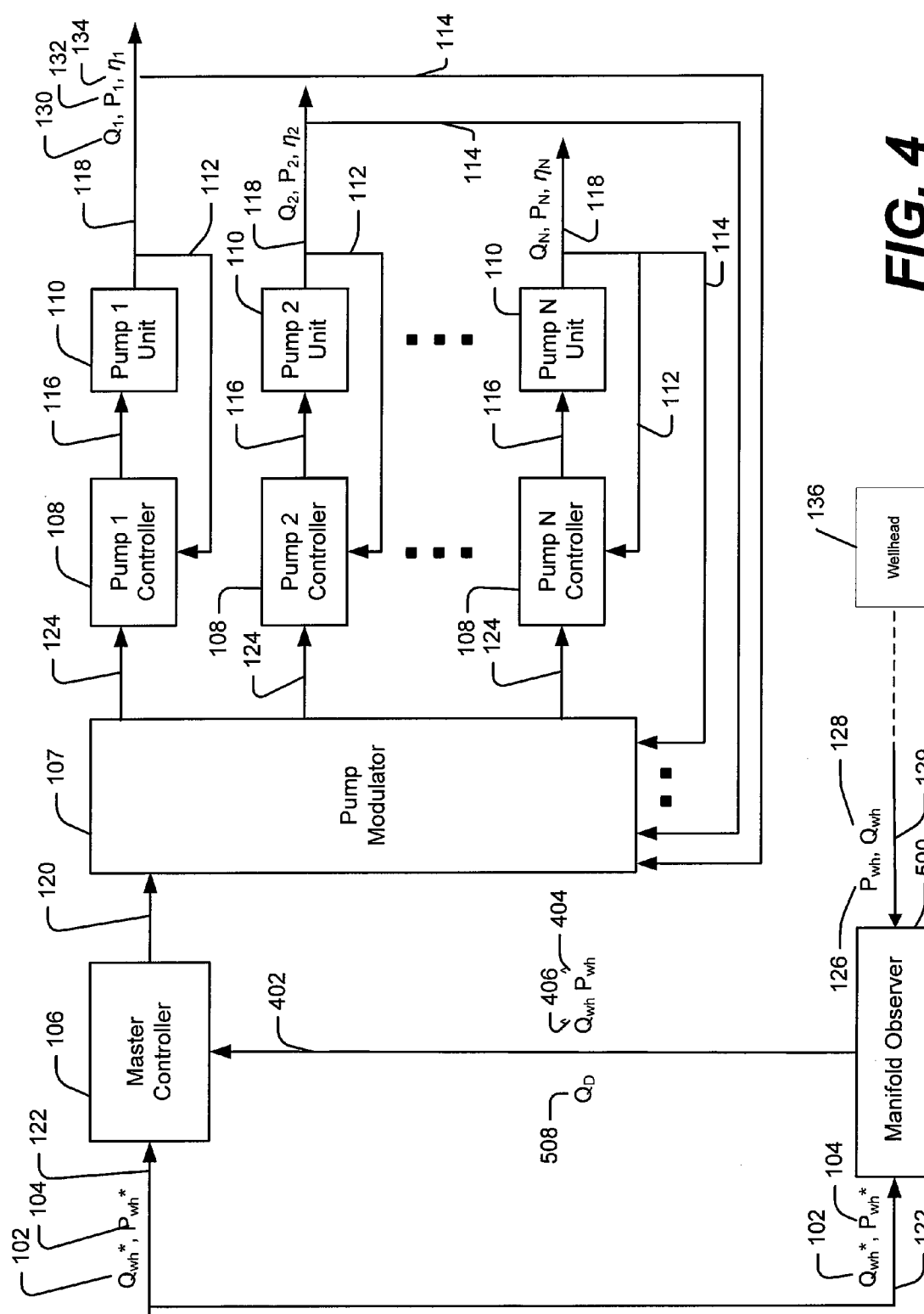


FIG. 4

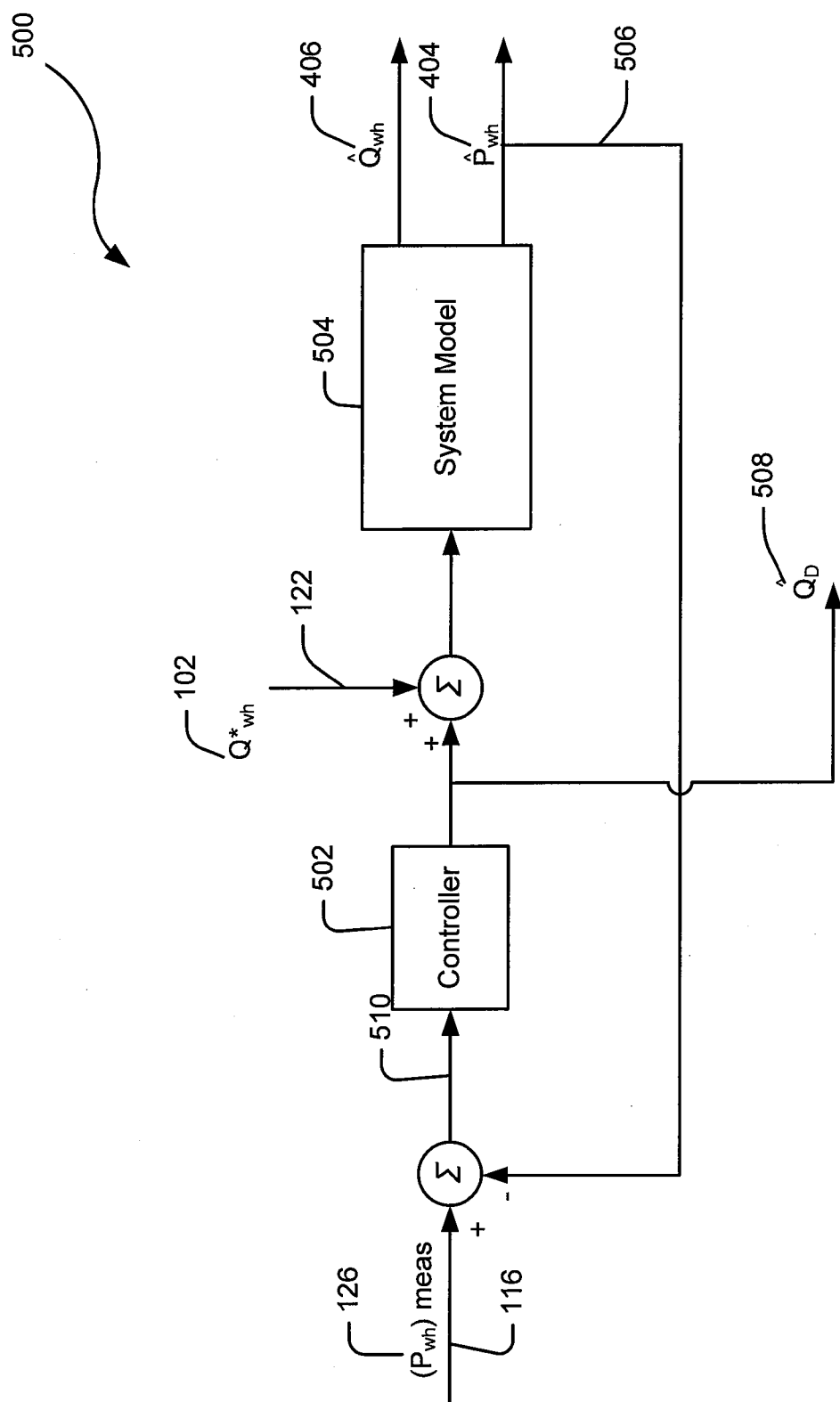


FIG. 5

INTEGRATED "ONE PUMP" CONTROL OF PUMPING EQUIPMENT

BACKGROUND

[0001] The present invention relates, in general, to process control, and more particularly to controlling a pumping process. Specifically, the present invention relates to methods and systems for improving the efficiency of a pumping process by controlling the operation of the pumps involved based on certain parameters characterizing the pump.

[0002] Pumps are used in a variety of industries to deliver fluids. For example, pumps may be used in conjunction with subterranean operations to deliver cement slurries, stimulation fluids, drilling fluids, or other fluids at a desired pressure or flow rate. In order to inject the requisite amount of fluid in a short period of time, multiple pumps are commonly used with the pumping load distributed among them. In a multiple pump set up each pump will handle part of the load and the pumps are adjusted so as to achieve the desired output.

[0003] Currently, the pumps are manually adjusted so that each pump operates at a particular level. Because there is no intelligent control system for deciding the level of operation of each pump, the pumps are assigned a certain load without taking into account the pump's characteristics such as its efficiency or horse power. As a result, some of the pumps operate at their maximum capacity while others are being under utilized.

[0004] The current methods of pump control have several disadvantages. One disadvantage of the current methods is that those pumps that are operating at their maximum capacity will be subject to wear and tear and have a shortened life span while other pumps are being under utilized. This problem is exasperated by the fact that a pump failure can be very costly to an operator who may have to halt the operations while the pump is being repaired or replaced.

[0005] Another drawback of the current methods is that a pump's horse power is not taken into account when assigning a load to the pump. As a result, one pump may run well under its maximum horse power and be underused, while another pump is running close to its maximum horse power thus shortening its life span.

[0006] Also, in some instances such as a fracturing application, the flow rate or pressure of the fluid entering a pump may change with time. Because the current pump control process is a static one, the pump operation is not modified with the change in the fluid flow through the pump. As a result, the pump will continue to operate at a preset operating level even when the fluid flow is reduced. Consequently, a pump may not get enough pressure and flow rate and be starved. When a pump is starved, it will suffer wear and tear.

[0007] Another disadvantage of the current methods is that any sensor readings monitoring the operation of the pumps will produce noisy readings. The effect of this noise is reduced in some instances by passing the sensor reading through a filter. However, the filter produces a lagged signal and the filters often fail to respond to the high frequency of changes in the sensor readings.

[0008] Another drawback of the current methods is that in case of a problem with a pump it may take a considerable amount of time before the rate and pressure of the dropped pump is compensated. Still another problem with the current

methods is that the operators on the field have no idea which pump or pumps would be able to compensate for the dropped pump load.

SUMMARY

[0009] The present invention relates, in general, to process control, and more particularly to controlling a pumping process. Specifically, the present invention relates to methods and systems for improving the efficiency of a pumping process by controlling the operation of the pumps involved based on certain parameters characterizing the pump.

[0010] In one embodiment the present invention is directed to a pumping apparatus comprising a pump unit; a pump controller coupled to the pump unit; a pump modulator coupled to the pump controller; and a master controller coupled to the pump modulator. The value of an output parameter from the pump unit is fed back to the pump controller which generates a first driving signal to the pump unit to drive the value of the output parameter closer to a first desired value received from the pump modulator. The value of an output parameter from the pump unit is also fed back to the pump modulator which generates a second driving signal to the pump controller representing the first desired value to drive the value of the output parameter closer to a second desired value. The master controller compares a first input and a second input and generates a third driving signal to the pump modulator representing the second desired value.

[0011] In another embodiment the present invention is directed to a method for driving a plurality of pump units comprising: generating a first drive signal from each of a plurality of pump controllers to a corresponding pump unit; generating a second drive signal from a pump modulator to each of the plurality of pump controllers; generating a third drive signal from a master controller to the pump modulator; and driving the master controller with a signal representing an actual value of an output parameter and a desired value of the output parameter.

[0012] In yet another embodiment, the present invention is directed to a method for estimating an output parameter of a pump comprising generating an estimated value of a first parameter and an estimated value of a second parameter using a system model; calculating a difference between the estimated value of the second parameter and a measured value of the second parameter; feeding the difference between the estimated value of the second parameter and the measured value of the second parameter to a controller; generating a disturbance signal corresponding to the first parameter; and feeding a sum of the disturbance signal corresponding to the first parameter and a desired value of the first parameter to the system model.

[0013] This type of intelligent system will increase the life of the pumps between maintenance thereby lowering costs and improving job efficiency. Another advantage of the present invention is the capability to develop a pattern on how long each part in a pumping unit can last if they are run at their maximum efficiency, and potentially replace them right before they fail. The present invention also allows monitoring for pump cavitations to prevent damage and make the operations safer.

[0014] The features and advantages of the present invention will be apparent to those skilled in the art from the description of the preferred embodiments which follows when taken in conjunction with the accompanying drawings. While numerous changes may be made by those skilled in the art, such changes are within the spirit of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] These drawings illustrate certain aspects of some of the embodiments of the present invention, and should not be used to limit or define the invention.

[0016] FIG. 1 illustrates a flow diagram for a one pump control system in accordance with an embodiment of the present invention.

[0017] FIG. 2 illustrates a block diagram of operation of the pump modulator in accordance with an embodiment of the present invention.

[0018] FIG. 3 illustrates a flow diagram of the pump modulator process for diagnosing a pump warning condition in accordance with an embodiment of the present invention.

[0019] FIG. 4 illustrates a one pump control system coupled to a manifold pressure and flow rate observer in accordance with an embodiment of the present invention.

[0020] FIG. 5 illustrates a manifold pressure and flow rate observer in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

[0021] The present invention relates, in general, to process control, and more particularly to controlling a pumping process. Specifically, the present invention relates to methods and systems for improving the efficiency of a pumping process by controlling the operation of the pumps involved based on certain parameters characterizing the pump.

[0022] The details of the present invention will now be discussed with reference to the figures. Turning to FIG. 1, an integrated "One Pump" control system in accordance with an embodiment of the present invention is shown generally by reference numeral 100. The master controller 106 of the present invention is responsible for comparing the desired wellhead pressure or rate to the corresponding measured wellhead pressure or rate and driving the pumping process to the desired wellhead pressure or rate. The exemplary embodiment of the present invention as depicted in FIG. 1 comprises a plurality of pump units 110 labeled Pump 1 Unit through Pump N Unit. Each pump unit 110 is coupled to a corresponding pump controller 108. In one embodiment, the pump controller may be a software program that drives the pump unit 110. The pump controller 108 may drive the pump unit 110 to run at a particular level of operation. A level of operation of the pump unit 110 may be defined by a number of parameters including, but not limited to, an output pressure, output flow rate and the gear rpm at which the pump unit 110 operates. The pump controller 108 controls the operation of the pump unit 110 by sending signals 116 to the pump unit 110.

[0023] The individual pump controllers 108 are able to estimate or measure information regarding the performance of the pump. In one embodiment, the performance of each pump unit 110 is measured at 118. The measured performance of a pump at 118 may include, but is not limited to, the output flow rate 130, the output pressure 132 or the output efficiency 134. In some embodiments a flow meter may be used to measure the output flow rate 130 of a pump unit 110 and a pressure transducer may be used to measure the output pressure 132 of a pump unit 110. In certain embodiments, the pump controller 108 has the capability to determine efficiency 134 of the pump unit 110. For example, in one embodiment the pump controller 108 may determine the efficiency of the pump unit 110 using the performance curve of the pump unit 110 and taking into account the pressure or flow rate at

the output 118 of the pump unit 110 and the desired pressure or flow rate the pump unit 110 is directed to provide. In certain embodiments the pump controller 108 may simply compare the desired pressure and flow rate a pump unit 110 is asked to provide with the actual pressure and flow rate provided by that pump unit 110 to determine the pump efficiency 134.

[0024] In one embodiment the performance of the pump unit 110 may be improved by creating a feed back loop 112 to the pump controller 108. The pump controller 108 may use a measured parameter at the output 118 of the pump unit 110, for example output pressure 132 or output flow rate 130, to adjust the driving signal 116 sent to the pump unit 110. By adjusting the driving signal 116 from the pump controller 108 to the pump unit 110 the output 118 at the pump unit 110 can be increased or decreased to match a desired output. As would be appreciated by those of ordinary skill in the art with the benefit of this disclosure, the various pump controllers 108 labeled Pump 1 Controller through Pump N Controller may use different measured parameters at the output of their respective pump units 110 to adjust the performance of the pump unit 110. For example, Pump 1 Controller may use the output pressure of the Pump 1 Unit to adjust its performance while the Pump 2 Controller uses the output flow rate of the Pump 2 Unit to adjust the performance of the Pump 2 Unit.

[0025] The output 118 parameters of each pump unit 110 are also fed into the pump modulator 107. These output parameters may include, but are not limited to, the output pressure, output flow rate, and output efficiency of the pump unit 110. The pump modulator 107 is an intelligent component which uses its knowledge about the system to integrate the operation of the various pump units 110 in the system. Specifically, in certain embodiments the pump modulator 107 knows the current state of performance of each pump unit 110. Based on this information the pump modulator 107 makes an intelligent decision on how to best distribute the load among the individual pumps and assigns pumps their flow rates and or pressures. In case of a problem, it can also determine which pump or pumps can pick up the load and still operate effectively, safely and efficiently.

[0026] In an exemplary embodiment this intelligent decision making process may involve considering the output flow rate of the pump units 110 and the power level at which the pump units 110 are operating. For example, if the output flow rates 114 of the pump units 110 do not match the desired flow rate 120 required by the master controller 106, then the pump modulator 107 will adjust the driving signal sent to each pump accordingly. If the output flow rate of the system is to be increased, then the pump units 110 would have to operate at a higher level and the pump modulator 107 will adjust the driving signal 124 sent to each pump controller 108 accordingly. However, in adjusting the driving signal 124 the pump modulator 107 will take into account the current state of performance of the corresponding pump units 110 as opposed to equally increasing the load on all pump units 110. For instance, if a pump unit is operating well below its maximum capacity, the increase in the driving signal to that pump unit's pump controller will be greater than the increase in the driving signal sent to the pump controller of a pump unit operating near its maximum capacity. Moreover, the driving signal to a pump controller may even be reduced if the pump modulator 107 determines that the pump unit corresponding to that pump controller is approaching its maximum capacity or is performing beyond its normal efficiency range.

[0027] The pump modulator 107 is driven by the master controller 106. In one embodiment, the master controller 106 may be a Proportional-Integral-Derivative controller. As would be appreciated by those of ordinary skill in the art, with the benefit of this disclosure, the master controller 106 may also be a Proportional-Integral controller or a Proportional controller. The master controller 106 treats the multiple pump system as one single pump and generates a driving signal 120 to the pump modulator 107. One or more current wellhead parameters, for example current pressure 126 or current flow rate 128, are measured at the wellhead 136 and fed back to the master controller 106 through the feed back loop 129 as a first input. The second input 122 to the master controller 106 consists of the desired wellhead parameters. For instance, the second input 122 may include, but is not limited to, a particular desired flow rate 102 or pressure 104 at the wellhead. The master controller 106 uses this information to drive the system to the desired job parameters such as a desired pressure 104 or a desired flow rate 102. Specifically, the master controller 106 will increase the driving signal 120 sent to the pump modulator 107 if the measured value of a parameter obtained through the feed back loop 129 is less than the desired value of that parameter provided through the second input 122. In contrast, the master controller 106 will reduce the driving signal 120 to the pump modulator 107 if the measured value of a parameter at the wellhead is greater than the desired value of that parameter.

[0028] As would be appreciated by those of ordinary skill in the art with the benefit of this disclosure one or a combination of different parameters may be measured at the wellhead and fed into the master controller 106. As discussed above, the master controller 106 compares the value of a desired wellhead parameter, such as the desired flow rate 102 or pressure 104, with the actual value of that parameter at the wellhead and generates a driving signal 120 that would drive the measured value closer to the desired value. The driving signal 120 from the master controller 106 to the pump modulator 107 provides the pump modulator 107 with an adjusted desired output parameter value. The adjusted desired output parameter value 120 may include, but is not limited to, a particular adjusted desired flow rate value or a particular adjusted desired pressure value for the system. The adjusted desired output parameter value 120 is obtained by comparing the measured value of the output parameter 129 with the desired value of the output parameter 122 and making adjustments to drive the measured value of the output parameter 129 closer to the desired value 122.

[0029] The pump modulator 107 translates its input driving signal 120 into a plurality of signals sent to the individual pump units 110 through their respective pump controllers 108 so that the system as a whole and each individual pump unit 110 can operate at a high efficiency. In certain embodiments the pump modulator 107 includes a model for the operation of the pump units 110 in the system. For example, the model of operation of the pump units 110 may comprise a pump curve.

[0030] Depicted in FIG. 2 is a flow diagram of the processing of information by the pump modulator in accordance with an embodiment of the present invention. In one embodiment, the pump modulator 107 has three pieces of information 202, 204, 206 that it will process to determine the level at which each pump should operate to achieve the best result. As would be appreciated by those of ordinary skill in the art with the benefit of this disclosure one or any combination of the three pieces of information discussed here may be used by the pump modulator 107 in different embodiments.

[0031] First, the pump modulator 107 contains information 202 regarding the characteristics of each pump unit 110 in the system. In an exemplary embodiment this information may include a model for operation of the pump units 110 such as a pump curve. In other embodiments this information may also include the specification for each pump unit 110 such as the pump unit's 110 horse power. Secondly, the pump modulator 107 receives information 204 regarding each pump unit's 110 current level of operation through the feedback loop 114. In an exemplary embodiment this information may include the pump unit's 110 current operating efficiency 134, flow rate 130 and/or differential pressure 132. Finally, the pump modulator 107 takes as input the driving signal 120 from the master controller 106. As discussed above, this signal provides the pump modulator 107 with an adjusted desired output parameter value. Using these three pieces of information, the pump modulator 107 optimizes and distributes the drive signals 124 sent to each individual pump controller 108 such that no single pump is operated beyond its normal operating range and that the overall system is operating at maximum efficiency. Consequently, the pump modulator 107 provides the system with flexibility in how the individual pumps are loaded.

[0032] Accordingly the pump modulator 107 distributes the load among the pump units 110 based on their characteristics including but not limited to the pump unit horse power or pump unit efficiency. Specifically, using its knowledge of each pump's specification, the pump modulator 107 assigns each pump unit a load in proportion to its capabilities and the under utilization or over use of the pump units is prevented.

[0033] In one embodiment, the pump modulator 107 may also act as a diagnostic tool. Shown in FIG. 3 is a flow diagram of the pump modulator 107 process for diagnosing a pump unit 110 failure in accordance with an embodiment of the present invention. Although the pump unit's efficiency is used as a parameter in this example, as would be appreciated by those of ordinary skill in the art, with the benefit of this disclosure, other pump parameters may be used during the diagnosing process. In one embodiment, the pump unit's efficiency may be used for diagnosing a pump failure. In the exemplary embodiment, at step 302, the pump modulator 107 receives information regarding a pump unit's 110 current efficiency value through the feed back path 114. Next, at step 304, the pump modulator compares the current efficiency value of the particular pump unit 110 with a threshold efficiency value that may be provided by the system operator. At step 306, the pump modulator 107 will compare the pump unit's current efficiency value with the threshold value provided. If the pump unit 110 is operating at an efficiency lower than the threshold value, the pump modulator 107 recognizes that the pump unit has encountered an abnormal operating condition and a warning is issued at step 308. For example, a lower efficiency value may be an indication of cavitation or an indication that the seals in the pump are wearing beyond the normal limits or that a pump has failed completely.

[0034] In certain embodiments the pump modulator 107 may shift the load away from a pump unit 110 which is performing poorly in order to improve the system performance. In some preferred embodiments the pump modulator 107 may completely take a pump unit 110 offline if it determines that the pump unit 110 has suffered a pump failure. In such instances, the pump modulator 107 can redistribute the load among the remaining pump units 110. As a result, the pump units' control parameters such as gear rpm, flow rate and pressure are set according to the specified system pumping requirements, individual pump specifications and existing operating conditions of the pump units. Consequently, each

pump unit **110** will operate at its optimal efficiency while maintaining overall job requirements of the system such as the system flow rate or pressure. In one exemplary embodiment, after the pump modulator **107** determines there is a pump warning condition **308**, it will act to correct the problem or minimizes the impact of the abnormal condition on the system (this step is not shown). For example, if a pump unit is cavitating, the pump modulator **107** may unload that pump unit, for example, by reducing pump unit's speed, which could potentially eliminate the cavitation. If a reduction in the pump unit's operating speed does not improve the efficiency, this may be an indication that the pump unit's seals need to be replaced or that the pump unit should be taken offline and inspected for damages. As would be appreciated by those of ordinary skill in the art with the benefit of this disclosure, a similar process may be used for diagnosing other system defects such as a sensor or pump controller failure.

[0035] Consequently, once the pump modulator **107** determines that a pump is nearing failure or that a pump unit is overloaded or underutilized, it can redistribute the load among the available equipment in order to maintain the job requirements without impacting the job itself. The job requirements include, but are not limited to, a particular job efficiency, flow rate or job pressure. As a result, the pump modulator **107** can in effect provide a real-time correction mechanism for efficiently running a system of pump units.

[0036] If the pump unit's current efficiency value is not less than the threshold efficiency value provided, the pump modulator **107** will look for and carry out a similar analysis on any remaining pump units. At step **310**, the pump modulator **107** will look for any remaining pump units. If there are any pump units remaining, at step **314** the next pump unit to be analyzed is selected. The pump modulator **107** will then obtain that pump unit's current efficiency value at step **316** and the process discussed above will be repeated for the new pump unit. If there are no pump units remaining, the process will terminate at step **312**. Although FIG. **3** depicts the diagnosis process being carried out one pump unit at a time, as would be appreciated by those of ordinary skill in the art, with the benefit of this disclosure, the same process may be carried out simultaneously on multiple pump units.

[0037] The performance of the master controller **106** may further be improved by coupling it to a Manifold Observer **500** as depicted in FIG. **4**. Turning to FIG. **5**, a manifold observer in accordance with an embodiment of the present invention is shown in more detail and is denoted generally by reference numeral **500**. The block **504** labeled "System Model" represents the fluid dynamics equations that may model the flow rates and pressures within the manifold, the pipes, the wellhead or at any other point in the process that is to be analyzed. The model may include a variety of different information including, but not limited to, information related to fluid properties as well as manifold, pipes and wellhead properties such as dimensions, fluid volumes and fluid characteristics such as, for example, orifice pressure losses. The signal **122** is depicted in FIG. **5** as the desired flow rate **102** at the wellhead which is a job specification. However, in another exemplary embodiment the signal **122** could be the combination of estimated and/or measured flow rates from each of the individual pump units **110**. In yet another embodiment, the signal **122** could be the combination of adjusted commanded **116** flow rates to each of the individual pump units **110**. The signal **122** is fed into the system model **504** and used to generate filtered, zero-lagged real-time estimates of the actual wellhead pressure **404** and flow rate **406**. As discussed in more detail below, the manifold observer **500** also gener-

ates a disturbance signal **508** representing any discrepancies between the system model **504** and the actual system.

[0038] The accuracy of the estimation of the wellhead pressure **404** and flow rate **406** by the system model **504** is improved by creating a closed loop control system. Specifically, the closed loop control system of the present invention compares the actual measured wellhead pressure **126** with the estimated wellhead pressure **404** from the system model **504** which feeds back through **506**. The difference between the two signals **510** is then passed through a controller **502**. Although a variety of controllers are available for use with the present invention, in an exemplary embodiment the controller **502** may be a Proportional-Integral-Derivative Controller. As would be appreciated by those of ordinary skill in the art, with the benefit of this disclosure, the controller **502** may also be a Proportional-Integral controller or a Proportional controller.

[0039] Using the pressure error **510** which is the difference between the estimated wellhead pressure **404** and the measured wellhead pressure **126**, the controller **502** in the closed loop of the present invention will enhance the signal being sent to the model so that the estimated signals more closely resemble the measured signals. In particular, the controller **502** uses the pressure error **510** to generate a flow rate disturbance signal **508**. The flow rate disturbance signal **508** is a filtered, zero-lagged signal which represents discrepancies in the model, flow performance through the manifold and errors in the sensors themselves. This flow rate disturbance signal **508** may serve several purposes. In one embodiment, the flow rate disturbance signal **508** is coupled to the input flow rate signal **102** at the input of the system model **504** and can be used to drive the estimated pressure **404** and flow rate **406** closer to the actual pressure **104** and flow rate **102** at the wellhead. As a result, the flow rate disturbance signal **508** helps adjust the model in real-time to better estimate the actual system.

[0040] Moreover, the estimated pressure **404** and flow rate **406** signals which are good estimations of the actual wellhead values have the advantage of being filtered and having a zero lag which makes them more favorable than the actual signals measured by sensors at the wellhead. Therefore, these estimated signals may be used through out a system to replace the actual measured signals which may not be filtered, and even if filtered have a time lag. In certain embodiments the flow rate disturbance signal **508** may also be used as a means to monitor sensor and pump performance. Specifically, a large flow rate disturbance signal **508** may indicate a possible sensor failure or a problem with a pump unit's **110** performance.

[0041] As would be appreciated by those of ordinary skill in the art with the benefit of this disclosure, the pressure and the flow rate parameters may alternatively be used in the manifold observer **500**. Therefore, although the system depicted in FIG. **5** shows the process as using the measured pressure **126** and the input flow rate **102**, the same process may be carried out using the measured flow rate **128** and the desired pressure **104**, measured pressure **126** and/or estimated pressure **132** to generate a pressure correction or disturbance signal (not shown).

[0042] Moreover, the disclosed system provides added flexibility because the manifold observer **500** is not limited to using the measured wellhead pressure **126** in the closed loop controller and may be adjusted to use the measured flow rate **128** instead. Specifically, the disclosed algorithm provides added flexibility in that using both pressure and flow rate sensors becomes redundant. This redundancy can be used to check the sensors in real-time and make adjustments on the fly as needed if a sensor fails to maintain job requirements. Additionally, in certain embodiments flow rate information

from individual pump flow sensors can be incorporated into the system to gain even more knowledge about how the individual pumps are performing.

[0043] The manifold observer 500 is discussed above in the context of estimating wellhead parameters. However, as would be appreciated by those of ordinary skill in the art with the benefit of this disclosure, the manifold observer may be used at any point in a system to provide an estimate of the output parameters at that point based on the measured value of a parameter and the desired value of a parameter at that point in the system.

[0044] Returning now to FIG. 4, a manifold observer 500 is coupled to the master controller 106 in order to further improve the system performance. The flow rate 406 and pressure 404 estimated by the manifold observer 500 are fed into the pump controller 106 through the path 402 thereby replacing the measured flow rate 128 and pressure 126. The estimated wellhead pressure 404 and flow rate 406 at the output of the manifold observer 500 are filtered, zero-lagged signals which with respect to monitoring and use with a control system are of superior quality when compared with traditional filtered signals. Specifically, the traditional low-pass signal filters produce time lagged signals with zero output at high frequencies. However, using the manifold observer 500 the estimated pressure 404 and flow rate 406 signals replacing the actual measured parameters have zero-lag, even at high frequencies, thereby allowing the master controller 106 to react quickly to changing conditions. As a result, the performance of the master controller 106 is improved using the manifold observer 500.

[0045] In certain exemplary embodiments the disturbance signal 508 generated by the manifold observer 500 is also fed into the master controller 106. The master controller 106 may use the disturbance signal 508 to help drive the output parameters toward the desired wellhead values. The availability of the disturbance signal 508 to the master controller 106 makes the master controller 106 more robust and enables the system to better track the desired parameters.

[0046] As would be appreciated by those of ordinary skill in the art, although the present invention is disclosed with a system comprising a plurality of pumps, the same system can be used to improve the operation of a single pump by dynamically adjusting the pump load in accordance with the pump characteristics.

[0047] Therefore, the present invention is well-adapted to carry out the objects and attain the ends and advantages mentioned as well as those which are inherent therein. While the invention has been depicted and described by reference to exemplary embodiments of the invention, such a reference does not imply a limitation on the invention, and no such limitation is to be inferred. The invention is capable of considerable modification, alternation, and equivalents in form and function, as will occur to those ordinarily skilled in the pertinent arts and having the benefit of this disclosure. The depicted and described embodiments of the invention are exemplary only, and are not exhaustive of the scope of the invention. Consequently, the invention is intended to be limited only by the spirit and scope of the appended claims, giving full cognizance to equivalents in all respects. The terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee.

What is claimed is:

1. A pumping apparatus comprising:

- a pump unit;
- a pump controller coupled to the pump unit;
- a pump modulator coupled to the pump controller; and
- a master controller coupled to the pump modulator;

wherein a value of an output parameter from the pump unit is fed back to the pump controller which generates a driving signal to the pump unit to drive the value of the output parameter closer to a first desired value received from the pump modulator;

wherein a value of an output parameter from the pump unit is fed back to the pump modulator which generates a driving signal to the pump controller representing the first desired value to drive the value of the output parameter closer to a second desired value;

wherein the master controller compares a first input and a second input and generates a driving signal to the pump modulator representing the second desired value.

2. The pumping apparatus of claim 1, wherein the output parameter of the pump unit comprises one of a flow rate, a pressure or an efficiency.

3. The pumping apparatus of claim 2, wherein the pump controller determines the efficiency of the pump unit.

4. The pumping apparatus of claim 2, wherein the flow rate is measured with a flow meter.

5. The pumping apparatus of claim 2, wherein the pressure is measured with a pressure transducer.

6. The pumping apparatus of claim 1, wherein the master controller is one of a Proportional-Integral-Derivative Controller, a Proportional-Integral controller or a Proportional controller.

7. The pumping apparatus of claim 1, wherein the first input of the master controller is a desired output parameter and the second input of the master controller is a measured output parameter.

8. The pumping apparatus of claim 7, wherein the desired output parameter and the measured output parameter include one of an output flow rate or an output pressure.

9. The pumping apparatus of claim 1, wherein the first input of the master controller is a desired output parameter and the second input of the master controller is an estimated output parameter.

10. The pumping apparatus of claim 9, wherein the estimated output parameter is obtained from a manifold observer comprising:

a system model generating an estimated value for a first parameter and an estimated value for a second parameter;

a feed back loop coupling the estimated value for the second parameter with a measured value for the second parameter;

a controller;

wherein an input of the controller comprises a difference between the estimated value for the second parameter and the measured value for the second parameter;

wherein the output of the controller comprises a disturbance signal corresponding to the first parameter; and

wherein an input of the system model comprises a sum of a desired value for the first parameter and the disturbance signal corresponding to the first parameter.

11. The pumping apparatus of claim 10, wherein the controller is one of a Proportional-Integral-Derivative Controller, a Proportional-Integral controller or a Proportional controller.

12. The pumping apparatus of claim 10, wherein an operator is notified if the disturbance signal is above a threshold value.

13. The pumping apparatus of claim 1, wherein the pump modulator includes a model for operation of the pump unit.

14. The pumping apparatus of claim 13, wherein the model includes a pump curve.

15. The pumping apparatus of claim 1, wherein the pump modulator includes information about a characteristic of the pump unit.

16. The pumping apparatus of claim 15, wherein the characteristic includes one of a power of the pump unit or an efficiency of the pump unit.

17. The pumping apparatus of claim 1, wherein the pump controller is a software program.

18. A method for driving a plurality of pump units comprising:

generating a plurality of first drive signals from each of a plurality of pump controllers to a corresponding pump unit;

generating a plurality of second drive signal from a pump modulator to each of the plurality of pump controllers;

generating a third drive signal from a master controller to the pump modulator; and

driving the master controller with a signal representing an actual value of an output parameter and a desired value of the output parameter.

19. The method of claim 18, wherein a value of a first drive signal depends on a value of a corresponding second drive signal and a value of an output parameter of the corresponding pump unit.

20. The method of claim 19, wherein the value of a first drive signal from a first pump controller depends on a value of a first output parameter and the value of a first drive signal from a second pump controller depends on a value of a second output parameter.

21. The method of claim 19, wherein the output parameter is one of an output flow rate, an output pressure or an output efficiency.

22. The method of claim 18, wherein a value of a second drive signal depends on a value of a corresponding third drive signal and a value of an output parameter of the corresponding pump unit.

23. The method of claim 22, wherein the output parameter is one of an output flow rate, an output pressure or an output efficiency.

24. The method of claim 18, wherein the value of a second drive signal depends on a characteristic of a corresponding pump unit.

25. The method of claim 24, wherein the characteristic of the corresponding pump unit includes one of horse power or efficiency.

26. The method of claim 18, wherein the signal representing the actual value of the output parameter is a measured value of the output parameter.

27. The method of claim 18, wherein the signal representing the actual value of the output parameter is an estimate of the actual value of the output parameter.

28. The method of claim 18, wherein the output parameter comprises one of an output pressure or an output flow rate.

29. The method of claim 18, wherein the pump modulator distributes a work load among the plurality of the pump controllers.

30. The method of claim 29, wherein the pump modulator distributes the work load among the plurality of the pump controllers based on a characteristic of the corresponding pump unit.

31. The method of claim 30, wherein the characteristic of the corresponding pump unit includes one of efficiency or horse power.

32. The method of claim 29, wherein upon a pump unit failure the pump modulator terminates the second driving signal to a pump controller corresponding to the pump unit.

33. The method of claim 32, wherein the pump modulator distributes the terminated signal among the plurality of pump controllers corresponding to an operational pump unit.

34. A method for estimating an output parameter of a pump comprising:

generating an estimated value of a first parameter and an estimated value of a second parameter using a system model;

calculating a difference between the estimated value of the second parameter and a measured value of the second parameter;

feeding the difference between the estimated value of the second parameter and the measured value of the second parameter to a controller;

generating a disturbance signal corresponding to the first parameter; and

feeding a sum of the disturbance signal corresponding to the first parameter and a desired value of the first parameter to the system model.

35. The method of claim 34 further comprising notifying an operator if the correction signal is above a threshold value.

36. The method of claim 34, wherein the system model comprises one of: a fluid dynamic equation; a fluid characteristic information; or a manifold characteristic information.

37. The method of claim 34, wherein the controller is one of a Proportional-Integral-Derivative Controller, a Proportional-Integral controller or a Proportional controller.

38. The method of claim 34, wherein the first parameter is a flow rate and the second parameter is a pressure.

39. The method of claim 34, wherein the first parameter is a pressure and the second parameter is a flow rate.

40. The method of claim 34, further comprising:

feeding the estimated value of the first parameter to a master controller;

feeding a desired value of the first parameter to the master controller;

generating a first driving signal from the master controller to a pump modulator;

generating a second driving signal from the pump modulator to a pump controller; and

generating a third driving signal from the pump controller to a pump unit.

41. The method of claim 40, wherein a value of the first driving signal depends on a difference between the estimated value of the first parameter and the desired value of the first parameter.

42. The method of claim 40, wherein a value of the second driving signal depends on a value of the first driving signal and a value of an output parameter of the pump unit.

43. The method of claim 42, wherein the output parameter comprises one of a flow rate or a pressure.

44. The method of claim 40, wherein a value of the third driving signal depends on a value of the second driving signal and a value of an output parameter of the pump unit.

45. The method of claim 44, wherein the output parameter comprises one of a flow rate or a pressure.