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(71) Applicant: **Danfoss Scotland Limited**
Edinburgh EH3 9DQ (GB)

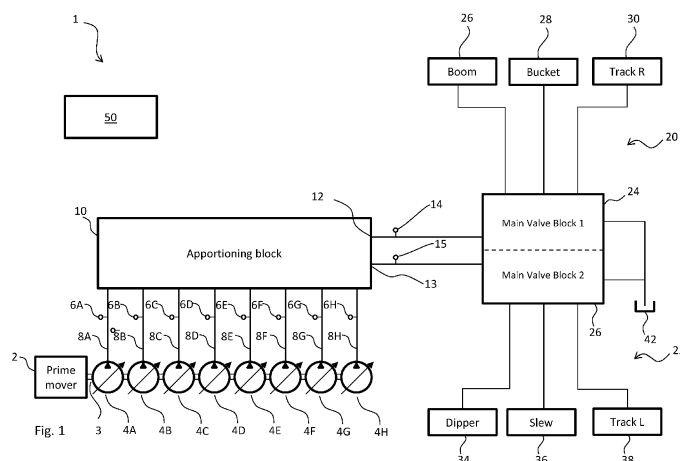
(72) Inventor: **PELLEGRI, Matteo**
Edinburgh (GB)

(74) Representative: **Hindles Limited**
Clarence House
131-135 George Street
Edinburgh, EH2 4JS (GB)

(54) **HYDRAULIC APPARATUS WITH MULTIPLE FLOWS AND OPERATING METHOD THEREOF**

(57) An apparatus comprises a hydraulic machine driven by a prime mover and a plurality of hydraulic circuit portions, each having one or more hydraulic actuators. Pump modules of the hydraulic machine are primarily connected to one of the hydraulic circuit portions at a time and may be reallocated from one hydraulic circuit portion to another. A variable flow regulator allows the flow from or to a pump module to or from a hydraulic circuit portion to be split or combined, or allows a flow

between manifolds which are connected to the hydraulic circuit portions. In each case the flow rate is regulated. The variable flow regulator may comprise a proportional flow valve which allows a controlled throttled flow there-through. The apparatus is useful when the demand for fluid flow is close to or exceeds the capacity of the hydraulic machine as fluid flows may be varied continuously in a controlled fashion.



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Description

Field of the invention

[0001] The invention relates to the field of apparatus which provide multiple pumped flows of hydraulic fluid to actuators in hydraulic machines such as vehicles (for example excavators) or industrial machines (e.g. injection moulding machines, waterjet cutting machines). The invention is also applicable to apparatus where multiple flows of hydraulic fluid are received from actuators in hydraulic machines.

Background to the invention

[0002] WO2021/044148 (Caldwell and Stein) discloses a hydraulic apparatus in which a plurality of pump modules is connectable to first and second hydraulic circuit portions to drive respective first and second groups of hydraulic actuators. Pump modules may be dynamically reallocated from one hydraulic circuit portion to another to address changing demands for fluid supply.

[0003] Difficulties arise when the individual demands for fluid by the actuators of each hydraulic circuit portion cannot be met concurrently. This is exacerbated by the requirement that each pump module is connected to a single hydraulic circuit portion meaning that there will be circumstances where one or more pump modules have spare capacity but this capacity cannot be utilised as re-allocation of the pump modules with spare capacity to meet the demand in other hydraulic circuit portions would cause the hydraulic circuit portions to which they were connected to become undersupplied. Still further, when a pump module is reallocated from one hydraulic circuit portion to another which had been undersupplied there is potential for there to be a surge in the supply of fluid to the new hydraulic circuit portion, due to the availability of a new pump module, leading to a sudden jump in displacement which can cause juddering, vibrations and other undesirable transient effects.

[0004] WO2021/044148 proposed addressing this problem by scaling back displacement to each hydraulic circuit portion when the total displacement exceeded a threshold. This can avoid sudden jumps in displacement but at the expense of some capacity.

[0005] The present invention seeks to provide an apparatus in which pump modules may be reallocated between hydraulic circuit portions while minimising any loss of capacity.

Summary of the Invention

[0006] According to a first aspect of the invention there is provided an apparatus comprising:

a prime mover;

a plurality of hydraulic circuit portions for supplying

or receiving hydraulic fluid to or from one or more actuators;

a hydraulic machine having a rotatable shaft in driven engagement with the prime mover and comprising at least three working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber of the hydraulic machine comprising a low-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a low-pressure manifold, and a high-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a high-pressure manifold, wherein the working chambers are formed into a plurality of pump modules each pump module comprising a group of one or more of the working chambers and a high-pressure manifold which is common to each working chamber in the group;

a hydraulic connecting circuit configured to selectively connect each hydraulic circuit portion to the high-pressure manifolds of one or more of the pump modules;

one or more variable flow regulators configured to selectively divert some of the flow of hydraulic fluid from or to one or more of the pump modules to or from a first hydraulic circuit portion to concurrently flow to or from a second hydraulic circuit portion; and

a controller configured to actively control at least the low pressure valves of the said working chambers to determine the net displacement of each working chamber during each cycle of working chamber volume, and also the one or more variable flow regulators, to independently regulate the flow of fluid to or from each of the hydraulic circuit portions.

[0007] The invention also extends in a second aspect to a method of operating an apparatus according to the first aspect, comprising determining the net displacement of each working chamber and also the one or more variable flow regulators, to independently regulate the flow of fluid to and from each of the hydraulic circuit portions.

[0008] In apparatus according to the invention, flow from or to one or more of the pump modules may be directed to or received from two (or more) of the hydraulic circuit portions. Each pump module may therefore be operated close to or at maximum displacement with the diversion of flow between the hydraulic circuit portions varied as and when required. Thus, the capacity of the pump modules can be utilised more than in the arrangement of WO 2021/044148 in circumstances where there are high or excessive competing demands for fluid flow. Furthermore, this arrangement is compatible with the flow rates or pressures in the hydraulic circuit portions being very different to each other. It may be that in at

least some circumstances in the normal operating mode the pressure in the first and second hydraulic circuit portions differs by a factor of at least two.

[0009] Typically, the one or more variable flow regulators comprise or are variable valves, typically having a variable internal cross-sectional area through which fluid flows, such as proportional flow valves. Usefully, variable valves are controllable and function to throttle (and thereby carefully control) flow between manifolds at substantially different pressures. Typically, the selective diversion of some of the flow of fluid has the effect that fluid flow from (or to) the one or more pump modules is split (or combined) to (or from) both the first and second hydraulic circuit portions concurrently, and typically also continuously, when the variable flow regulator is being used to selectively divert hydraulic fluid. Typically, as a result of the diversion, some of the flow of hydraulic fluid from or to one or more of the pump modules which would otherwise flow to or from a first hydraulic circuit portion concurrently flows to or from a second hydraulic circuit portion instead of the first hydraulic circuit portion.

[0010] Typically, the hydraulic connecting circuit comprises a plurality of connecting circuit valves. The controller may be configured to control the plurality of connecting circuit valves. The method may comprise controlling the plurality of connecting circuit valves. In some embodiments, one or more of the variable flow regulators comprise one or more of the plurality of connecting circuit valves.

[0011] Typically, the controller is configured to control the net displacement of each working chamber, the plurality of connecting circuit valves and the one or more variable flow regulators in concert to control the flow rate of hydraulic fluid to or from the one or more actuators, typically responsive to one or more demand signals (for example, for each hydraulic circuit portion, at least one demand signal associated with a demand for flow from or to the actuators connected to the respective hydraulic circuit portion). The method may comprise controlling the net displacement of each working chamber, the plurality of connecting circuit valves and the one or more variable flow regulators in concert to control the flow rate of hydraulic fluid to or from the one or more actuators, typically responsive to one or more demand signals.

[0012] It may be that the hydraulic connecting circuit further comprises at least a first pressurised fluid manifold which is connected to the first hydraulic circuit portion and a second pressurised fluid manifold which is connected to the second hydraulic circuit portion. Typically, the plurality of connecting circuit valves are controllable (by the controller) to connect the one or more pump modules to either the first or second hydraulic circuit portion at any given time.

[0013] Typically the method comprises controlling (or the controller is configured to control) the plurality of connecting circuit valves such that, in a normal operating mode, some or all of the pump modules are directly connected to and supply fluid to or receive fluid from only

one pressurised fluid manifold at a time and that for some or all of the pump modules, the pressurised fluid manifold to which the respective pump module is directly connected may be changed.

[0014] Typically, in use, in a normal operating mode, some or all of the pump modules are connected to and supply fluid to or receive fluid from only one pressurised fluid manifold at a time. Typically, in use, in a normal operating mode, for some or all of the pump modules, the pressurised fluid manifold to which the respective pump module is directly connected may be changed (for example by operating one or more said connecting circuit valves).

[0015] It may be that one or more variable flow regulators are connected between the high-pressure manifold of a pump module and two pressurised fluid manifolds to thereby controllably regulate the proportion of flow from or to the pump module which flows directly into or from each of the two pressurised fluid manifolds. Typically, fluid from or to the pump module flows predominantly to one of the two pressurised fluid manifolds with some of the flow diverted to or from the other of the two pressurised fluid manifolds. By some we refer to a fraction which is greater than none but less than all.

[0016] Thus, it may be that one or more variable flow regulators function as flow splitters or combiners, typically variable flow splitters or combiners. In this case the controller can regulate the proportion of flow output from or received by the pump module which is diverted to or received from each of the two pressurised fluid manifolds and thus to each of the hydraulic circuit portions. The method may comprise controlling a variable flow regulator to regulate the proportion of flow output from or received by the pump module which is diverted to or received from each of the pressurised fluid manifolds.

[0017] In this arrangement, the first and second hydraulic circuit portions are each connected to the high-pressure manifold of the pump, with the one or more variable flow regulators controlling the proportion of flow into or out of each of the first and second hydraulic circuit portions. The two hydraulic circuit portions function as the first and second hydraulic circuit portions.

[0018] It may be that the apparatus comprises n pressurised fluid manifolds, each connected to a respective one of n hydraulic circuit portions, wherein, in a normal operating mode, the flow from or to no more than $n-1$ pump modules is split between or combined from multiple hydraulic circuit portions and the high pressure manifold of each remaining pump module is connected only to one of the n pressurised fluid manifolds at a time.

[0019] The method typically comprises controlling the connecting circuit valves such that the flow from or to no more than $n-1$ pump modules is split between or combined from multiple hydraulic circuit portions and the flow from or to each remaining pump module is directed to or received from one hydraulic circuit portion at a time (without splitting or combining).

[0020] Thus, except for $n-1$ pump modules which out-

put split flow, or receive combined flow, the remaining pump modules are connected to only one pressurised fluid manifold at a time which can improve energy efficiency.

[0021] n may be 2. n may be 2 or more. n may be 3. n may be 3 or more.

[0022] It may be that the high-pressure manifold of a pump module is connected to the first hydraulic circuit portion through the hydraulic connecting circuit, and a variable flow regulator is controllable to provide a path for a variable amount of hydraulic fluid to flow concurrently to or from the second hydraulic circuit portion, from or to the high-pressure manifold of the pump module (instead of the first hydraulic circuit portion). It may be that, in an operating mode, the pump module is connected to the first hydraulic circuit portion through a variable flow regulator which is a valve which is fully opened (to minimise resistance to fluid flow) and the variable flow regulator (e.g. a further valve) provides an alternative path through which a variable (and controllable) amount of fluid is diverted to or from the second hydraulic circuit portion. It is possible that a pump module is connected to both the first and second hydraulic circuit portion through respective first and second variable valves (e.g. proportional flow valves) and that, in an operating mode, both the first and second variable valves are held partially open. However, it is typically more energy efficient for one of the valves (the one connected to what is referred to herein as the first hydraulic circuit portion) to be fully open in the operating mode.

[0023] In this arrangement, hydraulic fluid flows from or to the pump module into or out of the first hydraulic circuit portion and hydraulic fluid flows into or out of the second hydraulic circuit portion from or to the pump module via the first hydraulic circuit portion and the variable flow regulator.

[0024] It may be that the hydraulic connecting circuit comprises a first pressurised fluid manifold which is connected to the first hydraulic circuit portion and a second pressurised fluid manifold which is connected to the second hydraulic circuit portion, wherein the high pressure manifold of each pump module is connectable to the first or second pressurised fluid manifold (e.g. by the one or more connecting circuit valves) and wherein one or more variable flow regulators is connected between the first and second pressurised fluid manifolds, to thereby controllably regulate a flow rate of fluid between the pressurised fluid manifolds and regulate the flow rate of fluid to from the first and second hydraulic circuit portions.

[0025] Thus, a variable flow regulator controls the leakage of fluid from one pressurised fluid portion (whichever is at relatively higher pressure) to another pressurised fluid portion (which is at lower pressure). Thus the variable flow regulator modifies the flow rate from or two the hydraulic circuit portions from the pump modules connected to each pressurised fluid manifold.

[0026] The method typically comprises calculating (and the controller is typically configured to calculate) a

flow rate through the variable flow regulator, between the first and second pressurised fluid manifolds, to give a desired net flow of fluid to or from the first and second hydraulic circuit portions (to or from the plurality of pump modules).

[0027] Thus the controller controls the net flow rate of the working chambers of the one or more pump modules connected (directly) to the first pressurised fluid manifold and, independently, the net flow rate of the working chamber of the one or more pump modules connected (directly) to the second pressurised fluid manifold and the flow rate through the variable flow regulator, to give a desired net flow of fluid to or from the first and second hydraulic circuit portions.

[0028] In this case, typically the method comprises connecting (and the controller is configured to control the hydraulic connecting circuit to connect) the high pressure manifold of each of the pump modules directly to only one of the pressurised fluid manifolds. Nevertheless, although an individual pump module is connected directly to only one of the pressurised fluid manifolds, flow from or to the individual pump module may flow to or from the other pressurised fluid manifold indirectly, via the said only one of the pressurised fluid manifolds and the variable flow regulator.

[0029] The apparatus may comprise one or more further pressurised fluid manifolds, the or each further pressurised fluid manifold connected to a respective hydraulic circuit portion, wherein one or more variable flow regulators are connected to at least one or all of the further pressurised fluid manifolds to thereby controllably regulate the flow of fluid between the pressurised fluid manifolds and regulate the flow of fluid to from each of the hydraulic circuit portions.

[0030] It may be that at least one variable flow regulator comprises at least one valve.

[0031] The variable flow regulator may comprise a branched conduit. The variable flow regulator may comprise a hydraulic motor.

[0032] It may be that the at least one variable flow regulator comprises a valve having a variable internal cross-sectional area. By the internal cross-sectional area we refer to the cross-sectional area of the flow path through the valve. This may be varied by, for example, movement of a valve member by an actuator (e.g. a solenoid) under the control of the controller.

[0033] The method may comprise controlling the valve (and the controller may be configured to control the valve) by varying the internal cross-sectional area of the valve. Thus the valve may be a proportional flow valve.

[0034] It may be that the or each pump module is connected to the first hydraulic circuit portion through a first valve and to the second hydraulic circuit portion through a second valve, wherein the first and second valves are controllable (by the controller).

[0035] It may be that, in addition to the first and second valves, which are controllable, there are provided check valves between each of the first and second hydraulic

circuit portions and the pump module to ensure that the flow of hydraulic fluid is in one direction (from the pump module into the first and second hydraulic circuit portions or vice versa).

[0036] It may be that the first and second valves are each switching valves which are normally open or closed and are not held at an intermediate position therebetween.

[0037] It may be that the first and second valves are each proportional flow valves which may be open, closed or held at a position therebetween by the controller.

[0038] It may be that the apparatus comprises pressure sensors configured to measure the fluid pressure in the respective hydraulic circuit portions, wherein the controller is configured to control a variable flow regulator responsive to the pressures in the first and the second hydraulic circuit portions to regulate the flow of fluid to or from the first and second hydraulic circuit portions.

[0039] Thus, the controller independently regulates the flow of fluid to or from the one or more actuators connected to each of the first and second hydraulic circuit portions.

[0040] It may be that the method comprises calculating (and the controller is configured to calculate) a rate of flow of hydraulic fluid through the variable flow regulator taking into account the measured pressure in the first and second hydraulic circuit portions. The controller may also take into account the pressure in the high-pressure manifold of the pump module. (The pressure in the high-pressure manifold of the pump module is important when the variable flow regulator is connected between the high-pressure manifold of a pump module and two hydraulic circuit portions. Where the variable flow regulator is connected between two hydraulic circuit portions, it may be sufficient to measure the pressure in the two hydraulic circuit portions to determine the flow through the variable flow regulator). The calculated rate of flow may be the current rate of flow. The calculated rate of flow may be a target rate of flow. The method may comprise controlling (and the controller may be configured to control) the variable flow regulator to achieve a target rate of flow (for example by varying the internal cross-sectional area of a valve of the variable flow regulator).

[0041] In the case where the variable flow regulator is a valve with a variable internal cross-sectional area, the flow rate through the valve is given by the formula:

$$Q_i = K_i \sqrt{\Delta p_i}$$

[0042] Where the flow rate through valve i , K_i is a constant which is a function of the internal cross-sectional area of valve i and Δp_i is the pressure differential across valve i .

[0043] The controller may also regulate the displacement of the working chambers of one or more pump modules to regulate the pressure in the first and second hydraulic circuit portions.

[0044] It may be that the controller is configured to control the displacement of the working chambers of the pump module, and the connecting circuit valves and the variable flow regulator further wherein the controller is configured to vary the displacement of the working chambers of the pump module and/or the flow through the variable flow regulator prior to causing the switching valves to change which hydraulic circuit portion the pump module is connected to.

[0045] Typically, this smooths the change in the rate of working fluid flow to or from the one or more actuators connected to the hydraulic circuit portions to which the pump module is connected before and after the change.

[0046] It may be that the controller is configured to control the variable flow regulator to damp a change or oscillation in the amount of hydraulic fluid flowing to or from one or more actuators connected to a hydraulic circuit portion to which the variable flow regulator is connected.

[0047] The method may comprise controlling the variable flow regulator (for example varying the internal cross-sectional area of a proportional flow valve) to damp a change or oscillation in the amount of hydraulic fluid flowing to or from one or more actuators connected to a hydraulic circuit portion to which the variable flow regulator is connected.

[0048] It may be that the controller is configured to control the displacement of the working chambers of the pump module, and the connecting circuit valves and the variable flow regulator, to optimise one or more operating parameters.

[0049] The method may comprise control the displacement of the working chambers of the pump module, and the connecting circuit valves and the variable flow regulator, to optimise one or more operating parameters.

[0050] The one or more operating parameters may comprise overall energy efficiency of the apparatus. The one or more operating parameters may comprise energy efficiency while delivering a given flow rate of hydraulic fluid to a plurality of actuators connected to two or more hydraulic circuit portions. Energy efficiency is typically maximised. The one or more operating parameters may comprise smoothness of operation of one or more actuators, typically responsive to commands from a user through a user interface. Smoothness is typically maximised.

[0051] The method may further comprise controlling the switching valves in concert with the net displacement of each working chamber and the one or more variable flow regulators to regulate the displacement of hydraulic fluid to or from each of the hydraulic circuit portions.

Description of the Drawings

[0052] An example embodiment of the present invention will now be illustrated with reference to the following Figures in which:

Figure 1 is a schematic diagram of a hydraulic ap-

paratus;

Figure 2 is a more detailed diagram of an apportioning block according to the present invention;

Figure 3 is a schematic diagram of a valve arrangement associated with an individual pump module 4A, other pump modules 4B to 4H correspond;

Figure 4 is a schematic diagram of an individual pump module;

Figure 5 is a schematic diagram of a controller;

Figure 6 is a schematic diagram of the division of flow between connecting circuit outputs when demands are 25% and 30% of maximum flow rate respectively;

Figure 7 is a schematic diagram of the division of flow in a prior art arrangement according to WO 2021/044148;

Figure 8 is a schematic diagram of the division of flow in an apparatus according to the present invention;

Figure 9 is a schematic diagram of the split of flow from a high pressure manifold 8D of pump module 4D between the first and second pressurised fluid manifolds, through proportional flow valves, other pump modules 4A-4C and 4D-4H typically correspond;

Figure 10 is a schematic diagram of an apparatus with an alternative apportioning block arrangement using switching valves and a proportional flow valve connected between pressurised fluid manifolds;

Figure 11 is a schematic diagram of a connecting circuit valve arrangement 60A associated with an individual pump module 4A in the apparatus of Figure 10; valve arrangements 60B-60H for other pump modules 4B-4H correspond; and

Figure 12 is a schematic diagram of proportional flow valve connections in an apparatus with three pressurised fluid manifolds for supplying hydraulic fluid to three hydraulic circuit portions.

Detailed Description of an Example Embodiment

[0053] With reference to Figure 1, an excavator 1 (the apparatus) comprises an engine 2, which drives a plurality of pump modules 4A, 4B, 4C, 4D, 4E, 4F, 4G, 4H, each of which comprises a number of working chambers in the form of piston cylinder units, PCUs, which are driven by the prime mover through a common rotating shaft

3. The working chambers within a given pump module are connected so as to provide a common output of hydraulic fluid through a respective high pressure manifold 8A, 8B, 8C, 8D, 8E, 8F, 8G, 8H to an apportioning block 10 (functioning as the hydraulic connecting circuit) which has inlets (connecting circuit inputs) to receive fluid from each high pressure manifold, and outputs 12, 13 (connecting circuit outputs) which are inlets (hydraulic circuit portion inlets) to first and second hydraulic circuit portions 20, 22. Pressure sensors 6A, 6B, 6C, 6D, 6E, 6F, 6G, 6H measure the pressure in respective high pressure manifolds, at the inlets to the apportioning block, and pressure sensors 14, 15 measure the pressure at the inlets to the hydraulic circuit portions.

[0054] The first hydraulic circuit portion has a first control valve block 24 and a first plurality of actuators (26, 28, 30), in this example a boom 26, a bucket 28 and a right track 30. The second hydraulic circuit portion has a second control valve block 26 and a second plurality of actuators (34, 36, 38), in this example a dipper 34, a slew function 36, and a left track 38. The first and second control valve blocks 24, 26 control the distribution of fluid received into the hydraulic circuit portions to the various actuators. The first and second hydraulic circuit portions output fluid back to tank 42. A controller 50 controls working chamber valves which regulate the flow of fluid within each working chamber and connecting circuit valves within the apportioning block as will be described.

[0055] Figure 2 is a schematic diagram of connections within the apportioning block in a first example. Within the apportioning block, a first pressurised fluid manifold 16 is connected to output 12 and so to the first hydraulic circuit portion, and a second pressurised fluid manifold 17 is connected to output 13 and so to the second hydraulic circuit portion. Pressure sensors 18 and 2 measure the pressure in the respective manifolds, although the pressure sensors 14 and 15 at the inlets to the hydraulic circuit portions may be used instead because pressure variation between these sensing locations will typically be sufficiently small to be disregarded. The high pressure manifolds 8A - 8H of pump modules 4A - 4H are connected to respective inputs to the apportioning block. Their respective pressure sensors 6A - 6H may be within or outside the apportioning block. A series of connecting circuit valve arrangements 60A - 60H, one per pump module, shown in more detail in Figure 3, control the distribution of hydraulic fluid from the pump modules to the first and second pressurised fluid manifolds and thus to the hydraulic actuators connected to the first and second hydraulic circuit portions.

[0056] Figure 3 illustrates the connecting circuit valve arrangement 60A which selectively connects the high pressure manifold 8A of pump module 4A to the first and second pressurised fluid manifolds 16 and 17 under the control of the controller 50 and which functions as a variable flow regulator. The connecting circuit valve arrangements 60B - 60H for the high pressure manifolds 8B-8H of other pump modules 4B-4H typically correspond. The

high pressure manifold 8A is connected to a junction 70A. A first proportional flow valve 62A connects the junction and thus the manifold to the first pressurised fluid manifold 16 through a check valve 66A configured to prevent backflow and a second proportional flow valve 64A connects the junction and thus the manifold to the second pressurised fluid manifold 17 through a second check valve 68A. The first and second proportional flow valves 62A and 62B are under the active control of the controller 50 via control lines 72. Pump modules 4B-4H typically have corresponding valves 62B-62H, 64B-64H, 66B-66H, 68B-68H and junctions 70B-70H.

[0057] It can be seen from the orientation of the check valves 66A, 68A that in this example embodiment hydraulic fluid may flow in only one direction, from the pump modules to the pressurised fluid manifolds then to the hydraulic circuit portions and actuators, with the pump modules carrying out pumping. In embodiments in which one or more pump modules may also function as a motor to receive hydraulic fluid back from the actuators of a hydraulic circuit portion, certain check valves may be pilot operated check valves such that they can be actuated on command (at least for the pump modules which may function as motor). It would also be possible to substitute the check valves with a pair of solenoid operated single blocking valves, or pilot operated check valves or to include a selectively openable bypass around the check valves.

[0058] The controller transmits control signals to regulate the displacement of the pump modules. As we will describe this is achieved by sending active control signals to electronically controlled working chamber valves which regulate the flow of fluid into and out of the working chambers of the pump modules.

[0059] Accordingly, the controller can control which pump modules are connected to which pressurised fluid manifold and so which hydraulic circuit portion, and can control the net displacement of each individual pump module as we will describe further below. The controller may also regulate the proportional flow valves (functioning as the connecting circuit valves) in such a way as to cause a pump module to supply fluid which is divided between both hydraulic circuit portions. Thus in this embodiment the proportional flow valves can function as the connecting circuit valves and at least one of the proportional flow valves at a time functions as part of the variable flow regulator.

[0060] The pump modules will now be described further. Each typically contains a plurality of working chambers, for example n working chambers which are phased apart by $360^\circ / n$, where n is an integer such as 2, 3 or 4. The distributed phasing provides a relatively smooth output of fluid into the respective high pressure manifold. The allocation of working chambers to pump modules is typically fixed and is defined by the connection of the outputs of each working chamber in the pump module to the same high pressure manifold through conduits. Typically each working chamber within an individual pump

module is fixedly connected to the same shared high pressure manifold. The working chambers which form an individual pump module need not be located separately to the working chambers which form other pump modules, for example, working chambers from different pump modules may be interleaved along the shaft, which may be advantageous, for example to distribute torque along the shaft. The number of working chambers in each pump module, and their volume, need not be the same.

[0061] Figure 4 is a schematic diagram of a portion of an electronically commutated hydraulic machine (ECM) implementing a pump module 4A. The ECM comprising a plurality of working chambers having cylinders 80 which have working volumes 81 defined by the interior surfaces of the cylinders and pistons 82 which are driven from the rotatable shaft 3 by an eccentric cam 84 and which reciprocate within the cylinders to cyclically vary the working volume of the cylinders. The rotatable shaft is firmly connected to and rotates with a drive shaft. A shaft position and/or speed sensor 85 determines the instantaneous angular position and/or speed of rotation of the shaft, and transmits this to the controller 50 through signal line 86, which enables the machine controller to determine the instantaneous phase of the cycles of each cylinder.

[0062] The working chambers are each associated with Low Pressure Valves (LPVs) in the form of electronically actuated face-sealing poppet valves 87, which have an associated working chamber and are operable to selectively seal off a channel extending from the working chamber to a low-pressure hydraulic fluid manifold 88, which may connect one or several working chambers, or indeed all of the working chambers in the pump module as is shown here, to the low-pressure hydraulic fluid manifold of the apparatus and to tank 42. The LPVs are normally open solenoid actuated valves which open passively when the pressure within the working chamber is less than or equal to the pressure within the low-pressure hydraulic fluid manifold, i.e. during an intake stroke, to bring the working chamber into fluid communication with the low-pressure hydraulic fluid manifold but are selectively closable under the active control of the controller via LPV control lines 89 to bring the working chamber out of fluid communication with the low-pressure hydraulic fluid manifold. The valves may alternatively be normally closed valves.

[0063] The working chambers are each further associated with a respective High-Pressure Valve (HPV) 90 each in the form of a pressure actuated delivery valve. The HPVs open outwards from their respective working chambers and are each operable to seal off a respective channel extending from the working chamber to a high-pressure hydraulic fluid manifold 91, which may connect one or several working chambers, or indeed all as is shown in Figure 2, to the high-pressure hydraulic fluid manifold 8A of the pump module. The HPVs function as normally-closed pressure-opening check valves which open passively due to the pressure difference across the

valve, and taking into account the force of a biasing member within the HPV). The HPVs also function as normally-closed solenoid actuated check valves which the controller may selectively hold open via HPV control lines 93 once that HPV is opened by pressure within the associated working chamber. Typically, the HPV is not openable by the controller against pressure in the high-pressure hydraulic fluid manifold. The HPV may additionally be openable under the control of the controller when there is pressure in the high-pressure hydraulic fluid manifold but not in the working chamber, or may be partially openable.

[0064] In a pumping mode, the controller selects the net rate of displacement of hydraulic fluid from the working chamber to the high-pressure hydraulic fluid manifold by the hydraulic pump by actively closing one or more of the LPVs typically near the point of maximum volume in the associated working chambers cycle, closing the path to the low-pressure hydraulic fluid manifold and thereby directing hydraulic fluid out through the associated HPV on the subsequent contraction stroke (but does not actively hold open the HPV). The controller selects the number and sequence of LPV closures and HPV openings to produce a flow or create a shaft torque or power to satisfy a selected net rate of displacement. The above 'selection' by the controller is refreshed periodically, or continuously. The selection is refreshed, or updated, when pump modules are allocated to or deallocated from a particular part of the hydraulic circuit portion.

[0065] Some embodiments may include pump modules which are also capable of motoring, thereby regenerating energy from hydraulic fluid received back from the hydraulic circuit portions, and converting it into mechanical energy, for example when an actuator is lowered or when a wheel motor is operated as a pump in order to apply braking torque. In these cases, the working chambers of the pump modules are also adapted to motor in which case the controller actively controls the HPV as well as the LPV and can carry out a motoring mode of operation in which the controller selects the net rate of displacement of hydraulic fluid, displaced by the hydraulic machine, via the high-pressure hydraulic fluid manifold, actively closing one or more of the LPVs shortly before the point of minimum volume in the associated working chamber's cycle, closing the path to the low-pressure hydraulic fluid manifold which causes the hydraulic fluid in the working chamber to be compressed by the remainder of the contraction stroke. The associated HPV opens when the pressure across it equalises and a small amount of hydraulic fluid is directed out through the associated HPV, which is held open by the hydraulic machine controller. The controller then actively holds open the associated HPV, typically until near the maximum volume in the associated working chamber's cycle, admitting hydraulic fluid from the high-pressure hydraulic fluid manifold to the working chamber and applying a torque to the rotatable shaft.

[0066] As well as determining whether or not to close

or hold open the LPVs on a cycle by cycle basis, the controller is operable to vary the precise phasing of the closure of the HPVs with respect to the varying working chamber volume and thereby to select the net rate of displacement of hydraulic fluid from the high-pressure to the low-pressure hydraulic fluid manifold or vice versa.

[0067] Arrows on the manifolds 86, 92 indicate hydraulic fluid flow in the pumping mode; in a motoring mode the flow would be reversed.

[0068] In practice there are a number of pump modules, connected by a common shaft and a single controller that transmits the control signals to the valves associated with each working chamber of each of the pump modules.

[0069] Although the working chambers which make up each pump module are fixed, the pump modules which provide flow to a hydraulic circuit portion can be changed dynamically using the valves of the apportioning block. For example, in an example with 8 pump modules, there may at one time be 4 pump modules connected to the first hydraulic circuit portion and 4 pump modules connected to the second hydraulic circuit portion. At another time there may be 6 pump modules connected to the first hydraulic circuit portion and 2 pump modules connected to the second hydraulic circuit portion. With appropriate control of the proportional flow valves, one or more pump modules may provide flow to both the first and second hydraulic circuit portions. As will be described further below, where it is possible to provide the demanded flow to each hydraulic circuit portion with each pump module connected to only a single hydraulic circuit portion, the valves are kept either fully open or fully closed, to avoid energy losses due to throttling which occur when individual valves are kept in an intermediate position, between open and closed, with fluid flowing therethrough.

[0070] Figure 5 is a schematic diagram of the controller 50. The controller includes a processor circuit 100 in electronic communication with memory 102 which stores a database 104 of pump modules and which working chambers are fixedly associated with which pump modules, and a database 106 of which pump modules are currently connected to which hydraulic circuit portion. One or more pump modules may be connected to both hydraulic circuit portions with its flow split and this is also recorded in the database as is data specifying the current position of proportional flow valves 62A-H, 64A-H and calculated flow therethrough.

[0071] The controller receives demand signals 108 which are indicative of a demand for working fluid by each of the first and second hydraulic circuit portions and the shaft position and/or speed signal through signal line 86. The demand signal 108 could be a simple pressure signal, however as an alternate embodiment the demand signal might be in the form of an electronic joystick position signal, whilst an additional pressure signal is provided as an input to the controller. Output from the controller includes working chamber valve control lines 89, 93 (for controlling LPVs and, if required, HPVs) and valve control

lines 72 which actuate the valves 62A, 62B within the apportioning blocks.

[0072] The demand signals may be relatively simple, for example a measurement of pressure at the hydraulic input to the respective hydraulic circuit, or more complex, for example signals representing both pressure and flow requirements of the respective hydraulic circuits. The controller may receive signals indicative of demand by individual actuators or from an operator of the apparatus through manual controls. This latter approach enables compatibility with pre-existing hydraulic apparatus.

[0073] During operation, the controller processes the received demand signals and calculates from them a first displacement demand signal for the working chambers of the pump modules connected to the first hydraulic circuit portion and a second displacement demand signal for the working chambers of the pump modules connected to the second hydraulic circuit portion. The calculated demand signals may use any convenient units. In one known example, demands are expressed as "displacement fraction" which is a fraction of the maximum possible displacement per revolution of the rotating shaft, referred to as F_d . Target flow rate, in volumetric terms, is proportional to F_d and to the speed of rotation of the rotatable shaft.

[0074] Furthermore, the controller determines which pump modules are connected to which hydraulic circuit portion. The controller can also determine that the fluid flow from one of the pump modules may be split between the hydraulic circuit portions. That pump module may have a separate calculated displacement demand.

[0075] When the total demand for fluid flow is well within the capacity of the machine, the controller may proceed, as with known systems, to connect a first group of the pump modules only to the first hydraulic circuit portion and a second group of different pump modules only to the second hydraulic circuit portion, to calculate displacement fractions for the first and second groups of the pump modules and to implement these displacement fractions by controlling the low and high pressure valves of the working chambers (the working chamber valves) in each group in phased relationship with cycles of working chamber volume.

[0076] As the rotatable shaft turns, decision points are reached at different times (shaft positions) for the various working chambers. At the decision point for a given working chamber, the controller determines whether to transmit valve controls signals to cause the working chamber to carry out an active cycle in which the working chamber makes a net displacement of working fluid. Otherwise, it causes the working chamber to carry out an inactive cycle in which the working chamber makes no net displacement of working fluid (for example, the controller may transmit a signal to the LPV of the working chamber to hold the LPV open throughout a cycle of working chamber volume). In this way, the controller makes decisions for each working chamber as to whether or not to carry out active cycles depending on calculated displacement frac-

tions for the hydraulic circuit portion to which the working chamber is connected.

[0077] The connecting circuit valves 62A-H, 64A-H are used as switching valves and for each pump module, except a pump module for which flow is split, when this occurs, one of the valves 62A-H, 64A-H (e.g. 62A) is fully open and the other associated with the same pump modules is fully closed (e.g. 64A). Typically, when the flow from a pump module is split, one of the valves 62A-H, 64A-H is fully opened (e.g. 62A), so that the pump module is connected to one of the manifolds and fluid flows to that manifold, but the other of the valves 62A-H, 64A-H associated with the same pump module (e.g. 64A) is opened partially and so some fluid flow is diverted to the other manifold. It would alternatively be possible for both valve 62A-H and 64A-H associated with the same pump module (e.g. 62A and 64A) to be opened partially, but it is more energy efficient for one to be opened fully and the other to be partially opened to divert some flow.

[0078] In an example shown in Figure 6, the demand for fluid by the actuators of the first hydraulic circuit portion is 25% of the maximum output of the machine and the demand for fluid by the actuators of the second hydraulic circuit portion is 30% of the maximum output of the machine. Two of the eight pump modules are connected to the first hydraulic circuit portion and operated at full displacement. Three of the other pump modules are connected to the second hydraulic portion and operated at a displacement fraction of $30\% / (3/8) = 0.8$. There is an unused pump module which can be connected to a hydraulic circuit portion as and when it is required (or it may remain connected to one of the hydraulic circuit portions, with the displacement fraction for the group of pump modules connected to that hydraulic circuit portion scaled down proportionately) rather than being unused. Thus, a small increase in demand by one or both of the hydraulic circuit portions can be met.

[0079] However, problems may arise after a demand for working fluid cannot be met due to competing requirements for pump modules, when the pump modules connected to a hydraulic circuit portion are as a result unable to meet the demand, and when, due to a further increase in demand by actuators of the hydraulic circuit portion or a decrease in other competing demands, one or more additional pump modules are connected to the same pressurised fluid manifold, thereby increasing the maximum displacement to the connected hydraulic circuit portion. When this additional capacity becomes available, the actual displacement to the pressurised fluid manifold, and thereby to the hydraulic circuit portion and one or more actuators may suddenly jump, as the additional capacity of a pump module suddenly becomes available, leading to vibrations, juddering or difficulties in machine control (especially by a human operator).

[0080] Figure 7 illustrates a configuration known from WO 2021/044148 (Caldwell and Stein) which addresses this problem. When the total demand for fluid by the actuators of the first and second hydraulic circuit portions

exceeds a threshold, and where the pump modules all have the same capacity, the displacement fractions are scaled down so that their sum is $(n - 1) / n$ where n is the number of pump modules ($7 / 8$ in this example). These scaled down displacement fractions can be implemented with each pump module being connected to one hydraulic circuit portion or the other. If the demands for fluid by the hydraulic circuit portions are D_1 and D_2 respectively, and they are scaled down to displacement fractions F_{d1} , F_{d2} (which sum to $7/8$) then $F_{d1} * 8$, rounded up, pump modules are connected only to the first hydraulic circuit portion and $F_{d2} * 8$, rounded up, pump modules are connected only to the second hydraulic circuit portion. Thus the group of pump modules connected to each hydraulic circuit portion can implement the scaled down displacement fraction F_{d1} , F_{d2} . Furthermore, as the demands vary, it will be possible for pump modules to be reallocated from one hydraulic circuit portion to the other, without a jump in the displacement supplied to either hydraulic circuit portion. However, this has been achieved at the expense of not using the displacement of one of the pump modules.

[0081] According to the invention, when demand is sufficiently high, one of the pump modules provides flow which is split between both of the hydraulic circuit portions. In order to accomplish this, all but one of the pump modules are connected to only the first hydraulic circuit portion or only to the second hydraulic circuit portion by fully opening one of their respective connecting circuit valves 62, 64 and fully closing the other. However, for one of the pump modules, for example 4D, whichever of the respective connecting circuit valves, 62D, 64D, leads to the pressurised fluid manifold, 16 or 17, which is currently at highest pressure, is fully opened. The other connecting circuit valve 62D, 64D is partially opened under the control of the controller so that its internal cross sectional area is such as to cause a selected rate of fluid flow through the said other connecting circuit valve to the pressurised fluid manifold which is currently at the lower pressure. In an example, the pressure is higher in manifold 16 than 17 and so valve 62D is opened fully and valve 64D is opened partially.

[0082] In order to determine the correct internal cross sectional area of the valve 64D, the controller processes the pressures within the first and second pressurised fluid manifolds and within the respective high pressure manifold 8D, using pressure sensors 18, 21, 6D. The flow rate through the valve 64D, into the second pressurised fluid manifold 17, will be given by the orifice equation, Equation 1:

$$Q_i = K_i \sqrt{\Delta p_i} \quad (\text{Equation 1})$$

[0083] Where the flow rate through valve i , K_i is a constant which is a function of the internal cross-sectional area of valve i and Δp_i is the pressure differential across valve i . The remaining flow delivered by the respective

pump module, 4D in this example, is delivered to first pressurised fluid manifold. Thus, the proportional flow valve 64D has functioned as a variable flow regulator. The variable flow regulator has split the flow which is delivered concurrently and continuously to both the first and second hydraulic circuit portions.

[0084] When the relative demands for fluid by the actuators of the first and second hydraulic circuit portions change, the internal cross-sectional area of the respective proportional flow valve is varied to allow changes in the delivered flow rate to each hydraulic circuit portion. Any division of the fluid flow between the first and second hydraulic circuit portions can be achieved by operating the connecting circuit valves to change how many pump modules are connected to each pressurised fluid manifold and the extent to which the proportional flow valve connecting one of the pump modules to the hydraulic circuit portion which is at lower pressure is open. Typically, the pump module having an output which is split between pressurised fluid manifolds has a separate displacement fraction (F_{ds}) calculated by the controller, independent of displacement fractions F_{d1} and F_{d2} which the controller calculates for the groups of pump modules connected only to the first or second pressurised fluid manifolds respectively. Split flow is usually used when the total demanded flow is near to or exceeds the maximum capacity of the machine and so F_{d1} , F_{d2} and frequently F_{ds} are typically 1.0.

[0085] The internal cross sectional area of one of the valves connecting a pump module to the pressurised fluid manifold which is at lower pressure can be continuously controlled and thus it is possible to deliver a continuous range of fractions of output fluid to either hydraulic circuit portion, and to avoid surges in fluid flow when pump modules are switched from supplying fluid to one hydraulic circuit portion to supplying fluid to the other hydraulic circuit portion.

[0086] This approach enables the entire output of the hydraulic machine to be used, however this is at the expense of some energy loss because of heating arising from throttling as hydraulic fluid passes through a partially open proportional flow valve. Accordingly, it is preferred that only one proportional flow valve is partially open at any given time, with other connecting circuit valves either fully open or fully closed. (More generally, where there are n pressurised fluid manifolds providing fluid to a corresponding n hydraulic circuit portions, it is preferred to avoid having more than $n-1$ proportional flow valves partially open at any given time).

Worked Example

[0087] In an example according to Figure 2, a machine has 8 pump modules and each pump module has a maximum flow capacity of 24 cc per revolution of the rotatable shaft. There is a demand for fluid supply to the boom 26, which is connected to the first hydraulic circuit portion 20 and so to the first pressurised fluid manifold 16, of 160

cc per revolution (D1) and a demand for fluid supply to the dipper 34, which is connected to the second hydraulic circuit portion 22 and so to the second pressurised fluid manifold 17, of 180 cc per revolution (D2). There is no demand for flow by any other actuator (although if there was additional demand this could be readily dealt with by adding the demand for additional actuators onto to the total demand for the hydraulic circuit portions to which they are connected). The controller determined that the total demand is therefore 160 + 180 cc per revolution which exceeds the available supply of $8 \times 24 \text{ cc} = 192 \text{ cc}$.

[0088] The controller therefore operates the machine such that one of the pump modules will have its flow split and the others will be connected only to either first or second pressurised fluid manifold. The number of pump modules connected only to the first pressurised fluid manifold or only to the second pressurised fluid manifold is determined by calculating $D1 / (D1 + D2) \times$ the number of pump modules, and $D2 / (D1 + D2) \times$ the number of pump modules respectively, in each case rounding down. In this example, this gives $160 / 340 \times 8 = 3$ pump modules to be connected only to the first pressurised fluid manifold and $180 / 340 \times 8 = 4$ pump modules to be connected only to the second pressurised fluid manifold. If required, the controller operates the connecting circuit valves 62, 64, for each pump module as appropriate to make the required connections. For each of the group of pump modules connected to the first pressurised fluid manifold and the group of pump modules connected to the second pressurised fluid manifold, displacement fractions Fd_1 , Fd_2 , are set to 1.0 and this is used by the controller to determine which working chambers carry out active rather than inactive cycles (as the displacement fraction is 1.0 every working chamber of the respective pump modules will carry out an active cycle of working chamber volume, with maximum displacement, on each cycle of working chamber volume).

[0089] The pump module (in this example 4D) is connected directly to the first pressurised fluid manifold (which has a higher pressure than the second fluid manifold in this example) by fully opening valve 62D and the displacement fraction for the working chambers of the pump module 4D is also set to 1.0 because the total demand exceeds the maximum flow capacity of the hydraulic machine.

[0090] The cross sectional area of valve 64D is calculated by the controller by first calculating the flow, from the pump module with the split flow, which should pass through the proportional flow valves to the first and second pressurised fluid manifolds so that the total flow Q_1 , Q_2 to each manifold is proportional to the original demand signals, D1, D2. In this example, that is $(8 \times 24) \times (160 / (160 + 180)) - (3 \times 24) = 18.35 \text{ cc / revolution}$ to the first pressurised fluid manifold with the remainder of the 24 cc/revolution from the pump module with the split flow, i.e. 5.65 cc / revolution flowing to the second pressurised fluid manifold. This is illustrated schematically in Figure 8.

[0091] The controller then determines the internal

cross-sectional area (cross-sectional area of the internal flow-path) of the valve between the pump module 64D and the second pressurised fluid manifold 17 as follows. With reference to Figure 9, if p_1 is the measured pressure in the first pressurised fluid manifold 16 and p_2 is the measured pressure in the second pressurised fluid manifold 17, the pressure, p , in the pump module high pressure manifold 8D can be expressed as $p = p_1 + \Delta p_o$ where Δp_o is the pressure drop across first proportional flow valve 62D, and the total flow from the pump module, Q , is the sum of Q_1 , the flow to the first pressurised fluid manifold, and Q_2 , the flow to the second pressurised fluid manifold where the respective fluid line portions meet at junction 70D.

[0092] $\Delta p_o = Q_1 \times K_0$ where K_0 is an orifice characteristic coefficient relating to valve 62D when fully open.

[0093] The pressure drop across the second valve 64D, $\Delta p = p - p_2$ and the flow through the second valve

Q_2 , is $K_2 \sqrt{\Delta p_2}$ by the orifice equation.

[0094] K_2 is given by Equation 2:

$$K_2 = \frac{Q_2}{\sqrt{\Delta p_2}} \quad (\text{Equation 2})$$

[0095] K_2 is a flow parameter of the valve 64D which varies with the internal cross-sectional area of valve 64D. Thus, the controller can solve for the value of K_2 giving the desired flow Q_1 and Q_2 and then determine, for example using a look-up table, the proportional valve control voltage to cause valve 64D to have the internal cross-sectional area giving flow parameter K_2 .

[0096] Thus, the controller controls the flow to the first and second pressurised fluid manifolds and so to the first and second hydraulic circuit portions and the actuators (the boom and the dipper in this example), and valve 64D has functioned as a variable flow regulator which diverts a controlled amount of the flow from the shared pump module (4D) which would otherwise flow to the higher pressure pressurised fluid manifold (16) to the lower pressure pressurised fluid manifold (17). The whole flow capacity of the hydraulic machine is thereby used. Changes in relative demand for fluid can be readily implemented by controlling the number of pump modules which are connected only to the first pressurised fluid manifold 16 and the number of pump modules which are connected only to the second pressurised fluid manifold 17 and by controlling the valve position of the proportional flow valve which connects a shared pump module to whichever of the pressurised fluid manifolds 16, 17 has the lowest pressure at a given time. The valve 64D has split the flow from the pump modules connected to the higher pressure fluid manifold so that it flows continuously and concurrently to both the first and second hydraulic circuit portions.

[0097] One skilled in the art will appreciate that the

pressure and flow rate in the first and second pressurised fluid manifolds will be regulated by the controller depending on the requirements of the actuators connected to each hydraulic circuit portion. In some embodiments the pressurised fluid manifold which has the highest pressure at any given time may change although in other embodiments it will always be the case, in a normal operation mode, a specific one of the pressurised fluid manifolds has a higher pressure than the other.

[0098] In some circumstances the split flow is used even though the total demand is not quite sufficient for it to be necessary for the displacement fraction F_d for each pump module to be 1.0, for example where the total demanded flow rate is between $(n-1)/n$ and 1 times the maximum flow rate. In this case, the displacement fraction for the pump module which has its flow split is typically reduced to give the demanded total flow rate (and so for this pump module typically some inactive cycles of working chamber volume will be interspersed between active cycles although the volume displaced during each cycle could be reduced in a part-stroke mode instead). It would be possible for the displacement fraction for the group of pump modules connected to one or other of the pressurised fluid manifolds to have a displacement fraction of less than unity, however typically it is more energy efficient for the pump module with split flow to have its displacement reduced, to reduce overall energy losses due to throttled fluid flow.

Second Example

[0099] Figures 10 and 11 illustrate an alternative embodiment in which the connecting circuit valve arrangements 60A through 60H do not use proportional flow valves but instead comprise switching valves (63A, 65A for pump module 4A, and correspondingly for pump modules 4B-H), connected between the respective pump module high pressure manifold 8A and the first and second pressurised fluid manifolds 16, 17 respectively. These switching valves are in an open state or a closed state during operation and are not maintained in a partially open state (although they will pass through partially opened states transiently while being opened or closed). Check valves 66A and 68A are provided as before.

[0100] In this example, a single proportional flow valve 67, connected between the first and second pressurised fluid manifolds and functions as the variable flow regulator. The proportional flow valve 67 is controlled to cause a controlled amount of fluid flow from whichever pressurised fluid manifold is at a higher pressure to flow to the other.

[0101] In this example, the controller controls the switching valves to cause each pump module to be connected to either the first or the second pressurised fluid manifold, with the number connected to each manifold depending on the relative demand for fluid from the actuators connected to each hydraulic circuit portion. When the demand is high, the number of pump modules con-

nected to each hydraulic circuit portion is determined by first calculating the number of pump modules required to be connected to each hydraulic circuit portion to give fluid flow in a ratio corresponding to the ratio of demanded flow. However, in this case, where the number of pump modules calculated in this way is not an integer, the number of pump modules is rounded up for the pump modules connected to the hydraulic circuit portion which has the highest measured pressure and rounded down for the pump modules connected to the other hydraulic circuit portion. Thus, the flow of fluid to the higher pressure pressurised fluid manifold from the pump modules will be higher than required and the flow to the other pressurised fluid manifold will be lower than required.

[0102] The controller then calculates the flow, Q , required from the higher pressure pressurised fluid manifold, to the other pressurised fluid manifold, through proportional flow valve 67 so that the net flow from the pump modules to the first and second hydraulic circuit portions is in the appropriate ratio. In order to achieve this, the controller sets the internal cross-sectional area of the proportional flow valve 67 to obtain the required flow rate from the higher pressure pressurised fluid manifold to the other pressurised fluid manifold, taking into account the pressure in both of the pressurised fluid manifolds 16, 17. Thus, some flow which would have passed through the higher pressure pressurised fluid manifold to the respective hydraulic circuit portion is instead diverted through proportional flow valve 67, to the other (lower pressure) pressurised fluid manifold and so flow to the other hydraulic circuit portion.

Worked Example According to Second Example

[0103] In a second worked example a machine according to Figures 10 and 11, instead of a machine according to Figures 2 and 3, is used to provide the same output as in the first worked example. There are again 8 pump modules each with a capacity of 24 cc/revolution of the rotatable shaft and the demands are again 160 cc for the boom connected to the first hydraulic circuit portion and 180 cc for the dipper connected to the second hydraulic circuit portion. In this example, the pressure in the first pressurised manifold 16 is higher than in the second pressurised manifold 17 due to the higher pressure requirement of the boom. Thus the flow to each hydraulic circuit portion would ideally be $160 / (160 + 180) \times 8 \times 24$ and $180 / (160 + 180) \times 8 \times 24$ respectively, i.e. 90.35 cc per revolution and 101.65 cc per revolution respectively.

[0104] In order to provide flow in the ratio of 160 to 180 cc per revolution $160 / (160 + 180) \times 8 = 3.76$ pump modules would in principle be required to displace fluid to the first hydraulic circuit portion and the remaining 4.24 would be required to displace fluid to the second hydraulic circuit portion. As the pressure is higher in the first pressurised fluid manifold than the second pressurised fluid manifold, 3.76 is rounded up to 4 and 4 pump modules are connected to each hydraulic circuit portion. Thus, fluid flow

of $4 \times 24 = 96$ cc per revolution will flow from pump modules to each pressurised fluid manifold. Thus $96 - 90.35 = 5.65$ cc / revolution requires to be diverted from the first pressurised fluid manifold to the second pressurised fluid manifold through the proportional flow valve 67.

[0105] The controller calculates the required internal cross sectional area of the proportional flow valve to give this flow rate, $Q_{16 \rightarrow 17}$, given the measured pressures in the first and second pressurised fluid manifold, the difference between which gives $\Delta p_{16 \rightarrow 17}$, using the orifice equation.

$$Q_{16 \rightarrow 17} = K \sqrt{\Delta p_{16 \rightarrow 17}}$$

[0106] The controller calculates K and relates this to the required control voltage of the proportional flow valve for example using a look-up table.

[0107] The flow rate to the first hydraulic circuit portion equals the flow rate into the first pressurised fluid manifold from the pump modules connected to it minus the flow through the proportional flow valve ($4 \times 24 - 5.65 = 90.35$ cc/revolution) and the flow rate to the second hydraulic circuit portion equals the flow rate into the second pressurised fluid manifold from the pump modules connected to it plus the flow through the proportional flow valve ($4 \times 24 + 5.65 = 101.65$ cc/revolution).

[0108] During operation when the demand exceeds a threshold, the control voltage to the proportional flow valve 67 is varied continuously to give the required ratio of flow to the first and second hydraulic circuit portions and pump modules are reallocated from one pressurised hydraulic manifold to the other by operating the switching valves 63A-H and 65A-H. The switching valves are typically fast acting valves which are quickly operated between open and closed positions using a solenoid actuator.

[0109] When demand for fluid flow to each hydraulic circuit portion is sufficiently low that the proportional flow valve is not required, it is kept closed to increase overall efficiency.

[0110] Figure 12 is a schematic diagram of an alternative embodiment in which there are three pressurised hydraulic manifolds 16, 17 and 19, configured to supply fluid to three different hydraulic circuit regions. Pressure sensors 18, 21, 23 are associated with the pressurised hydraulic manifolds. Switching valves are provided to connect pump modules to pressurised hydraulic manifolds. It is not necessary for each pump module to be connectable to each pressurised hydraulic manifold. As with other embodiments, there may one or more pump modules which are fixedly connected to an individual pressurised hydraulic manifold. Proportional flow valves 74, 76 and 78 are connected such that there is one extending between each pair of pressurised fluid manifolds.

[0111] In the embodiment of Figure 12, there are three demand signals received, D1, D2 and D3. When demand

is high, scaled back demand signals, D1', D2', D3' which sum to the at most the maximum total flow rate of the hydraulic machine are calculated. Pump modules are connected to the individual pressurised fluid manifolds such that whichever pressurised fluid manifold has the highest pressure is supplied with more flow than is indicated by its scaled back demand signal and whichever pressurised fluid manifold has the lowest pressure is supplied with less flow than indicated by the corresponding scaled back demand signal. The third pressurised fluid manifold with an intermediate pressure may receive more or less flow than is indicated by the corresponding scaled back demand signal. The controller process the pressure in each pressurised fluid manifold and the fluid flow rates into each pressurised fluid manifold from pump modules and calculates flow rates between the manifolds, from higher pressure to lower pressure, to give the required net fluid flow into the manifolds and so the respective connecting circuit portions. One, or two or all three proportional flow valves 74, 76, 78 are then held at an intermediate position using appropriate control voltages generated by the controller to give the desired flow between the manifolds such that the net flow into each manifold, from the pump modules which are connected to it, plus or minus net flow through the proportional flow valves, gives net flow into the respective hydraulic circuit portions corresponding to D1', D2' and D3'. Whether the proportional flow valve from the highest pressure manifold to the lowest pressure manifold or the intermediate pressure manifold is held partially open and whether the proportional flow valve between the intermediate pressure manifold and the lowest pressure manifold is held partially open is determined from a calculation by the controller of the energy losses in each possible combination of valve openings taking into account the orifice equation, Equation 1, and calculated energy losses through each proportional flow valve due to the throttling of fluid.

[0112] From time to time, the controller will determine that there is a requirement to reallocate a pump module from one hydraulic circuit module to another hydraulic circuit module in order to meet changing demand for hydraulic fluid and/or to vary the setting of a proportional flow valve to change the distribution of flow from a pump module to the first and second hydraulic circuit portions. The moment in time that is chosen to reallocate a pump module is important, and the moment may be chosen in relation to the timing of the cycle of one or more working chambers, so as to minimise pulsation / ripple arising from those corresponding chambers. A forecast of flow, arising from the connected working chambers, can be used during this allocation process in particular to choose the moment in time to perform reallocation. Reallocation may be performed to increase flow provision, or simply flow capacity for some future time.

[0113] Notably, the controller may deliver hydraulic fluid with quite different pressure and flow rates to each hydraulic circuit portion at the same time. In a simple example, the pressure at the input to the hydraulic circuit

portions is measured and the accumulator for each hydraulic circuit portion is incremented with time in proportion to the error between the measured pressure and a set point pressure. The error may also be integrated over time and added to the accumulator. The pressure set points may be different for each hydraulic circuit portion and may be rapidly varied in response to loads on the actuators, or control block valve positions. For example in response to a significant increase in pressure set point, each allocated working chamber could carry out an active cycle until the revised pressure set points was obtained. Additionally, if an actuator increased the amount of flow it was absorbing, the many working chambers would need to undergo active cycles to maintain the pressure set point. Furthermore, the hydraulic circuit portions may receive very different volumes of hydraulic fluid as the net displacement of working fluid by the pump modules connected to each hydraulic circuit portion are entirely independent although working chambers connected to each hydraulic circuit portion are driven by the same engine through the same shaft.

[0114] In the above examples, pump modules are typically connected to pressurised fluid manifolds and proportional flow valve voltages are typically set such as to minimise energy consumption of the apparatus while supplying a given flow of hydraulic fluid to actuators. Generally, the configuration of the valves is such as to minimise the loss of energy by throttled flow through one or more proportional flow valves. However, the apparatus and its control may be optimised in at least some circumstances for factors other than energy efficiency, for example for speed or accuracy of response to operator instructions, or to suppress undesirable movements such as juddering or resonances.

[0115] In the above examples, fluid flows from the pump modules to the hydraulic circuit modules. However, in some embodiments, flow may flow in the other direction, for example in a regenerative operating mode. In this case, the same principles will apply with the flow directions reversed and fluid flow being combined by the variable flow regulator rather than divided and with the pump modules carrying out motoring cycles and so receiving fluid and driving the rotatable shaft 3.

[0116] Although the controller is shown here as being implemented by a single processor one skilled in the art will appreciate that the function of the controller may readily be distributed between a plurality of processors and/or circuits.

Claims

1. An apparatus comprising:

- a prime mover;
- a plurality of hydraulic circuit portions for supplying or receiving hydraulic fluid to or from one or more actuators;

a hydraulic machine having a rotatable shaft in driven engagement with the prime mover and comprising at least three working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber of the hydraulic machine comprising a low-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a low-pressure manifold, and a high-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a high-pressure manifold, wherein the working chambers are formed into a plurality of pump modules each pump module comprising a group of one or more of the working chambers and a high-pressure manifold which is common to each working chamber in the group;

a hydraulic connecting circuit configured to selectively connect each hydraulic circuit portion to the high-pressure manifolds of one or more of the pump modules;

one or more variable flow regulators configured to selectively divert some of the flow of hydraulic fluid from or to one or more of the pump modules to or from a first hydraulic circuit portion to concurrently flow to or from a second hydraulic circuit portion; and

a controller configured to actively control at least the low pressure valves of the said working chambers to determine the net displacement of each working chamber during each cycle of working chamber volume, and also the one or more variable flow regulators, to independently regulate the flow of fluid to or from each of the hydraulic circuit portions.

2. An apparatus according to claim 1, wherein the hydraulic connecting circuit further comprises at least a first pressurised fluid manifold which is connected to the first hydraulic circuit portion and a second pressurised fluid manifold which is connected to the second hydraulic circuit portion, and a plurality of connecting circuit valves, wherein the controller is configured to control the plurality of connecting circuit valves such that, in a normal operating mode, some or all of the pump modules are directly connected to and supply fluid to or receive fluid from only one pressurised fluid manifold at a time and that for some or all of the pump modules, the pressurised fluid manifold to which the respective pump module is directly connected may be changed.

3. An apparatus according to claim 2, wherein one or more variable flow regulators are connected between the high-pressure manifold of a pump module and two pressurised fluid manifolds to thereby controllably regulate the proportion of flow from or to the pump module which flows directly into or from each

of the two pressurised fluid manifolds.

4. An apparatus according to claim 2 or claim 3, comprising n pressurised fluid manifolds, each connected to a respective one of n hydraulic circuit portions, wherein, in a normal operating mode, the flow from or to no more than n-1 pump modules is split between or combined from multiple hydraulic circuit portions and the high pressure manifold of each remaining pump module is connected only to one of the n pressurised fluid manifolds at a time. 5 10
5. An apparatus according to any one of claims 2 to 4, wherein when the high-pressure manifold of a pump module is connected to the first hydraulic circuit portion through the hydraulic connecting circuit, and a variable flow regulator is controllable to provide a path for a variable amount of hydraulic fluid to flow concurrently to or from the second hydraulic circuit portion, from or to the high-pressure manifold of the pump module. 15 20
6. An apparatus according to any one preceding claim, wherein the hydraulic connecting circuit comprises a first pressurised fluid manifold which is connected to the first hydraulic circuit portion and a second pressurised fluid manifold which is connected to the second hydraulic circuit portion, wherein the high pressure manifold of each pump module is connectable to the first or second pressurised fluid manifold and wherein one or more variable flow regulators is connected between the first and second pressurised fluid manifolds, to thereby controllably regulate a flow of fluid between the pressurised fluid manifolds and regulate the flow of fluid to or from the first and second hydraulic circuit portions. 25 30 35
7. An apparatus according to any one preceding claim, wherein at least one variable flow regulator comprises at least one valve. 40
8. An apparatus according to claim 7, wherein at least one flow regulator comprises a valve having a variable internal cross-sectional area. 45
9. An apparatus according to claim 7 or claim 8, wherein the or each pump module is connected to the first hydraulic circuit portion through a first valve and to the second hydraulic circuit portion through a second valve, wherein the first and second valves are controllable (by the controller). 50
10. An apparatus according to any one preceding claim, comprising pressure sensors configured to measure the fluid pressure in the respective hydraulic circuit portions, wherein the controller is configured to control a variable flow regulator responsive to the pressures in the first and the second hydraulic circuit portions 55

tions to regulate the flow of fluid to or from the first and second hydraulic circuit portions.

11. An apparatus according to claim 10, wherein the controller is configured to calculate a rate of flow of hydraulic fluid through the variable flow regulator, taking into account the measured pressure in the first and second hydraulic circuit portions and in the high-pressure manifold of the pump module, and to control the variable flow regulator to achieve a target rate of flow.
12. An apparatus according to any one preceding claim, wherein the controller is configured to control the displacement of the working chambers of the pump module, and the connecting circuit valves and the variable flow regulator further wherein the controller is configured to vary the displacement of the working chambers of the pump module and the flow through the variable flow regulator prior to causing the switching valves to change which hydraulic circuit portion the pump module is connected to.
13. An apparatus according to any one preceding claim, wherein the controller is configured to control the variable flow regulator to damp a change or oscillation in the amount of hydraulic fluid flowing to or from one or more actuators connected to a hydraulic circuit portion to which the variable flow regulator is connected.
14. An apparatus according to any one preceding claim, wherein the controller is configured to control the displacement of the working chambers of the pump module, and the connecting circuit valves and the variable flow regulator, to optimise one or more operating parameters.
15. A method of operating an apparatus according to any one preceding claim, comprising determining the net displacement of each working chamber and also the one or more variable flow regulators, to independently regulate the flow of fluid to and from each of the hydraulic circuit portions, typically further comprising controlling the switching valves in concert with the net displacement of each working chamber and the one or more variable flow regulators to regulate the displacement of hydraulic fluid to or from each of the hydraulic circuit portions.

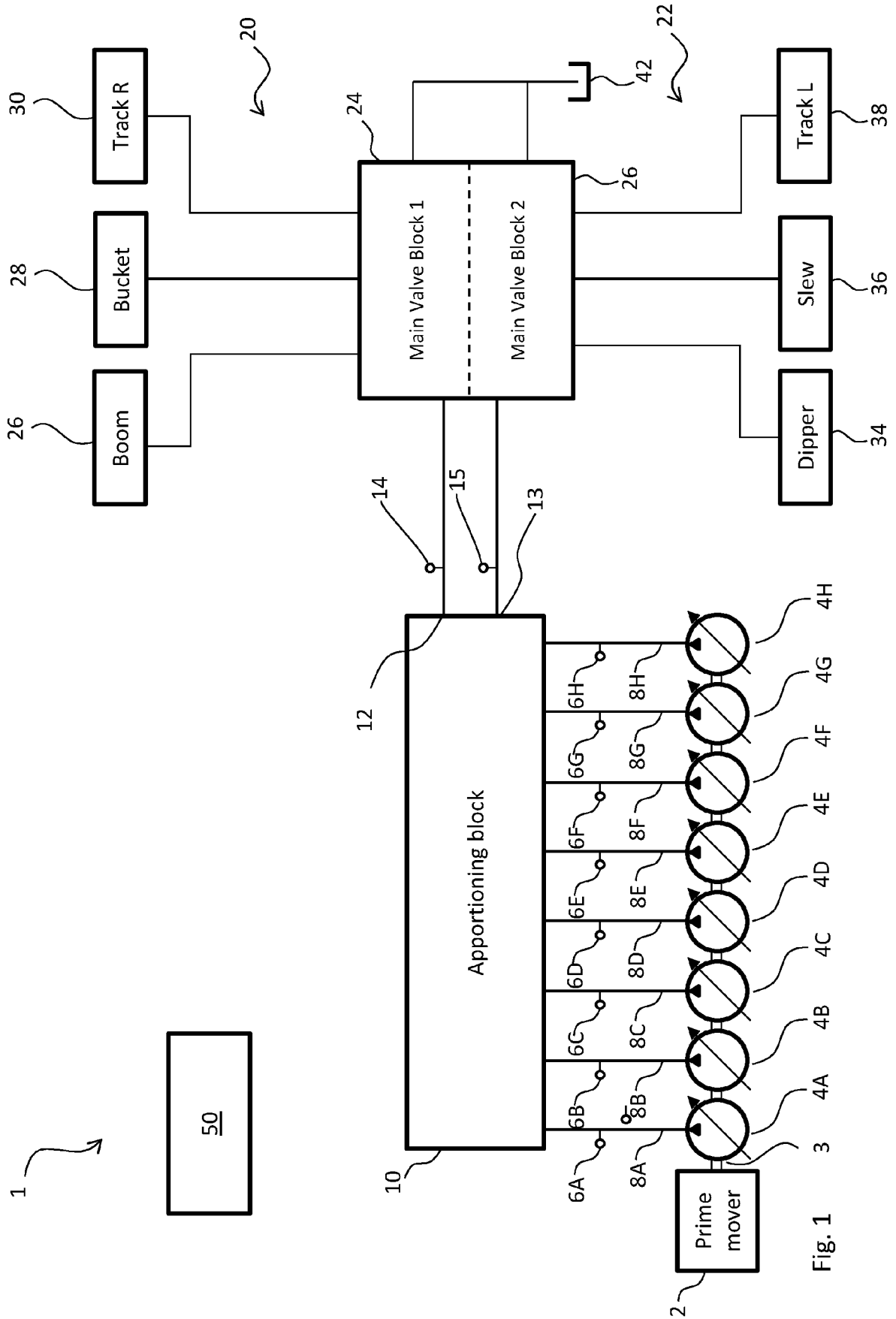


Fig. 1

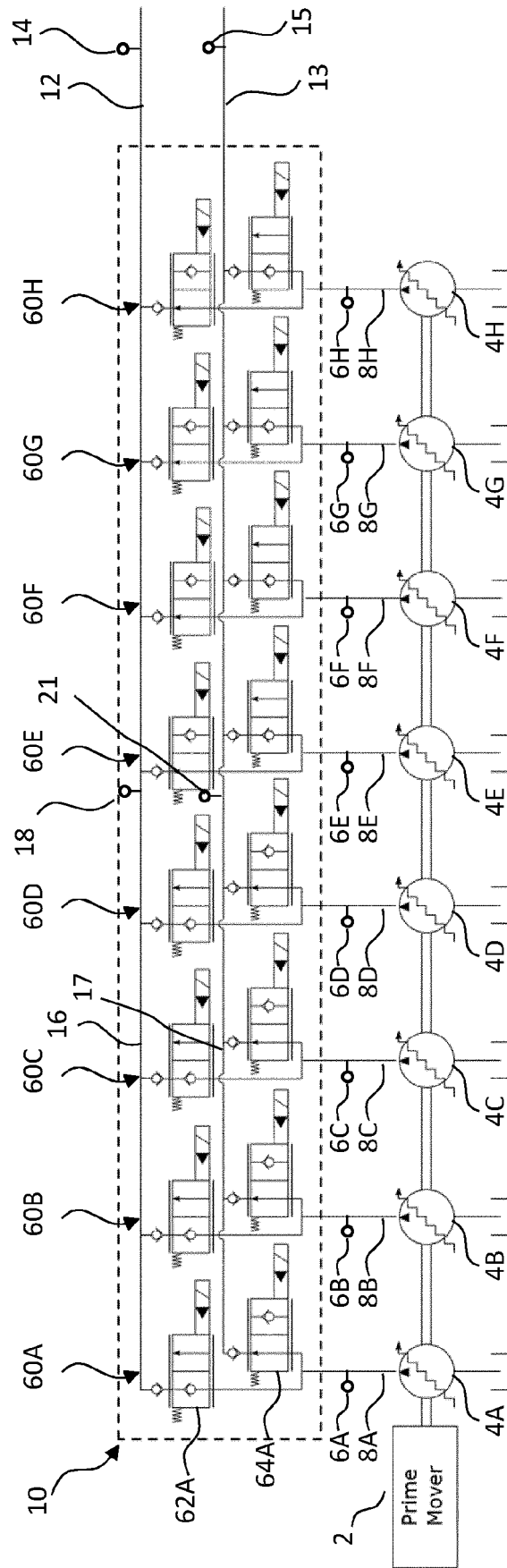


Fig. 2

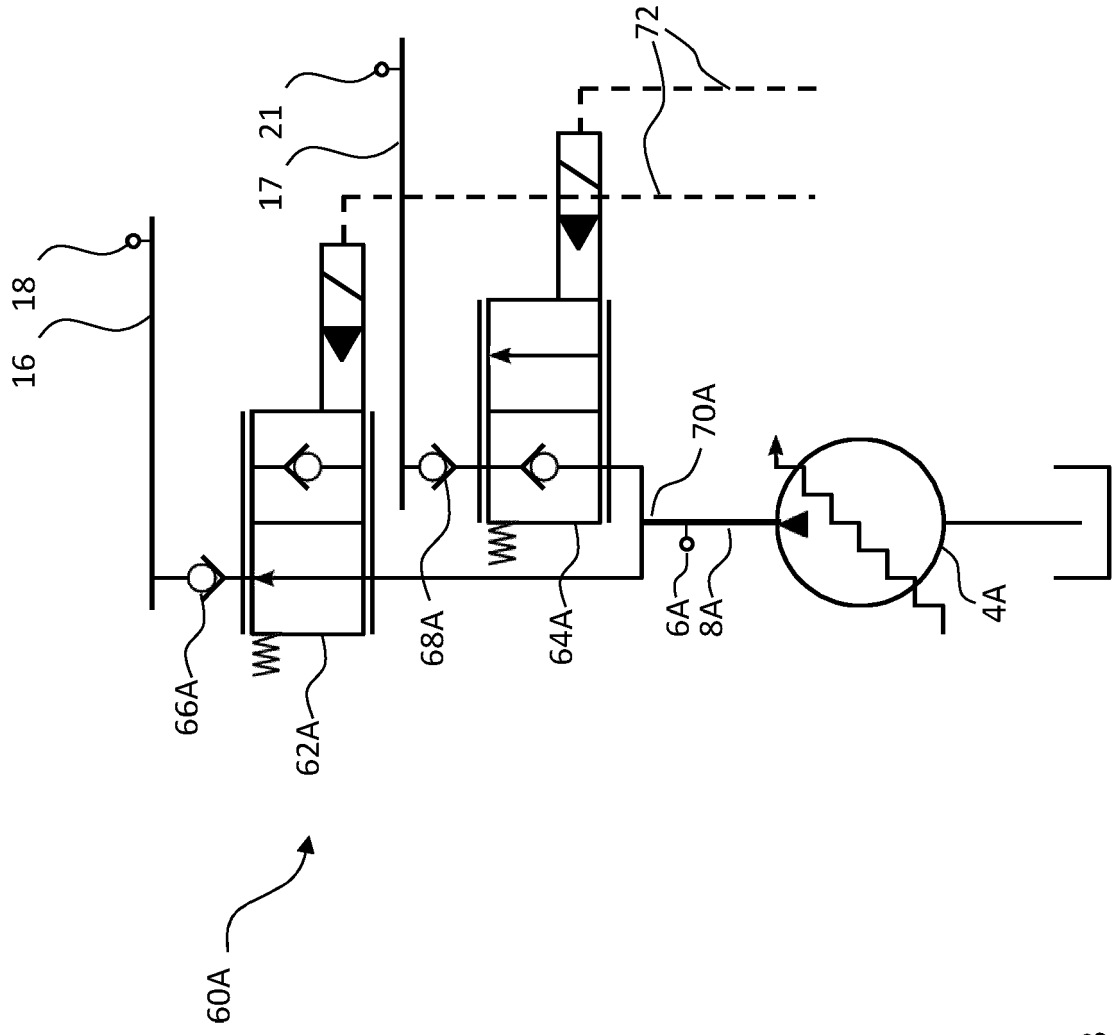


Fig. 3

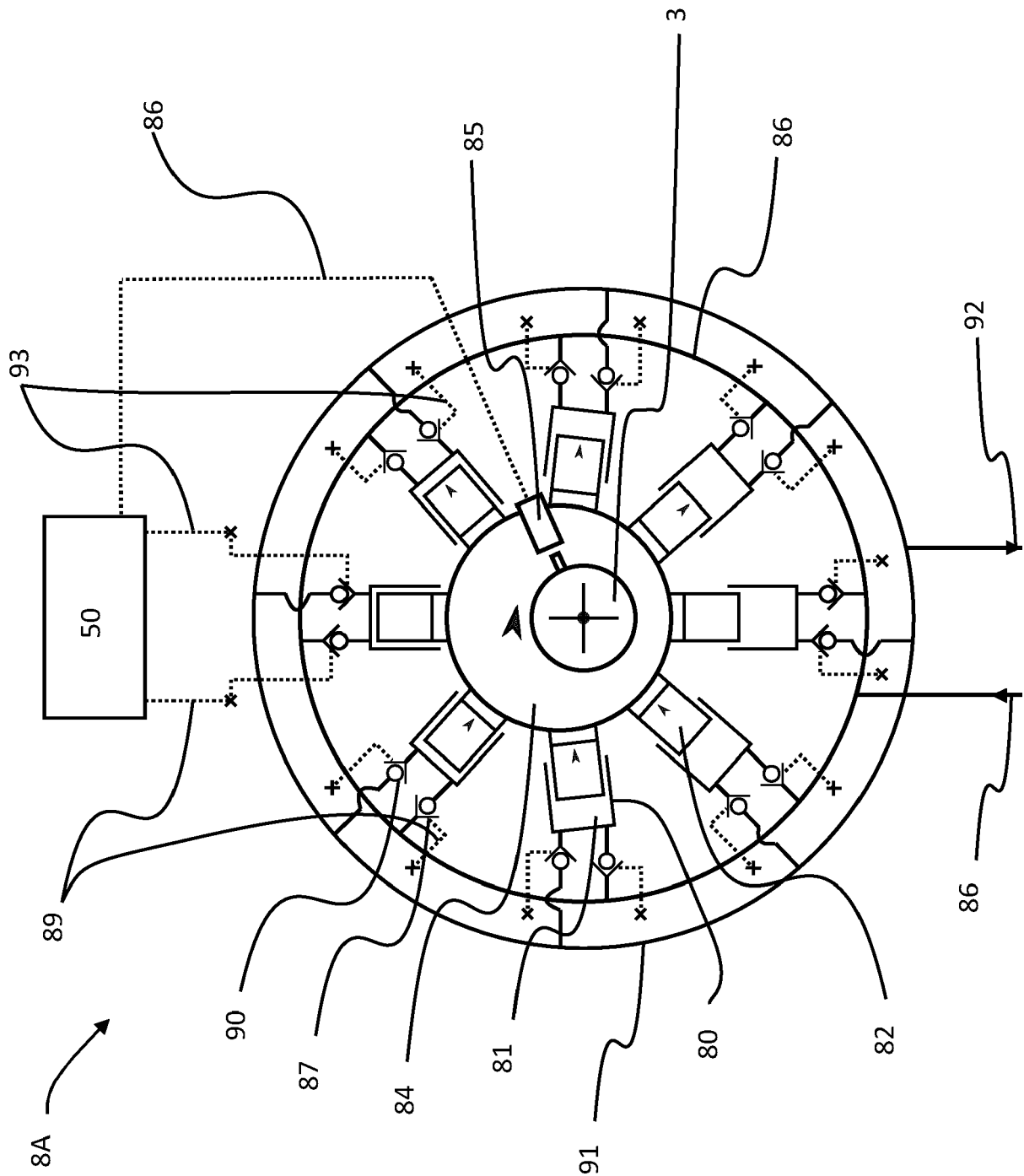


Fig. 4

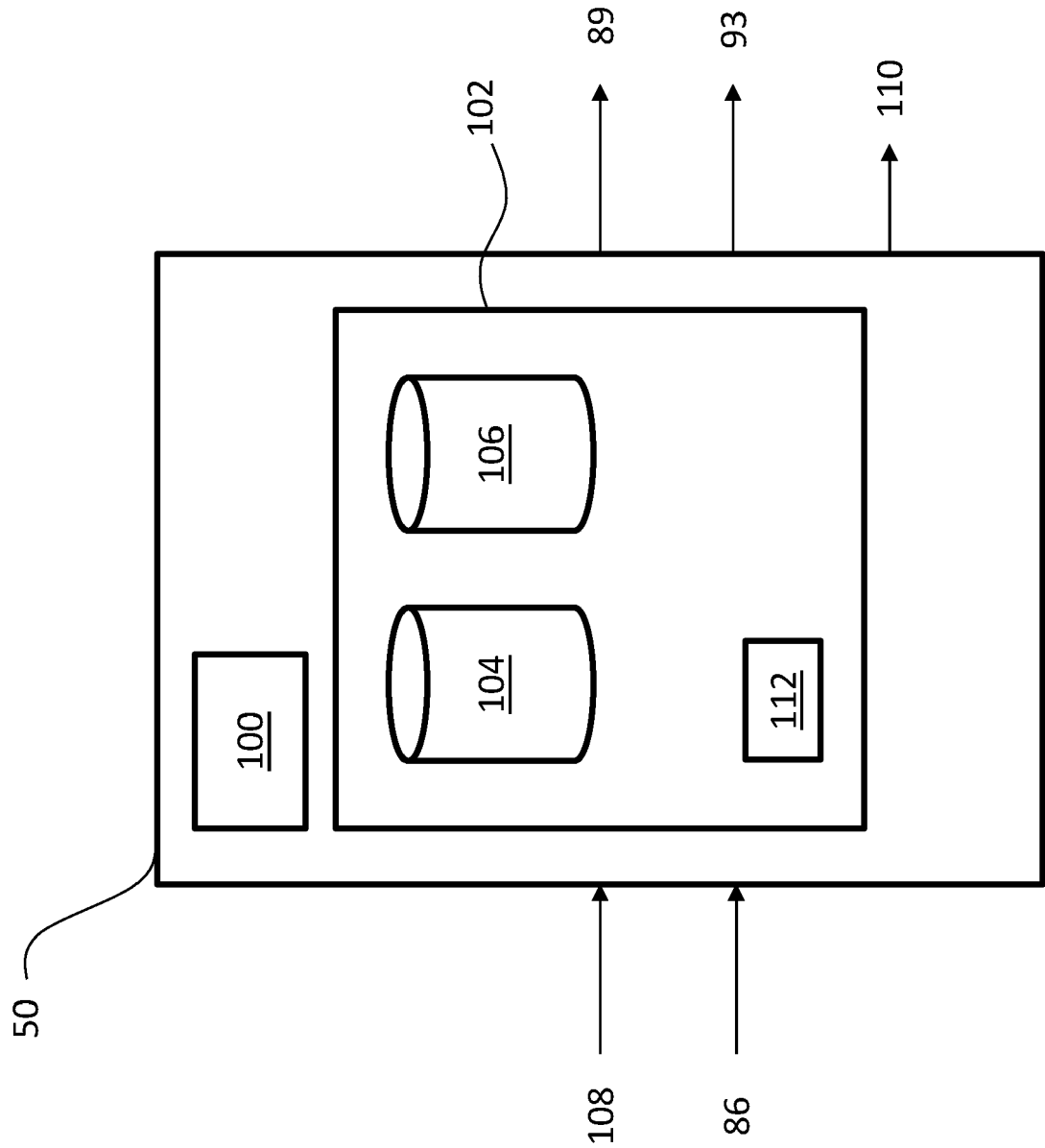


Fig. 5

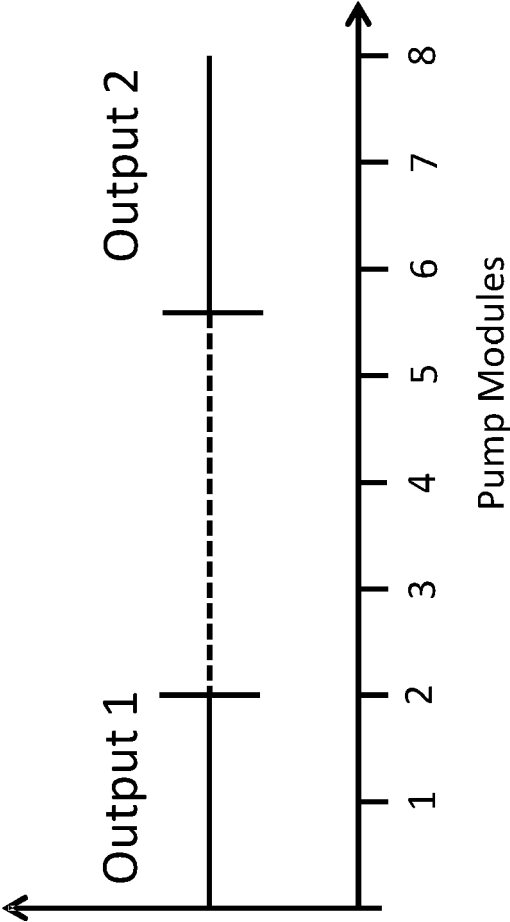


Fig. 6

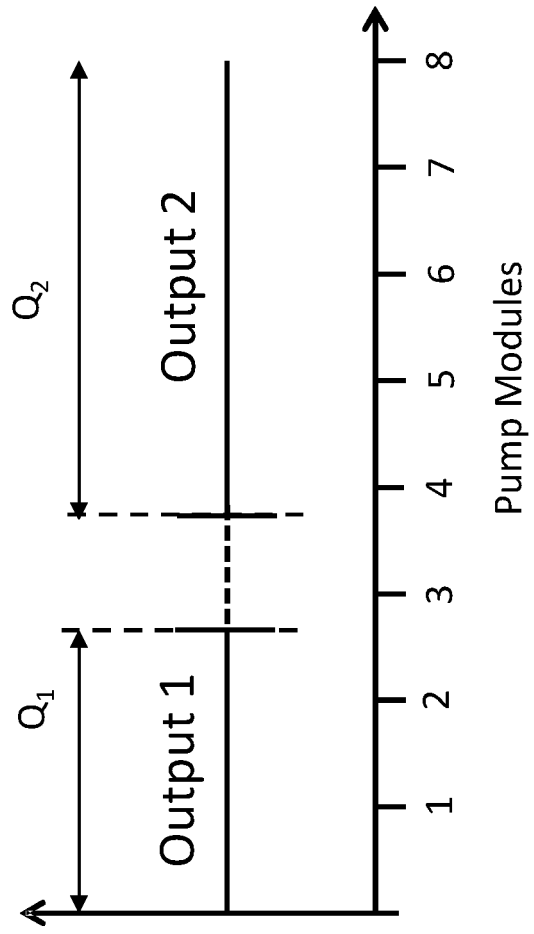


Fig. 7

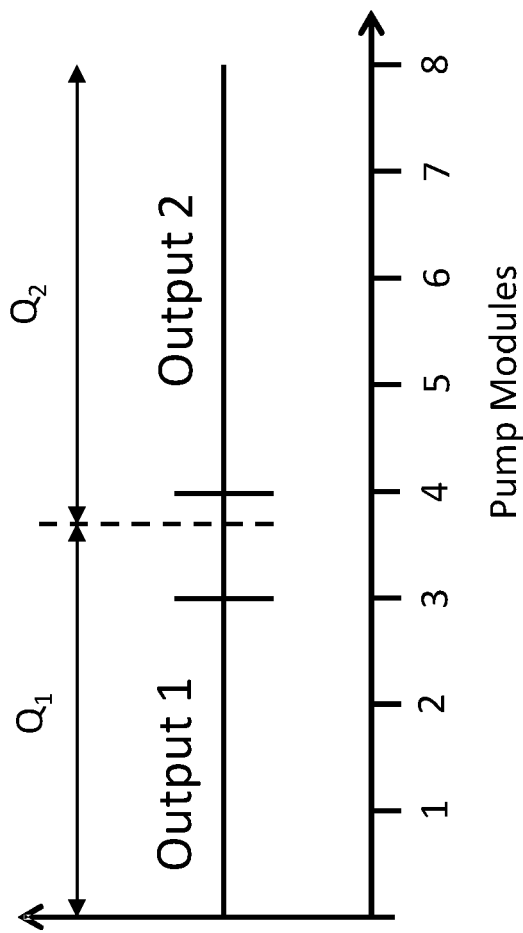


Fig. 8

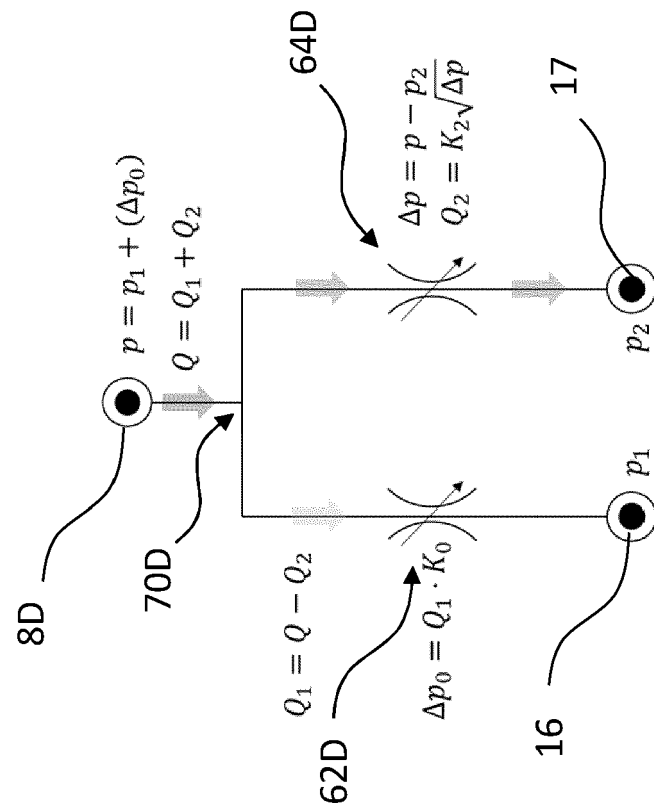


Fig. 9

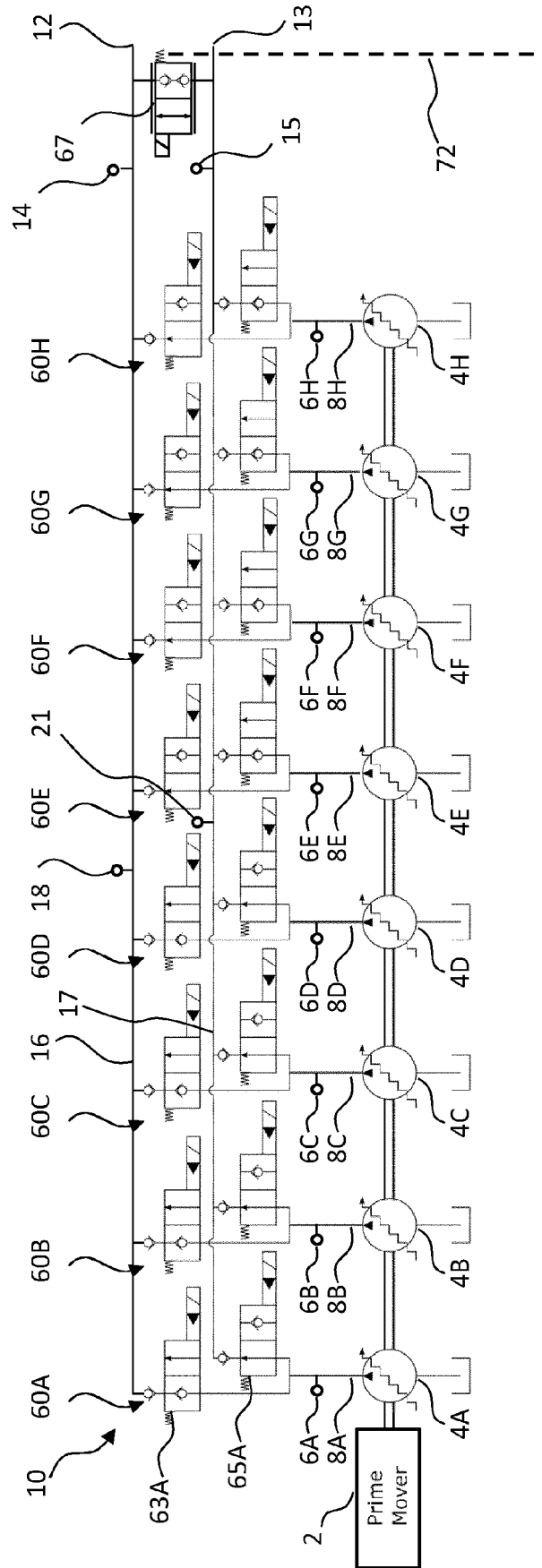


Fig. 10

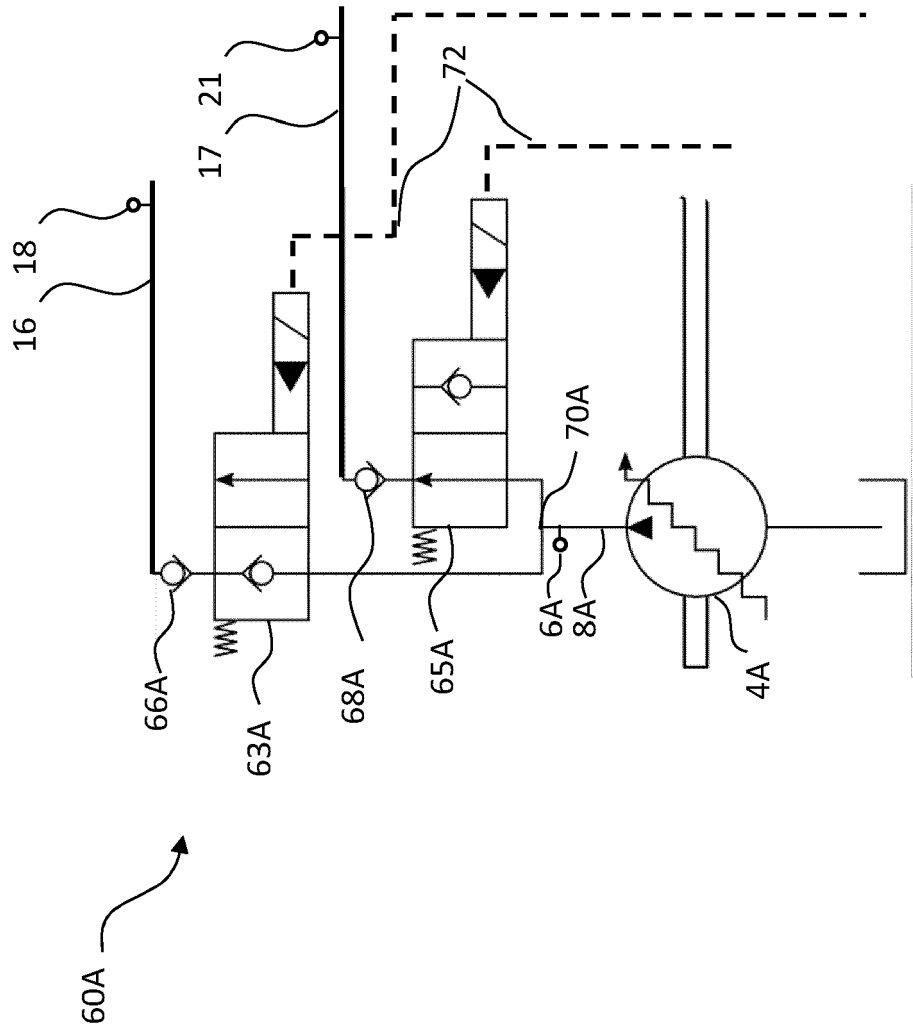


Fig. 11

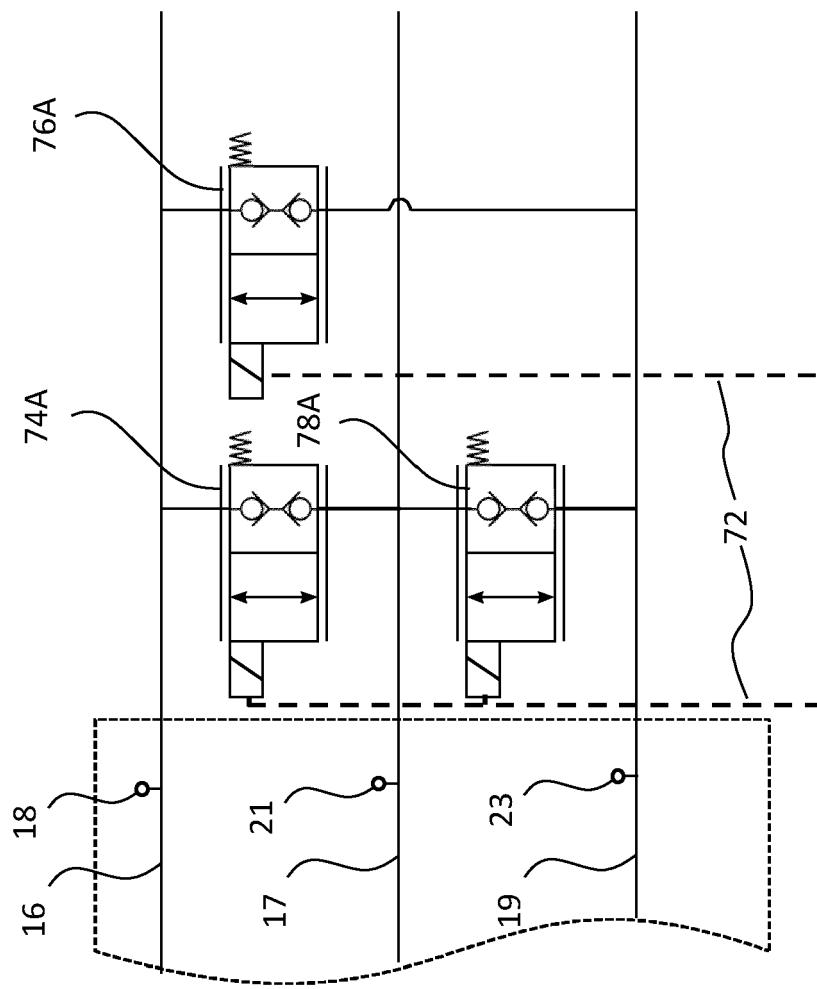


Fig. 12



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Application Number

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A	* paragraph [0070] - paragraph [0072]; figures 22, 23 *	4, 6, 10-13	E02F9/22 F04B1/0536 F04B23/06
A, D	WO 2021/044148 A1 (ARTEMIS INTELLIGENT POWER LTD [GB]) 11 March 2021 (2021-03-11) * figures 1-2 * * figure 7 * * page 51, line 21 - page 52, line 16; figures 12, 13 *	1-15	F04B49/06 F04B49/22
A	US 11 162 514 B2 (DANFOSS POWER SOLUTIONS APS [DK]; ARTEMIS INTELLIGENT POWER LTD [GB]) 2 November 2021 (2021-11-02) * column 4, line 8 - line 31; figure 1 * * column 5, line 38 - line 64 *	1-15	
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The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 20 September 2022	Examiner Díaz Antuña, Elena
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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