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(54) METHOD OF CONTROLLING A VALVE

(57) According to an aspect of the invention, there is provided a method of operating a hydraulic apparatus, the hydraulic apparatus comprising: a hydraulic machine having a rotatable shaft in driven engagement with a prime mover and comprising at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft, the at least one working chamber comprising one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold; a controller configured to control operation of the one or more electronically actuated valves of the hydraulic machine; and one or more components of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller, the method comprising: receiving the phase signal from the first sensor assembly; in a first mode of operation of the hydraulic machine, outputting a first valve control signal depending on the phase signal, the first valve control signal configured to cause at least one of the one or more electronically actuated valves to operate in accordance with the first mode; determining that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger; and in response to determining that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, outputting a second valve control signal independently of the phase signal, the second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

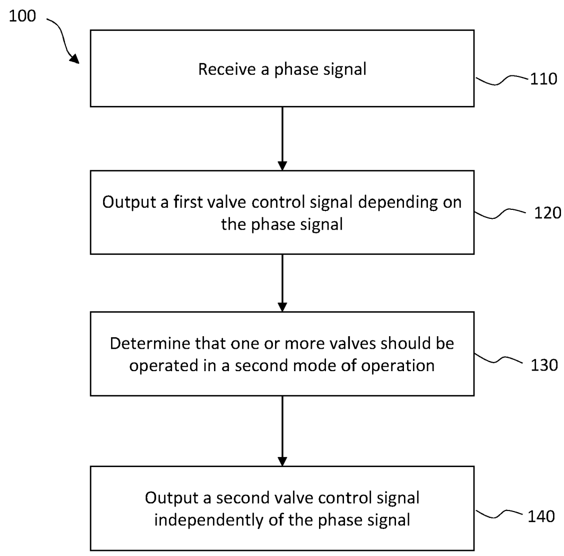

Fig. 1

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Description

Field of the invention

[0001] The present invention relates to a method of operating a hydraulic apparatus to control operation of one or more electronically actuated valves and to a controller of a hydraulic apparatus configured to control operation of one or more electronically actuated valves.

Background to the invention

[0002] The flow of hydraulic fluid through a hydraulic machine to cause pumping and/or motoring relies upon electronically controlled valves which must open or close to controllably permit or prevent flow of hydraulic fluid into or out of chambers of the hydraulic machine. The electromagnetic valves are actuated using valve control signals from a controller. The signals are received by the electromagnetic valves, typically solenoid valves. However, there are many reasons why a controller may fail to send valve control signals to the valves at the optimum times for ensuring the hydraulic machine is operated efficiently. For example, there may be a loss of power, loss of encoder signal or other signal or a software glitch. In some applications that use electronically controlled valves, it is suitable for the hydraulic machine to stop producing flow in case of a failure or fault. However, in other applications that use electronically controlled valves, it is important to maintain production of flow in the hydraulic machine for safety and/or reliability purposes.

[0003] It is in this context that the present disclosure has been devised.

Summary of the invention

[0004] An aspect of the invention provides a method of operating a hydraulic apparatus, the hydraulic apparatus comprising: a hydraulic machine having a rotatable shaft in driven engagement with a prime mover and comprising at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft. The at least one working chamber comprises one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold. The hydraulic machine further comprises a controller configured to control operation of the one or more electronically actuated valves of the hydraulic machine. The hydraulic machine further comprises one or more components of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller. The method comprising receiving the phase signal from the first sensor assembly. The method further comprising in a first mode of operation of the hydraulic machine, outputting a first valve control signal depending on the phase signal. The first valve control signal configured to cause at least one of the one or more electronically actuated valves to operate in accordance with the first mode. The method further comprising determining that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger. The method further comprising, in response to determining that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, outputting a second valve control signal independently of the phase signal. The second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

[0005] Another aspect of the invention provides a hydraulic apparatus comprising: a hydraulic machine having a rotatable shaft in driven engagement with a prime mover and comprising at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft. The at least one working chamber comprising one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold. The hydraulic machine further comprises a controller configured to control operation of at least one of the one or more electronically actuated valves of the hydraulic machine. The hydraulic machine further comprises one or more components of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller. The controller being further configured to receive the phase signal from the first sensor assembly. The controller being further configured to, in a first mode of operation of the hydraulic machine, output a first valve control signal depending on the phase signal. The first valve control signal configured to cause the at least one of the one or more electronically actuated valves to operate in accordance with the first mode. The controller being further configured to determine that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger. The controller being further configured to, in response to determination that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, output a second valve control signal independently of the phase signal. The second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

[0006] A further aspect of the invention provides a controller configured to control operation of at least one of one or more electronically actuated valves of a hydraulic machine. The controller being further configured to receive a phase signal from a first sensor assembly of the hydraulic machine. The controller being further configured to in a first mode of operation, output a first valve control signal depending on the phase signal. The first valve control signal configured to cause the at least one of the one or more electronically actuated valves to operate in accordance with the first mode. The controller being further configured to determine that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger. The controller being further configured to, in response to determination that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, output a second valve control signal independently of the phase signal. The second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

[0007] Advantageously, the hydraulic machine is able to continue operating at least one of the one or more electronically actuated valves even when the phase signal is unable to be used to output the first valve control signal. This results in continued controllable displacement of hydraulic working fluid. This is particularly advantageous in applications of hydraulic machines in which it is important to maintain flow and pressure in the circuit at all times, e.g. pumping in cooling fans or hydraulic steering of a vehicle.

[0008] Typically, the controller and the one or more electronically actuated valves are for use in hydraulic apparatus, for example in a hydraulic circuit, and/or in a hydraulic machine in a hydraulic circuit. The hydraulic machine may be a pump and/or a motor and/or a pump-motor. It may be that at least one of the one or more electronically actuated valves is a high-pressure valve used to control flow into or out of working chambers of the hydraulic machine to/from a high-pressure manifold. It may be that at least one of the one or more electronically actuated valves is a low-pressure valve used to control flow into or out of working chambers of the hydraulic machine from a low-pressure manifold. The at least one working chamber may be a chamber of the hydraulic machine which has a cyclically-varying volume during operation of the hydraulic machine, as is known in the field of hydraulic machines. It will be understood that typically a hydraulic machine also comprises a rotatable shaft mechanically coupled to a working surface of the working chamber. Cyclic variation of the volume of the working chamber is achieved by movement of a working surface within a cylinder, each working surface partially defining the working chamber. Rotation of the rotatable shaft causes or is caused by relative movement of the working surfaces. The hydraulic machine may be electronically controlled. The hydraulic machine may be synthetically commutated. The hydraulic machine may be a variable displacement hydraulic machine. The hydraulic machine may be a digital displacement hydraulic machine.

[0009] The invention may relate particularly to electronically commutated hydraulic machines which intersperse, in a first mode of operation, active cycles of working chamber volume, where there is a net displacement of hydraulic working fluid, with inactive cycles of working chamber volume, where there is no net displacement of hydraulic working fluid between the working chamber and the hydraulic circuit. Typically, the majority or all of the active cycles are full stroke cycles, in which the working chambers displace a predetermined maximum displacement with the high pressure manifold of working fluid by suitable control of the timing of valve control signals. It is also known to regulate the one or more low- and optionally high-pressure valves of the at least one working chamber to regulate the fraction of maximum displacement made during an active cycle by operating so-called part stroke cycles. However, such machines typically intersperse active and inactive cycles, with the active cycles being full stroke cycles, with the fraction of cycles which are active cycles (the active cycle fraction) varied to achieve a demanded fractional displacement, instead of relying on part stroke cycles to provide some fraction of maximum hydraulic machine displacement.

[0010] The controller is typically configured (e.g. programmed) to control the one or more electronically actuated valves (e.g. the low-pressure valve) of the at least one working chambers to cause each working chamber to carry out either an active or an inactive cycle of working chamber volume during each cycle of working chamber volume. The controller may control at least one of the one or more electronically actuated valves using a valve control signal. The valve control signal may control actuation of at least one of the one or more electronically actuated valves. It may be that the controller (and optionally a further controller) is configured to control the one or more electronically actuated valves in phased relationship with cycles of working chamber volume.

[0011] Typically, the one or more electronically actuated valves may be at least one low-pressure valve and/or at least one high-pressure valve. The one or more electronically actuated valves may each comprise a valve member operable to move between a first position corresponding to a first valve state of said valve (e.g. an open position corresponding to an open state) and a second position corresponding to a second valve state of said valve (e.g. a closed position corresponding to a closed state). An operation of the one or more electronically actuated valves may correspond to a configuration of the valve member into the first position or the second position or any position therebetween. The one or more electronically actuated valves are actuated to trigger displacement to/from the cylinders, thereby leading to torque being applied to the rotatable shaft.

[0012] In the first state, the valve member may restrict or seal a channel from a manifold to the working chamber the valve is associated with, to restrict or prevent fluid flow between the channel and the working chamber. The valve member may move into the first state depending on a valve control signal and/or an underlying bias (such as a mechanical bias) and/or fluid flow forces from the transmission of fluid through the valve. In the second state, the valve member may move into the second state depending on a valve control signal and/or a mechanical bias and/or fluid flow forces from the transmission of fluid through the valve. It may be that the valve member is actively controlled by the controller into the first position during an exhaust stroke. It may be that the valve member is positioned into the second position during an intake stroke depending on a mechanical bias which acts to move said valve.

[0013] The electronically actuated valve may be an electromagnetic valve. Thus, a valve control signal causes excitation of an electromagnet (e.g. by directly or indirectly causing current to flow through a coil). The excitation of the electromagnet causes a force to be applied to an armature of a solenoid, formed of the electromagnet and the armature. The force is arranged to urge the armature towards a central region of the coil. Typically, one of the movable components of the solenoid (e.g. the armature) is mechanically connected to the valve member. In this way, it can be seen that when a valve member of an electromagnetic valve moves into the first state or the second state depending on the valve control signal being applied to the electromagnetic valve, the valve control signal causes an electromagnetic force to be exerted by an electromagnet of the electromagnetic valve.

[0014] It will be understood that the underlying bias is typically any bias which causes the valve member to be urged in a given direction (in the absence of any further biases) caused without the use of an electrically generated magnetic field. The mechanical bias is typically any underlying bias caused by a resiliently deformable mechanical component. Typically, the mechanical bias is caused by a spring. In other words, when a valve member of a valve, such as an electromagnetic valve, moves into the first state or the second state depending on the mechanical bias, the mechanical bias may be caused by a force exerted by a resiliently deformable member (e.g. a spring).

[0015] It may be that groups of the at least one working chambers are dynamically allocated to respective groups of one or more hydraulic components in the hydraulic circuit to thereby change which one or more working chambers are connected to (e.g. a group of) hydraulic components, for example by opening or closing at least one of the electronically actuated valves (e.g. high-pressure valves and low-pressure valves, described herein), e.g. under the control of a controller. Groups of (e.g. one or more) the at least one working chamber may be dynamically allocated to (respective) groups of (e.g. one or more) hydraulic components to thereby change which working chambers of the machine are coupled to which hydraulic components, for example by opening and/or closing at least one of the electronically actuated valves, e.g. under the control of the or a further controller. Groups of one or more working chambers are typically connected to a respective group of one or more said hydraulic components through a said manifold.

[0016] It may be that the rate of flow of hydraulic fluid accepted by, or output by, each working chamber is independently controllable. It may be that the flow of hydraulic fluid accepted by, or produced by, each working chamber can be independently controlled by selecting the net displacement of hydraulic fluid by each working chamber on each cycle of working chamber volume. This selection is typically carried out by the controller.

[0017] It may be that the first sensor assembly is an assembly of one or more components configured to output a phase signal to the controller. Typically, the first sensor assembly comprises one or more components. The one or more components may comprise one or more sensors. For example, the one or more sensors may comprise one or more of: a shaft position sensor to detect the position of the rotatable shaft and a speed sensor configured to detect the speed of rotation of the rotatable shaft. The one or more sensors may comprise a rotary encoder to covert the position and or speed of the rotatable shaft to a digital signal. The one or more components may comprise one or more communication interfaces. For example, the one or more communication interfaces may comprise a controller area network (CAN). The one or more component may comprise a control assembly comprising the one or more sensors and the one or more communication interfaces. The one or more components may comprise at least one of: one or more interface circuits, one or more microcontrollers, cabling and software. The one or more interface circuits may convert a detected signal to a signal readable by the controller. The one or more microcontrollers may at least partially control operation of other components of the first sensor assembly. The cabling may be used to transmit signals between the first assembly and other components of the hydraulic apparatus (e.g. the controller). The software may be executable on the controller of the hydraulic apparatus and/or one or microcontrollers of the first sensor assembly. The one or more components of the first sensor assembly may comprise a rotating component coupled to the rotatable shaft. The phase signal may be indicative of phase information of the rotatable shaft. It may be that the phase signal is indirectly indicative of phase information of the rotatable shaft. That is, the phase signal may be associated with a rotating component coupled to the rotatable shaft. It may be that the phase signal is directly indicative of phase information of the rotatable shaft (i.e. the one or more sensors measure the position of the rotatable shaft directly).

[0018] The phase signal may comprise data indicative of information associated with the phase of the rotatable shaft. The phase signal may comprise data from which information regarding the phase of the rotatable shaft can be determined. The phase information may comprise data indicative of a position of the rotatable shaft within the hydraulic machine. The phase information may be indicative of a position and/or speed of the rotatable shaft within the hydraulic machine.

[0019] Typically, the controller may receive the phase signal from the first sensor assembly. The phase signal may be transmitted through the cabling of the first sensor assembly. The controller may be configured to determine the phase information from the phase signal. It may be that the method comprises determining the phase information from the phase signal. For example, the controller may calculate or extract the phase information from the phase signal. The method may comprise determining the phase information from the phase signal.

[0020] Advantageously, determining phase information from the phase signal enables the controller to calculate the position of the rotatable shaft. The controller may then output the valve control signals depending on the position of the shaft. In this way, the controller is able to determine the appropriate timing to output the valve control signals to open and/or close the valves to control the flow output of the hydraulic machine.

[0021] It may be that the controller is configured to determine the content of the valve control signal. For example, the content of the valve control signal may be indicative of instructions to configure (i.e. operate by moving or maintaining the position) at least one of the one or more electronically actuated valves into the open or the closed position. Typically, the valve control signal may be indicative of electrical energy to be supplied to the one or more electronically actuated valves. The electrical energy may be supplied by electric current and electric potential (e.g. voltage). As such, typically, the valve control signal may be indicative of a current (i.e. electric current) signal and/or a voltage signal. The current signal may be output by the controller or by another component of the hydraulic apparatus (e.g. a second controller). The current signal may be indicative of a current to be applied to the at least one of the one or more electronically actuated valves. The at least one of the one or more electronically actuated valves may be actuated in accordance with the applied current.

[0022] The method may comprise operating the hydraulic machine in a first mode of operation. It may be that "operation" of the hydraulic machine refers to displacement of flow with either a high-pressure valve or low-pressure valve. The first mode of operation may correspond to a "normal" mode of operation of the hydraulic machine. The "normal" mode of operation may be when the hydraulic apparatus is operating without any faults or failure in any component of the hydraulic apparatus. In the first mode of operation, the method may comprise outputting the first valve control signal depending on the phase signal. The first mode of operation may be a mode of operation of the hydraulic machine in which the controller uses the phase signal to determine the first valve control signal to be output by the controller. For example, the phase signal may be indicative of phase information representing that the rotatable shaft is in a phase position corresponding to bottom dead centre (BDC). Depending on the phase position corresponding to BDC, the controller may determine not to output a valve control signal such that the at least one of the one or more electronically actuated valves may be configured into the open position depending on a mechanical bias. In some examples, depending on the phase position corresponding to BDC, the controller may determine to output a valve control signal to configure (i.e. operate by moving or maintaining the position) at least one of the one or more electronically actuated valves into the open position. In another example, the phase signal may be indicative of phase information representing that the rotatable shaft is in a phase position corresponding to top dead centre (TDC). Depending on the phase position corresponding to TDC, the controller may determine to output a valve control signal to configure the at least one of the one or more electronically actuated valves into the closed position. In some examples, depending on the phase position corresponding to TDC, the controller may determine not to output a valve control signal such that the at least one of the one or more electronically actuated valves may be configured into the closed position depending on a mechanical bias. The controller may determine to output a valve control signal to configure the at least one of the one or more electronically actuated valves into the closed position depending on the phase signal being indicative of phase information representing that the rotatable shaft is in a phase position corresponding a position between TDC and BDC in the exhaust stroke. When the at least one of the one or more electronically actuated valves are mechanically biased into the open position in the absence of a valve control signal, the controller may determine, when the phase signal is indicative of phase information representing that the rotatable shaft is in a phase position corresponding a position between BDC and TDC in the intake stroke, not to output a valve control signal that would cause the valve to close. As a result, the valve may be configured in the open position. In this case, the valve may be configured into the open position depending on the phase signal being indicative of phase information representing that the rotatable shaft is in a phase position corresponding a position between BDC and TDC in the intake stroke. In this way, the valve control signal causes at least one of the one or more electronically actuated valves to operate in accordance with the first mode of operation of the hydraulic machine in that said valve is actuated in response to the first control signal output by the controller operating in the first mode of operation.

[0023] It may be that at least one of the one or more electronically actuated valves (e.g. a low-pressure inlet valve) exhibits a positional bias (e.g. a first positional bias) towards a first position (e.g. open position) depending on a mechanical bias. The at least one of the one or more electronically actuated valves may exhibit the positional bias towards the first position in the absence of a valve control signal (e.g. the first or second valve control signal). The at least one of the one or more electronically actuated valves may exhibit a positional bias (e.g. a second positional bias) towards a second position (e.g. closed position) depending on (e.g. application of) a valve control signal (e.g. the first or second valve control signal).

[0024] It will be understood that a positional bias of a valve corresponds to a position towards which the movable valve member is urged by at least one of: mechanical; magnetic; and electromagnetic forces, but can also be understood to relate to a substantially unbiased configuration in which the movable valve member is not significantly urged by mechanical, magnetic or electromagnetic forces into any position. In such a case, the positional bias of the valve would be understood to be an unbiased positional bias.

[0025] The controller may determine that the at least one of the one or more electronically actuated valves should be operating in a second mode of operation of the hydraulic machine. The method may comprise operating in the hydraulic machine in a second mode of operation, for example pumping or motoring. The second mode of operation may correspond to a mode of operation in which the hydraulic apparatus is operating with one or more faults or failures in one or more components of the hydraulic apparatus. In the second mode of operation, the method may comprise outputting the second valve control signal independently of the phase signal. The second mode of operation may be a mode of operation of the hydraulic machine in which the controller, after having determined to operate in the second mode of operation, does not use the phase signal to determine the second valve control signal to be output by the controller. For example, the controller may output the second valve control signal to configure (i.e. operate by moving or maintaining the position) the at least one of the one or more electronically actuated valves into the closed position (or the open position) without consideration of the phase position of the rotatable shaft to determine the second control signal or the type of stroke (e.g. intake stroke or exhaust stroke).

[0026] It may be that, in the second mode of operation, the hydraulic machine is configured to transfer energy between the rotatable shaft and the hydraulic fluid by movement of the rotatable shaft and a working surface of at least one of the at least one working chambers. That is, in the second mode of operation, the controller is configured to control the at least one of the one or more electronically actuated valves to at least partially approximate at least some aspects of the first mode of operation of the hydraulic machine. In this way, the hydraulic machine is able to perform at least part of one or more active cycles of working chamber volume, even without the phase signal, thereby causing a net displacement of hydraulic working fluid. Again, this is particularly advantageous in hydraulic machine applications where it is important (e.g. for safety) to continue at least partial operation with at least some net displacement of fluid.

[0027] Typically, the trigger used to determine that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation of the hydraulic machine may be associated with the hydraulic apparatus. The trigger may be associated with a fault or failure of the hydraulic apparatus which prevents the hydraulic machine from being able to operate in the first mode of operation. For example, the trigger may comprise at least one of: loss of power to a component of the hydraulic apparatus, loss of encoder signal (e.g. a signal from a rotary encoder) of the first sensor assembly, loss of signal from at least one of the one or more sensors (e.g. a pressure sensor) of the first sensor assembly or from a sensor other than the one or more sensors of the first sensor assembly, and a software glitch of the hydraulic apparatus. Alternatively, the trigger may be associated with a device external to the hydraulic apparatus. In some examples, the trigger may be associated with a request to operate the hydraulic machine in the second mode of operation from a component external to the first sensor assembly.

[0028] It may be that the failure corresponds to at least one of: a failure of the first sensor assembly, a failure of the controller, and a failure of a component other than the controller and the first sensor assembly. The failure of the first sensor assembly may comprise at least one of: damage to the rotating component coupled to the rotating shaft, failure of or damage to the shaft speed and/or shaft position sensor (e.g. physical problem with the sensor and/or related wiring, or a software malfunction) and damage to the cabling. The failure of the controller may comprise at least one of: failure of or damage to a sensor interface circuit, failure of or damage to one or microcontrollers, failure of or damage to the valve output circuit, software fault(s), and overheating of the controller. The failure of the component other than the controller and the first assembly may comprise at least one of: failure of other components of the hydraulic apparatus, loss of power to the hydraulic apparatus and loss of signals separate to those associated with the first sensor assembly).

[0029] Advantageously, the hydraulic machine is able to continue operation despite failure of the first sensor assembly, failure of the controller and failure of a component other than the controller and the first sensor assembly. In this way, the hydraulic machine is able to operate in the second mode of operation in response to a failure from a wide variety of components of the hydraulic apparatus.

[0030] It may be that the trigger corresponds to a failure associated with the phase signal. Typically, the trigger corresponds to a full or partial loss of the phase signal. The failure of the phase signal may be a failure to receive the phase signal from the first sensor assembly such that there is a full (i.e. complete) loss of the phase signal. The failure of the phase signal may be a failure to receive a complete phase signal from the first sensor assembly such that there is a partial loss of the phase signal. The failure of the phase signal may be a failure to receive an accurate phase signal from the first sensor assembly. The failure of the phase signal may be a failure to identify whether a received phase signal is an accurate phase signal.

[0031] It may be that the trigger corresponds to a full or partial loss of the phase information. That is, the controller may receive at least part of the phase signal from the first sensor assembly but may not be able to determine all or part of the phase information from the phase signal. It may be that the trigger corresponds to a full or partial loss of reliable phase information from the phase signal. That is, the controller may receive at least part of phase signal from the first sensor assembly but may not be able to determine all or part of the reliable phase information from the phase signal.

[0032] It may be that the controller is configured to detect (i.e. identify) the trigger. For example, the controller may detect (i.e. identify) the failure of the phase signal and/or the failure of at least one of: a failure of the first sensor assembly, a failure of the controller and a failure of a component other than the controller and the first sensor assembly. It may be that the method comprises detecting (i.e. identifying) the trigger. For example, the method may comprise detecting (i.e. identifying) the failure of the phase signal and/or the failure of at least one of: a failure of the first sensor assembly, a failure of the controller and a failure of a component other than the controller and the first sensor assembly. The controller may detect (i.e. identify) the trigger by comparing measured input(s) (e.g. the phase signal, one or more inputs from the first sensor assembly and/or one or more inputs from the component other than the controller and the first sensor assembly) to an expected value. The measured input(s) may correspond to the absence of the input(s). The controller may detect (i.e. identify) the trigger by monitoring operation of the controller itself to determine whether the controller is experiencing a fault or failure.

[0033] It may be that the method comprises outputting, as the second valve control signal, a current signal to the at least one of the one or more electronically actuated valves. The current signal typically being out of phased relation with the rotatable shaft. It may be that the controller is further configured to output, as the second valve control signal, a current signal to the at least one of the one or more electronically actuated valves. The current signal typically being out of phased relation with the rotatable shaft.

[0034] The current signal (as the second valve control signal) may be out of phased relation with the rotatable shaft in that the current signal may not have an intentional relationship or correspondence with the phase of the rotatable shaft. The rotatable shaft may rotate with a cycle having a first period. The second valve control signal may be out of phased relation with the first period. In this way, the second valve control signal is outputted by the controller independently of the cycle of the rotatable shaft. The controller may determine to output the second valve control signal with a timing independent of the cycle of the rotatable shaft. The second valve control signal may be output at a rate determined independently of the rate of rotation of the rotatable shaft. The rate at which to output the second valve control signal may be predetermined (e.g. pre-programmed onto the controller during manufacture).

[0035] It may be that the current signal is substantially out of phased relation with the rotatable shaft. It may be that the current signal is out of phased relation with the rotatable shaft more than 50%, such as more than 70%, or even more than 90% of the time.

[0036] Typically, the method may comprise outputting, as the first valve control signal, a current signal to the at least one of the one or more electronically actuated valves. In contrast to the second valve control signal, the current signal of the first valve control signal may typically be in phased relation with the rotatable shaft. It may be that the controller is further configured to output, as the first valve control signal, a current signal to the at least one of the one or more electronically actuated valves. The current signal typically being in phased relation with the rotatable shaft. The current signal output as the first valve control signal may be in phased relation with the rotatable shaft in that the current signal may have an intentional relationship or correspondence with the phase of the rotatable shaft.

[0037] As mentioned previously, the current signal may be indicative of a current to be applied to the at least one of the one or more electronically actuated valves. In response to the applied current, the valve may be configured into a valve state, which may correspond to a position of the valve member. The applied current may cause a force to be generated by a component of the valve (e.g. an electromagnet). The force generated may be an electromagnetic force. The force may be exerted on another component of the valve, for example an armature. The armature may be connected to the valve member. The armature may be moveable in response to the exerted force caused by the current. As a result, the force caused by the applied current may cause the valve to exhibit a positional bias. In this way, the one or more electronically actuated valves may each be associated with a positional bias.

[0038] It may be that the second valve control signal is configured to change a positional bias of the at least one of the one or more electronically actuated valves. When the second valve control signal is applied to a valve, a force is generated which causes the position of the valve to change position from the position of the valve when no current is applied to the valve (e.g. a positional bias caused by a mechanical bias). The positional bias may refer to a preference for a particular valve state (i.e. a particular position of the valve member) compared to other valve states (i.e. other positions of the valve member). When the current is not applied to the valve, the valve may be configured into the first position. Typically, the valve may be configured into the second position depending on a current being applied to the valve. For example, the valve may be configured in the second position or a position between the first position and the second position. It may be that when no current is applied to the valve, the valve is not biased into any position and is freely moveable in response to fluid flow forces acting on the valve.

[0039] Advantageously, the second valve control signal changing the positional bias of the valve means that the valve can be moved between the open and closed positions. As a result, the hydraulic apparatus is able to produce flow without requiring use of the phase signal to output the valve control signals. By configuring the valve in the open or closed position during the correct part of the cycle (i.e. exhaust stroke or intake stroke), the valves are able to allow for the new displacement of hydraulic fluid.

[0040] In some examples, the positional bias of the valve may be influenced (i.e. caused) by a mechanical component causing a mechanical bias (e.g. a resiliently deformable member such as a spring). For example, a resiliently deformable member may exert a spring force on the armature thereby causing the valve to exhibit a positional bias. The positional bias may be influenced (i.e. caused) by a combination of the force generated by the current and the mechanical component.

[0041] It may be that the second valve control signal is configured to reduce or remove the positional bias of the at least one of the one or more electronically actuated valves for one or more complete working chamber cycles. Typically, the second valve control signal may be indicative of a current with an average magnitude. Typically, a flow output of the hydraulic machine is proportional to the average magnitude of the second valve control signal. The second valve control signal configured to reduce or remove the positional bias of the at least one of the one or more electronically actuated valves for one or more complete working chamber cycles may be referred to as a first variant of the second valve control signal. That is, the first variant of the second valve control signal may be such that the positional bias on the valve is at least partially overcome for all of the one or more complete working chamber cycles. When the first variant of the second valve control is applied, the valve may be positioned between the open position and the closed position.

[0042] Advantageously, it is possible to increase the average magnitude of the current of the first variant of the second valve control signal to increase the flow output of the hydraulic apparatus even without use of the phase signal to determine the appropriate valve control signal. By removing or reducing the positional bias, it is possible to at least partially overcome a positional bias of the valve exhibited when no current is applied to the valve.

[0043] When the first variant of the second valve control signal is applied to a valve, a force is generated which causes reduction or removal (e.g. through overcoming) of the biasing force which causes the positional bias of the valve when no current is applied to the valve (i.e. due the force causing the mechanical bias).

[0044] This occurs for one or more complete working chamber cycles because the first variant of the second valve control signal is applied continuously (typically, over a prolonged period corresponding to a plurality of complete working chamber cycles). As a result, the positional bias of the valve, that would otherwise be exhibited when no current is applied to the valve, is reduced or removed for the entire cycle (i.e. the strength of the force, such as a spring force, causing the positional bias when the no current is applied to the valve, is at least partially overcome by another force generated by the current, such as a magnetic force).

[0045] For example, at least one of the one or more electronically actuated valves may comprise an armature coupled to the valve member and a resiliently deformable member (e.g. a spring) arranged to exert a spring force on the armature. When no current is applied to the valve, the spring force may cause the armature, and therefore the valve member, to exhibit a positional bias (i.e. a preference) towards (e.g. in to) the first position. The first position may correspond to an open position of the valve. When the first variant of the second valve control signal is applied to the valve, a resulting magnetic force may be exerted on the armature. The resulting magnetic force may oppose the spring force. In response, the valve (e.g. valve member) may be moved away from the first position, towards the second position. As a result, the positional bias exhibited by the valve when no current is present may be reduced, or removed entirely such that the valve is no longer biased towards the open position when the first variant of the second valve control signal is applied.

[0046] The average magnitude of the second valve control signal may be the average magnitude of current applied over a time period. The time period may be less than 10 seconds, less than 30 seconds or less than 60 seconds or less than 5, less than 10 or less than 50 revolution(s) of the rotatable shaft. The second valve control signal may be indicative of a current with an average magnitude in that a constant current is applied, in which case the magnitude of the current is the same for all time periods and the magnitude of the constant current is the same as the average magnitude. The second valve control signal may be indicative of a current with an average magnitude in that a Pulse Width Modulation (PWM) signal is applied having a current with an average magnitude applied across the period of the PWM signal. For example, an average magnitude of the first variant of the second valve control signal may be greater than 200mA, 500mA, 1A, 2A or 5A. For example, the average magnitude of the second variant (defined further below) of the second valve control signal may be less than 1A, 2A, 5A, 8A or 10A.

[0047] The flow output of the hydraulic machine may refer to a volume displaced per unit of time. The flow output may depend on the speed of rotation of the rotatable shaft. For example, the flow output may be measured in litres per minute at a given rpm (e.g. a maximum flow output may be 144 L/min at 1500 rpm or 173 L/min at 1800 rpm). The displacement may be measured in volume per revolution.

[0048] Typically, a flow output of the hydraulic machine is proportional to the average magnitude of the second valve control signal. In this way, when the average magnitude of the second valve control signal is increased, the flow output of the hydraulic machine may also increase. Similarly, when the average magnitude of the second valve control signal is decreased, the flow output of the hydraulic machine may also decrease. The proportionality relationship between the average magnitude of the second valve control signal and the flow output of the hydraulic machine may be linear or non-linear.

[0049] It may be that the second valve control signal is indicative of a current with an average magnitude within a threshold magnitude range. The threshold magnitude range typically having a lower bound greater than zero and an upper bound less than a current at which a force, generated by the current and causing the positional bias of the at least one of the one or more electronically actuated valves, overcomes a fluid flow force acting on the at least one of the one or more electronically actuated valves for all of the one or more complete working chamber cycles.

[0050] Advantageously, provision of an average magnitude within the threshold magnitude range allows for the valve member to be forced closed at some point during each exhaust stroke. However, the valve member can still open to admit oil in each intake stroke. This means that the valve position is able to be influenced by flow forces of the fluid. Therefore, the selected cylinders will achieve net pumping. If the average magnitude of the current is too low, the valve may not close reliably during the exhaust stroke. If the average magnitude of the current is too high, filling of the cylinder may be inhibited during the intake stroke.

[0051] The threshold magnitude range may refer to a range of values for an appropriate magnitude of the average current. By providing the first variant of the second valve control signal at an appropriate average magnitude, the valve (i.e. an inlet valve) will be forced closed during each exhaust stroke. This will occur as the flow of fluid moving out of the cylinder forces the valve into the closed position. By providing the first variant of the second valve control signal at an appropriate average magnitude, the valve (i.e. inlet valve) will be able to open during each intake stroke. This will occur as the flow of fluid (e.g. oil) moving into the cylinder forces the valve into the open position to admit oil into the cylinder. In a hydraulic pump, this is particularly advantageous as it allows pumping to occur even if the phase signal is not used to control the valves. The fluid flow force may be caused by the flow of fluid into/out of the cylinder and may be exerted on the valve member.

[0052] Therefore, the appropriate current magnitude may be a magnitude at which the force generated by the current is sufficiently low (e.g. at the lower bound) to allow fluid intake to the cylinder in the intake stroke (i.e. the spring force and fluid flow force of fluid into the valve is able to overcome the force caused by the current) during at least part of the one or more complete working chamber cycles. In addition, the appropriate current magnitude may be a magnitude at which the force generated by the current is sufficiently high (e.g. at the upper bound) to force fluid to leave the cylinder via the high pressure manifold during the exhaust stroke by closing the channel to the low pressure manifold (i.e. the force generated by the current and the fluid flow force of fluid out of the cylinder is able to overcome the spring force) during at least part of the one or more complete working chamber cycles. The threshold magnitude range may comprise a lower bound greater than 500mA, 1A, 2A or 4A. The threshold magnitude range may comprise an upper bound less than 5A, 8A or 10A.

[0053] If the average magnitude of the current is too low, the low pressure valve will not close reliably during the exhaust stroke to force fluid to exit the cylinder via the high pressure manifold. The force generated by the applied current will be insufficient to overcome the spring force and the fluid flow force acting on the valve (from fluid exiting the cylinder). As a result, the valve may be unable to close during the exhaust stroke to force fluid to leave the cylinder via the high pressure manifold (rather than via the low pressure valve to the low pressure manifold). The lower bound of the threshold magnitude range may be an average magnitude greater than zero.

[0054] If the average magnitude of the current is too high, the force generated by the applied current will be too large, such that the fluid flow force acting on the valve (from fluid entering the cylinder) and the spring force will be unable to overcome the force caused by the applied current. As a result, the valve may be unable to open during the intake stroke to admit fluid into the cylinder from the low pressure manifold. In addition, in this situation, electrical power usage will be high, causing heating of the valve, which may lead to inefficiency or even failure of the valve.

[0055] The first variant of the second valve control signal may be indicative of a constant current (i.e. a current having a constant magnitude). For example, the current signal may cause a constant current to be applied to the at least one of the one or more electronically actuated valves from a secondary power source (e.g. a battery connected to the valve).

[0056] The first variant of the second valve control signal may be associated with a Pulse Width Modulation (PWM) signal applied to the one or more electronically actuated valves. The PWM signal may have a fixed voltage. In other words, the maximum magnitude of the PWM signal may be fixed. For example, the current signal may cause a PWM signal to be applied to the at least one of the one or more electronically actuated valves by a driver circuit, of the controller, for the valve. The driver circuit may comprise at least one of: one or more MOSFETs, one or more flyback diodes and one or more H-bridges. The driver circuit may be controlled by a microcontroller or a FPGA.

[0057] It may be that the hydraulic apparatus comprises a second valve control signal circuit. The second valve control signal circuit may include using a relay switch to enable and disable the second valve control signal. The relay switch may be controlled depending on data external to the controller. For example, the relay switch may be controlled depending on a control signal from a sensor (e.g. a pressure sensor) and/or an operational status of the controller (e.g. monitoring a 'heartbeat' signal of the controller) and/or data from other systems (e.g. engine data). It may be that the second valve control signal circuit comprises one or more resistors to regulate the current to each valve. It may be that the second valve control signal circuit comprises one or more diodes to reduce reverse current flow in case the driver circuit was activated whilst the relay was closed.

[0058] It may be that the second valve control signal is configured to cause the positional bias to the at least one of the one or more electronically actuated valves for only part of a complete working chamber cycle. The second valve control signal configured to cause the positional bias to the at least one of the one or more electronically actuated valves for only part of a complete working chamber cycle may be referred to as a second variant of the second valve control signal of the second mode of operation. That is, a positional bias of the at least one of the one or more electronically actuated valves is caused by the second variant of the second valve control signal for only part of a complete working chamber cycle. When the second variant of the second valve control is applied, the valve may be positioned in the open position or the closed position.

[0059] Advantageously, the second valve control signal causing the positional bias means that the current signal is sufficient to fully close the valve. If this happens during the exhaust stroke, some pumping will occur. Between pulses the valve is able to open to admit hydraulic fluid during the intake stroke.

[0060] When the second variant of the second valve control signal is applied to a valve, a force is generated which causes a positional bias of the valve. That is, the second variant of the second valve control signal may provide sufficient energy to overcome the spring force which causes the positional bias when no current is applied to the valve. As a result, the fluid flow forces are unable to influence the position of the valve because they are unable to overcome the force generated by the applied current of the second variant of the second valve control signal. The positional bias of the valve caused by the applied current may be different to the positional bias of the valve when no current is applied to the valve. The positional bias of the valve when no current is applied to the valve may be a first positional bias. The positional bias of the valve caused by the applied current may be a second positional bias. The first positional bias (e.g. open position) may be the opposite of the second positional bias (e.g. closed position).

[0061] This occurs for only part of a complete working chamber cycle because the second variant of the second valve control signal is not applied continuously. That is, the second variant of the second valve control signal is applied at intervals, which may be regular or irregular intervals. As a result, the positional bias of the valve changes between the first positional bias (e.g. the positional bias that would be exhibited when no current is applied to the valve) and the second positional bias (e.g. the positional bias caused by the force generated by the current signal of the second valve control signal) throughout each complete working chamber cycle.

[0062] Typically, in use in a hydraulic pump, the second variant of the second valve control signal is output during the exhaust stroke. As a result, the valve (i.e. inlet valve) exhibits the second positional bias (i.e. in the closed position) so that fluid is unable to return to the low-pressure manifold and will instead be forced out of a high-pressure valve in fluid communication with the cylinder. Advantageously, some pumping will occur to allow the hydraulic pump to operate, at least partially, as intended, to cause pumping. Between pulses the valve is influenced by the spring force and/or the fluid flow forces to open, which is particularly advantageous to admit fluid into the cylinder during the intake stroke.

[0063] It may be that the average magnitude of the second variant of the second valve control signal is typically greater than the average magnitude of the first variant of the second valve control signal.

[0064] Since the valve is configurable in the first positional bias or the second positional bias, the valve is able to either fully open or fully close when the second variant of the second valve control signal is applied. However, when the first variant of the second valve control signal is applied, the valve is urged towards the first or second positional bias with less force than the second variant of the second valve control signal. As a result, the flow output of the first variant of the second valve control signal may be less than the flow output of the second variant of the second valve control signal because the valves are neither fully open nor fully closed when the first variant of the second valve control signal is applied.

[0065] It may be that the method comprises outputting the second valve control signal as a plurality of pulses, at least some of adjacent pulses of the plurality of pulses spaced apart in time by an interval different to a cycle period of at least one of the working chambers. It may be that the second valve control signal has a pulse waveform equal to a pulse waveform of the first valve control signal. It may be that the method further comprises adjusting a rate of the plurality of pulses to alter a flow output of the hydraulic machine. It may be that the controller is configured to output the second valve control signal as a plurality of pulses, at least some of adjacent pulses of the plurality of pulses spaced apart in time by an interval different to a cycle period of at least one of the working chambers. It may be that the second valve control signal has a pulse waveform equal to a pulse waveform of the first valve control signal. It may be that the controller is further configured to adjust a rate of the plurality of pulses to alter a flow output of the hydraulic machine.

[0066] Advantageously, when a time interval of the pulses is different to a cycle period of the working chamber, the possibility of no flow output occurring in the second mode of operation is reduced. If the pulses were spaced apart with an interval corresponding to the cycle period of the working chamber to be output in phased relation with the shaft, it may be that no flow output occurs in the second mode of operation. For example, if a pulse configuring a low-pressure valve into a closed position were to be output at the beginning of the intake stroke, there would be no flow output.

[0067] The pulses may be sufficient in magnitude and duration to cause the bias towards the second positional bias (e.g. the closed position). The pulse may comprise a first portion which is applied at a sufficiently high magnitude for a sufficient duration to cause the valve to move into the second positional (overcoming a first positional bias). The pulse may further comprise a second (i.e. latching) portion to maintain the second positional bias. The latching portion may be applied for a shorter duration and at lower magnitude than the first portion.

[0068] It may be that the second variant of the second valve control signal (e.g. controlling the low-pressure valve to close) affects flow through the manifold (e.g. the high-pressure manifold) by changing the (low-pressure) valve state only when output during a particular stoke (e.g. the exhaust stroke). When output during the alternative stroke (e.g. the intake stroke), the second variant of the second valve control signal may have no effect on the flow through the (high-pressure) manifold because it does not change the (low-pressure) valve state. The second variant of the second valve control signal may not change the valve state because the actuation force caused by the second valve control signal may be insufficient to overcome the flow forces of fluid entering the working chamber through the manifold.

[0069] It may be that the second variant of the second valve control signal (e.g. controlling the low-pressure valve to close) does not affect flow through the manifold (e.g. the high-pressure manifold) because the valve state has already been changed during the same stroke. For example, the first pulse of the second variant of the second control signal output during the exhaust stroke may close the LPV. This may cause displacement through the high-pressure manifold. A subsequent pulse within the same exhaust stroke will not close the LPV as the LPV is already closed.

[0070] It may be that the second variant of the second valve control signal comprises a current signal with a plurality of pulses. The interval between the adjacent pulses may be regular (i.e. each pulse is separated by the same amount of time) or irregular (i.e. each pulse is separated by a different amount of time). The interval between adjacent pulses may be random, such that the interval between a pair of adjacent pulses may be the same or different to another pair of adjacent pulses. The interval between adjacent pulses may be pseudorandom.

[0071] It may be that the interval is different to a cycle period of at least one of the working chambers. That is, the rate of pulses of the second valve control signal may be different to the rate of the rotatable shaft (and working chamber cycle). At least some of the intervals between adjacent pulses may be greater than the cycle period, greater than 50% of the cycle period, greater than 25% of the cycle period, greater than 10% of the cycle period or greater than 5% of the cycle period. It may be that each of the intervals between adjacent pulses is greater than the cycle period, greater than 50% of the cycle period, greater than 25% of the cycle period, greater than 10% of the cycle period or greater than 5% of the cycle period.

[0072] Typically, the waveform of the pulse of the second valve control signal may be the same the waveform of the first valve control signal. This may allow the valves to replicate the operation of the first mode of operation in the second mode of operation.

[0073] When the second variant of the second valve control signal is applied randomly, around 50% of the randomly timed pumping cycles may occur in the exhaust stroke. This is a result of the exhaust stroke making up 50% of the working chamber cycle, with the intake stroke making up the remaining 50%. When the second variant of the second valve control signal is applied during the exhaust stroke, the valve exhibits a positional bias towards the closed position (i.e. of a low-pressure valve) so the fluid is forced out of the cylinder (i.e. through a high-pressure valve) as the piston compresses the working surface, resulting in pumping.

[0074] The controller may be configured to determine an average (e.g. random) firing frequency of the second valve control signal. The method may comprise determining an input indicative of an average (e.g. random) firing frequency of the second valve control signal. The average firing frequency may be associated with a rate of random pulses to be output as the second valve control signal. The average firing frequency may be calculated depending on an input to the controller. The average firing frequency (i.e. the average rate of pulses) can be adjusted to affect the output flow. That is, by increasing the rate of pulses, the chance that the valve will be closed, for some portion of the exhaust stroke, is increased. Therefore, the expected volume pumped will increase.

[0075] The controller may be configured to determine one or more suitable working chambers from the at least one working chamber to control with the second variant of the second valve control signal. The method may comprise determining one or more suitable working chambers from the at least one working chamber to control with the second variant of the second valve control signal. For example, the controller may determine the one or more suitable working chambers depending on a service connected to the working chamber or a reliability of each working chamber. The service may be an input or output connected to the hydraulic circuit, such as an accumulator for storing hydraulic fluid, a hydraulic motor for causing propulsion or movement and/or a hydraulic ram for causing movement. The one or more suitable working chambers may be determined depending on a phase (e.g., an equally spaced set of 6 or 12 working chambers) or orientation (e.g. lower cylinders are more likely to be filled with fluid) of each working chamber.

[0076] Typically, the controller may be configured to calculate a random delay based on the selected average firing frequency. Typically, the method may comprise calculating a random delay based on the selected average firing frequency. After this delay elapses, the controller may select one of the one or more suitable working chambers and output the second valve control signal to the one of the one or more suitable working chambers. The method may comprise selecting one of the one or more suitable working chambers and outputting the second valve control signal to the one of the one or more suitable working chambers.

[0077] It may be that the controller records a time of firing for each working chamber. If the selected working chamber was fired previously within a predetermined time period, the controller may select another one of the one or more suitable working chambers. It may be that the method comprises recording a time of firing for each working chamber. If the selected working chamber was fired previously within a predetermined time period, the method may comprise selecting another one of the one or more suitable working chambers. Advantageously, this reduces the chance of the same valve being fired multiple times in quick succession which could cause undesirable heating of the coil, wiring, fuse or driver circuit. The predetermined time period may be greater than one quarter of a cycle period. The predetermined time period may be greater than 0.5 seconds.

[0078] It may be that the method comprises determining whether to output the first variant or the second variant of the second valve control signal. It may be that the controller is configured to determine whether to output the first variant or the second variant of the second valve control signal. Typically, the determination of whether to output the first variant or the second variant of the second valve control signal may depend on fault information. The fault information may be the trigger discussed above, including the failure of the phase signal.

[0079] That is, the controller may selectively choose to enable the first variant or the second variant of the second valve control signal. The controller may use data from sensors, information from other control units and information about faults which are currently active to choose which variant of the second valve control signal to output. However, with either variant of the second valve control signal, output flow is produced, without requiring phase information of the rotatable shaft, by sending a current signal to the valves which does not vary in phased relation to the rotatable shaft.

[0080] Advantageously, the provision to select the first variant or second variant of the second valve control signal is advantageous because some valve designs will be more suitable for one variant over the other. Typically, the suitability of a valve to a particular variant may depend on properties including: magnetic circuit design, spring rate and/or flow forces on the valve member. Typically, providing the first variant of the second valve control signal is more straightforward than the second variant of the second valve control signal.

[0081] It may be that the controller is pre-programmed to output the first variant of the second valve control signal (e.g. during manufacture or during installation). It may be that the controller is pre-programmed to output the second variant of the second valve control signal (e.g. during manufacture or during installation).

[0082] It may be that the method comprises determining that the one or more electronically actuated valves should be operated in the second mode of operation depending on measured data from one or more components of a second sensor assembly. It may be that the hydraulic apparatus comprises the second sensor assembly. It may be that the controller is configured to determine that the one or more electronically actuated valves should be operated in the second mode of operation depending on measured data from one or more components of a second sensor assembly. It may be that the hydraulic apparatus comprises the second sensor assembly.

[0083] Advantageously, this provides a form of monitoring the operation of the hydraulic apparatus to determine whether to operate in the second mode. This is particularly advantageous as it allows the machine to determine when to operate in the second mode of operation without the need for human monitoring.

[0084] It may be that the controller determines that the one or more electronically actuated valves should be operated in the second mode of operation. It may that a supervisory controller determines that the one or more electronically actuated valves should be operated in the second mode of operation and transmits a signal to the controller to operate in the second mode of operation. In either case, the determination that the one or more electronically actuated valves should be operated in the second mode of operation by the controller or supervisory controller typically depends on information from other sources, such as the measured data from one or more components of the second sensor assembly. The determination that the one or more electronically actuated valves should be operated in the second mode of operation may comprise determining if the controller can actuate the at least one of the one or more electronically actuated valves in the usual way (i.e. operate the valves in accordance with the first mode of operation). For example, the controller or supervisory controller may compare a speed measurement or determination of the rotatable shaft from the controller (e.g. from the first sensor assembly) with a speed measurement from a connected second speed sensor or device (e.g. a second sensor assembly), such as an electronic control unit of an engine. The controller or supervisory controller may determine whether there is a significant difference between the measurement from the first sensor assembly and the measurement from the second sensor assembly. If it is determined that there is a significant difference, a fault could be identified and it may be determined that the at least one or more electronically actuated valves should be operated in accordance with the second mode of operation.

[0085] For the second variant of the second valve control signal, the average firing frequency may be selected based on an expected flow required by a load of the hydraulic machine. The average firing frequency and/or the pulse waveform of the second valve control signal may be selected based on the measurement from the second sensor assembly in order to achieve the desired average flow.

[0086] The controller may be configured to perform any steps of the methods described herein. The controller for the hydraulic apparatus may comprise one or more processors. The controller may comprise a non-transitory computer readable memory storing instructions. The instructions, when executed by the one or more processors may cause the controller to operate the hydraulic apparatus as described herein. The one or more processors may be located in a single unit. In other examples, where the one or more processors is a plurality of processors, the controller may be distributed, which is to say that at least one of the plurality of processors may be located separated from at least one other of the plurality of processors. The controller may be configured to receive at least one input from the one or more components of the first sensor assembly. The controller may be configured to transmit at least on output to at least one of the one or more electronically actuated valves. Typically, the hydraulic apparatus comprises the controller, but in other examples, the controller may be provided separate from the hydraulic apparatus and in wireless data communication therewith. The controller may be a 'main controller' with additional controllers (e.g. secondary controllers or microcontrollers) also included in the hydraulic apparatus.

[0087] In some control systems for a hydraulic apparatus, a main microcontroller interfaces to one or more secondary controllers (e.g. field-programmable gate arrays (FPGAs) or complex programmable logic devices (CPLDs)). The one or more secondary controller may provide low-level control signals for the valve power electronics. As a result, the second valve control signal may be implemented in the one or more secondary controllers as a "back-up" in the event of a fault with the main microcontroller. For example, the one or more secondary controllers may monitor a 'heartbeat signal' from the main microcontroller. If the 'heartbeat signal' fails, the one or more secondary controllers may determine that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation.

Description of the Drawings

[0088] An example embodiment of the present invention will now be illustrated with reference to the following Figures in which:

Figure 1 is a flow diagram illustrating a method of operating a hydraulic apparatus in accordance with an aspect of the present invention;

Figure 2 is a schematic illustration of a controller in accordance with an aspect of the present invention;

Figure 3 is a schematic illustration of states of components of the hydraulic apparatus in accordance with an aspect of the present invention;

Figure 4 is a representation of different valve control signals according to an aspect of the present invention;

Figure 5 is a schematic diagram of part of the hydraulic apparatus in accordance with an aspect of the present invention; and

Figure 6 is a representation of a valve control signal in accordance with an aspect of the present invention.

Detailed Description of an Example Embodiment

[0089] Figure 1 shows a method 100 of operating a hydraulic apparatus. The hydraulic apparatus comprises a hydraulic machine having a rotatable shaft in driven engagement with a prime mover. The hydraulic machine comprises at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft. The at least one working chamber comprising one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold. The hydraulic apparatus further comprises a controller configured to control operation of the one or more electronically actuated valves of the hydraulic machine.

[0090] The method 100 comprises receiving 110 the phase signal. The phase signal is received from the first sensor assembly. The first sensor assembly comprises one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller.

[0091] The method 100 comprises operating the hydraulic machine in a first mode of operation. In the first mode of operation, the method 100 comprises outputting 120 a first valve control signal depending on the phase signal. In other words, the phase signal is used to determine the first valve control signal. The first valve control signal causes at least one of the one or more electronically actuated valves to operate in accordance with the first mode of operation of the hydraulic machine.

[0092] The method 100 further comprises determining 130 that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine. The determination is made depending on a trigger. Typically, the trigger is associated with a failure associated with an inaccuracy or absence of the phase signal.

[0093] The method 100 comprises operating in a second mode of operation of the hydraulic machine. The method comprises, in response to determining that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, outputting 140 a second valve control signal independently of the phase signal. In other words, the second valve control signal is determined without making use of the phase signal. The second valve control signal causes the at least one of the one or more electronically actuated valves to operate in accordance with the second mode of operation of the hydraulic machine.

[0094] Figure 2 is a schematic illustration of a controller in accordance with an aspect of the present invention. The controller 210 comprises one or more processors 220 and a non-transitory computer readable memory 230. The non-transitory computer readable memory 230 stores instructions which, when executed by the one or more processors 220, causes operation of the methods described herein. The controller 210 is part of the hydraulic apparatus 200. The controller 210 exchanges and/or transmits data and/or control signals 225 with other components 240 of the hydraulic apparatus 200. In this example, the controller 210 transmits the first valve control signal and the second valve control signal to one or more electronically actuated valves, being among the other components 240 of the hydraulic apparatus 200. The controller 210 causes the operation of the one or more electronically actuated valves in both the first mode of operation and the second mode of operation. Alternatively, the controller 210 may be separate to the hydraulic apparatus 200 or distributed between the hydraulic apparatus 200 and a device external to the hydraulic apparatus 200. The controller 210 may exchange and/or transmit data and/or control signals with components external to the hydraulic apparatus 200.

[0095] Figure 3 is a schematic illustration of states of components of the hydraulic machine providing a series of snapshots of the positions of those components, when operating the machine in a first mode of operation. The '...a' row of images in Figure 3 illustrates transient stages (310a, 320a, 330a, 340a) of progression of a working chamber through a single working chamber cycle comprising an exhaust stroke 360 and an intake stroke 370.The working chamber comprises cylinder 314 which is defined by the interior surfaces of the cylinders and a piston 312 with working surface 316. The cylinder 314 is in fluid communication with a high-pressure valve 318a (an outlet valve) and a low-pressure valve 318b (an inlet valve). In the exhaust stroke 360, the flow of fluid is through the high-pressure valve 318a. In the intake stroke 370, the flow of fluid is through the low-pressure valve 318b. The '...b' row of images in Figure 3 illustrates positions (310b, 320b, 330b, 340b) of the piston corresponding to stages of the cycle of a rotatable shaft, said stages having a direct implication for the operating positions of the valves. The mark 'x' refers to the position of the rotatable shaft, and a corresponding eccentric, relative to the TDC and BDC points with exhaust stroke 360 and the intake stroke 370. Intake occurs during motion from TDC to BDC, and exhaust during motion from BDC to TDC. The '...c' row of images in Figure 3 illustrates valve positions (310c, 320c 330c, 340c) of the low-pressure valve 318b. The low-pressure valve 318b comprises valve member 380 which is moveable to open and close the valve to prevent fluid flow through the low-pressure valve 318b.

[0096] In stage 310a which represents both the start and end point in a working chamber cycle, the piston 312 is positioned at bottom dead centre (BDC), as shown in position 310b. The inlet valve 318b is closed as shown in valve position 310c. When the phase signal indicates that the piston 312 is at BDC (or at a point just before BDC, i.e. at the beginning of the exhaust stroke 360), the controller may determine to send a first valve control signal to position the low-pressure valve 318b in the closed position. The high pressure valve 318a is open when the inlet valve 318b is closed in stage 310a.

[0097] In stage 320a, the piston is mid-stroke (positioned as shown in 320b) and fluid is being expelled from the cylinder through the high-pressure valve 318a during the exhaust stroke. The inlet valve 318b remains closed, at least whilst fluid is expelled via the open high-pressure valve 318a. In stage 330a, the piston 312 is positioned at top dead centre (TDC) as shown in position 330b. The inlet valve 318b is open as shown in valve position 330c. When the phase signal indicates that the piston 312 is at TDC (or at a point just before TDC, i.e. at the beginning of the intake stroke 370), the controller may determine to send a first valve control signal to position the inlet valve 318b in the open position. The high pressure valve 318a is closed when the inlet valve 318b is open in stage 330a. In stage 340a, the piston is mid-stroke (positioned as shown in 340b) as fluid is being admitted to the cylinder through the low-pressure valve 318b during the intake stroke. The inlet valve 318b remains open as shown in valve position 340c and the high-pressure valve 318a is closed in stage 340a.

[0098] Figure 4 is a representation of valve control signals according to another aspect of the present invention. Graph 410 represents a first variant of the second valve control signal in which a constant current 450 is applied. The graph 410 includes time on the x axis and current on the y axis. Graph 420 represents a first variant of the second valve control signal in which a PWM signal 425 is applied. The PWM signal 425 shown in graph 420 has a 50% duty cycle. However the graphs in this Figure are exemplary, and other duty cycles will be envisaged. The average magnitude of the signal 425 is shown by dashed line 426. The graph 430 represents a second variant of the second valve control signal 435. The second variant of the second valve control signal 435 comprise a pulse

436 with the illustrated waveform. The graph 430 represents four pulses 436 output at irregular (e.g. pseudorandom) intervals. The interval between the first and second pulse is shown by arrow 437a. The interval between the second and third pulse is shown by arrow 437b. The interval between the third and fourth pulse is shown by arrow 437c. The intervals 437a, 437b and 437c are different periods from one another. Over a sufficiently long time period, because the actuations are independent of the shaft phase, at least some of the resulting cycles will cause pumping. The pulse 436 comprises a first portion 436a which causes movement of the valve member. The pulse 436 comprises a latching portion 436b, applied at a lower magnitude and for a shorter duration than the first portion, which maintains the position of the valve caused by the movement during application of the first portion of the second valve control signal.

[0099] When a current is applied to the valve, for example the pulse 436, the valve may be configured into the closed position. In this way, the second valve control signal configures the valve into the closed position such that the valve exhibits a positional bias towards the closed position. When a current is applied to the valve, for example the constant current 450 or the current corresponding to the PWM signal 425, the valve may be configured into a position between the open position and the closed position. In this way, the second valve control signal reduces or removes an existing positional bias of the valve (e.g. to the open position or the closed position).

[0100] Figure 5 is a schematic diagram of part of the hydraulic apparatus shown in Figures 1 and 2, and shows a single group of working chambers currently connected to one or more hydraulic components (e.g. an actuator) through a high pressure manifold 554. Figure 5 provides detail on the first group 500, said group comprises a plurality of working chambers (8 are shown) having cylinders 524 which have working volumes 526 defined by the interior surfaces of the cylinders and pistons 528 (providing working surfaces 528) which are driven from a rotatable shaft 530 by an eccentric cam 532 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 speed sensor 534 sends electrical signals through a signal line 536 to a controller 550, which thus enables the controller to determine the instantaneous angular position and speed of rotation of the shaft, and to determine the instantaneous phase of the cycles of each cylinder.

[0101] The working chambers are each associated with Low Pressure Valves (LPVs) in the form of electronically actuated face-sealing poppet valves 552, 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 554, which may connect one or several working chambers, or indeed all as is shown here, to the low-pressure hydraulic fluid manifold hydraulic circuit. 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 556 to bring the working chamber out of fluid communication with the low-pressure hydraulic fluid manifold. The valves may alternatively be normally closed valves. As well as force arising from the pressure difference across the valve, flow forces from the passage of fluid across the valve, also influence the net force on the moving valve member.

[0102] The working chambers are each further associated with a respective High-Pressure Valve (HPV) 564 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 through a valve block to a high-pressure hydraulic fluid manifold 558, which may connect one or several working chambers, or indeed all as is shown in Figure 5. The HPVs function as normally-closed pressure-opening check valves which open passively when the pressure within the working chamber exceeds the pressure within the high-pressure hydraulic fluid manifold. The HPVs also function as normally-closed solenoid actuated check valves which the controller may selectively hold open via HPV control lines 562 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.

[0103] 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 motor by actively closing one or more of the LPVs typically near the point of maximum volume in the associated working chamber's 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.

[0104] In a motoring mode of operation, the controller selects the net rate of displacement of hydraulic fluid, displaced 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 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.

[0105] 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.

[0106] Arrows on the low pressure fluid connection 506, and the high-pressure fluid connection 521 indicate hydraulic fluid flow in the motoring mode; in the pumping mode the flow is reversed. A pressure relief valve 566 may protect the first group from damage.

[0107] In normal operation, the active and inactive cycles of working chamber volume are interspersed to meet the demand indicated by the hydraulic machine control signal.

[0108] Figure 6 is a representation 600 of a valve control signal in accordance with an aspect of the present invention. In particular, Figure 6 represents an exemplary output of the second variant of the second valve control signal. The first row 601 illustrates the position of the rotatable shaft. The upwards portion of the curve from BDC to TDC represents the exhaust stroke and the downwards portion of the curve from TDC to BDC represents the intake stroke. The second row 602 represents the output of a valve control signal to control (in particular, to close) the LPV, also referred to as 'firing' of the LPV. First firings 610, 640 of the LPV are identified by their occurrence at any point during the exhaust stroke, and they will cause flow through the high-pressure manifold for the remaining duration of the exhaust stroke when the LPV is closed. The first firing 610, occurs at substantially BDC, and therefore at the beginning of an exhaust stroke. The first firing 640 occurs part way through an exhaust stroke. As a result of the first firings 610, 640, the LPV closes, and thus pressure rises in the working chamber at the beginning of the exhaust stroke, causing the high pressure valve member to open, and fluid from the working chamber flows through the high-pressure manifold as represented in row 603, thereby doing work. Further firings 620 within the same exhaust stroke have no effect on the already closed LPV and thus no effect on the flow through the high-pressure manifold. The LPV remains closed throughout the rest of the exhaust stroke following the first firing 610. Firings 630 of the LPV are identified by their occurrence at any point during the intake stroke, and they have no effect on flow through the high-pressure manifold because no fluid flows through the high-pressure manifold during the intake stroke during this conventional pumping cycle. Row 604 represents the cumulative displacement out of the high-pressure manifold. The cumulative displacement of the high-pressure manifold remains constant, until the LPV valve is open during the exhaust stroke, during which the cumulative displacement of the high-pressure manifold increases.

[0109] In general, the present invention relates to a method of operating a hydraulic apparatus, the hydraulic apparatus comprising: a hydraulic machine having a rotatable shaft (530) in driven engagement with a prime mover and comprising at least one working chamber (524) having a volume which varies cyclically with rotation of the rotatable shaft. The at least one working chamber comprising one or more electronically actuated valves (552, 564) which regulate the flow of hydraulic fluid between the working chamber and a manifold (554, 558). The hydraulic apparatus comprises a controller (200) configured to control operation of the one or more electronically actuated valves of the hydraulic machine. The hydraulic apparatus further comprises one or more components (534) of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller. The method comprising: receiving (110) the phase signal from the first sensor assembly; in a first mode of operation of the hydraulic machine, outputting (120) a first valve control signal depending on the phase signal, the first valve control signal configured to cause at least one of the one or more electronically actuated valves to operate in accordance with the first mode; determining (130) that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger associated with the first sensor assembly; and in response to determining that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, outputting (140) a second valve control signal independently of the phase signal, the second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

[0110] Throughout the description and claims of this specification, the words "comprise" and "contain" and variations of them mean "including but not limited to", and they are not intended to and do not exclude other components, integers, or steps. Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

[0111] Features, integers, characteristics, or groups described in conjunction with a particular aspect, embodiment, or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith. All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive. The invention is not restricted to the details of any foregoing embodiments. The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

Claims

1. A method of operating a hydraulic apparatus, the hydraulic apparatus comprising:

a hydraulic machine having a rotatable shaft in driven engagement with a prime mover and comprising at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft, the at least one working chamber comprising one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold;
a controller configured to control operation of the one or more electronically actuated valves of the hydraulic machine; and
one or more components of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller, the method comprising:

receiving the phase signal from the first sensor assembly;
in a first mode of operation of the hydraulic machine, outputting a first valve control signal depending on the phase signal, the first valve control signal configured to cause at least one of the one or more electronically actuated valves to operate in accordance with the first mode;
determining that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger; and
in response to determining that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, outputting a second valve control signal independently of the phase signal, the second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

2. A hydraulic apparatus comprising:

a hydraulic machine having a rotatable shaft in driven engagement with a prime mover and comprising at least one working chamber having a volume which varies cyclically with rotation of the rotatable shaft, the at least one working chamber comprising one or more electronically actuated valves which regulate the flow of hydraulic fluid between the working chamber and a manifold;
a controller configured to control operation of at least one of the one or more electronically actuated valves of the hydraulic machine; and
one or more components of a first sensor assembly, the one or more components configured to output a phase signal indicative of phase information of the rotatable shaft to the controller, the controller being further configured to:

receive the phase signal from the first sensor assembly;
in a first mode of operation of the hydraulic machine, output a first valve control signal depending on the phase signal, the first valve control signal configured to cause the at least one of the one or more electronically actuated valves to operate in accordance with the first mode;
determine that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger; and
in response to determination that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, output a second valve control signal independently of the phase signal, the second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.

3. The method or the apparatus of any preceding claim, wherein, in the second mode of operation, the hydraulic machine is configured to transfer energy between the rotatable shaft and the hydraulic fluid by movement of the rotatable shaft and a working surface of at least one of the at least one working chambers.

4. The method or the apparatus of any preceding claim, wherein the trigger corresponds to a failure associated with the phase signal, and optionally wherein the trigger corresponds to a full or partial loss of the phase signal.

5. The method or the apparatus of claim 4, wherein the failure corresponds to at least one of: a failure of the first sensor assembly, a failure of the controller and a failure of a component other than the controller and the first sensor assembly.

6. The method or the apparatus of any preceding claim, wherein either, the method comprises:
determining, the phase information from the phase signal, and optionally wherein the trigger corresponds to a full or partial loss of the phase information or a full or partial loss of reliable phase information from the phase signal; or
the controller is configured to:
determine the phase information from the phase signal, and optionally wherein the trigger corresponds to a full or partial loss of the phase information or a full or partial loss of reliable phase information from the phase signal.

7. The method or the apparatus of any preceding claim, wherein either the method comprises:
outputting, as the second valve control signal, a current signal to the at least one of the one or more electronically actuated valves, the current signal being out of phased relation with the rotatable shaft, or the controller is further configured to:
output, as the second valve control signal, a current signal to the at least one of the one or more electronically actuated valves, the current signal being typically out of phased relation with the rotatable shaft.

8. The method or the apparatus of any preceding claim, wherein the second valve control signal is configured to change a positional bias of the at least one of the one or more electronically actuated valves.

9. The method or the apparatus of claim 8, wherein the second valve control signal is configured to reduce or remove the positional bias of the at least one of the one or more electronically actuated valves for one or more complete working chamber cycles, optionally wherein the second valve control signal is indicative of a current with an average magnitude and wherein a flow output of the hydraulic machine is proportional to the average magnitude of the second valve control signal.

10. The method or the apparatus of claim 9, wherein the second valve control signal is indicative of a current with an average magnitude within a threshold magnitude range having a lower bound greater than zero and an upper bound less than a current at which a force, generated by the current and causing the positional bias of the at least one of the one or more electronically actuated valves, overcomes a fluid flow force acting on the at least one of the one or more electronically actuated valves for all of the one or more complete working chamber cycles.

11. The method or the apparatus of claim 8, wherein the second valve control signal is configured to cause the positional bias to the at least one of the one or more electronically actuated valves for only part of a complete working chamber cycle.

12. The method or the apparatus of claim 11, wherein either the method comprises:
outputting the second valve control signal as a plurality of pulses, at least some of adjacent pulses of the plurality of pulses spaced apart in time by an interval different to a cycle period of at least one of the working chambers, optionally wherein the second valve control signal has a pulse waveform equal to a pulse waveform of the first valve control signal further optionally wherein the method further comprises adjusting a rate of the plurality of pulses to alter a flow output of the hydraulic machine, or
the controller is configured to:
output the second valve control signal as a plurality of pulses, at least some of adjacent pulses of the plurality of pulses spaced apart in time by an interval different to a cycle period of at least one of the working chambers, and optionally, wherein the second valve control signal has a pulse waveform equal to a pulse waveform of the first valve control signal, further optionally wherein the controller is further configured to adjust a rate of the plurality of pulses to alter a flow output of the hydraulic machine.

13. The method or the apparatus of any claim dependent on claim 8, wherein either the method comprises:

determining whether to:

output the second valve control signal of claim 9 or claim 10; or
output the second valve control signal of claim 11 or claim 12,

optionally depending on fault information, or

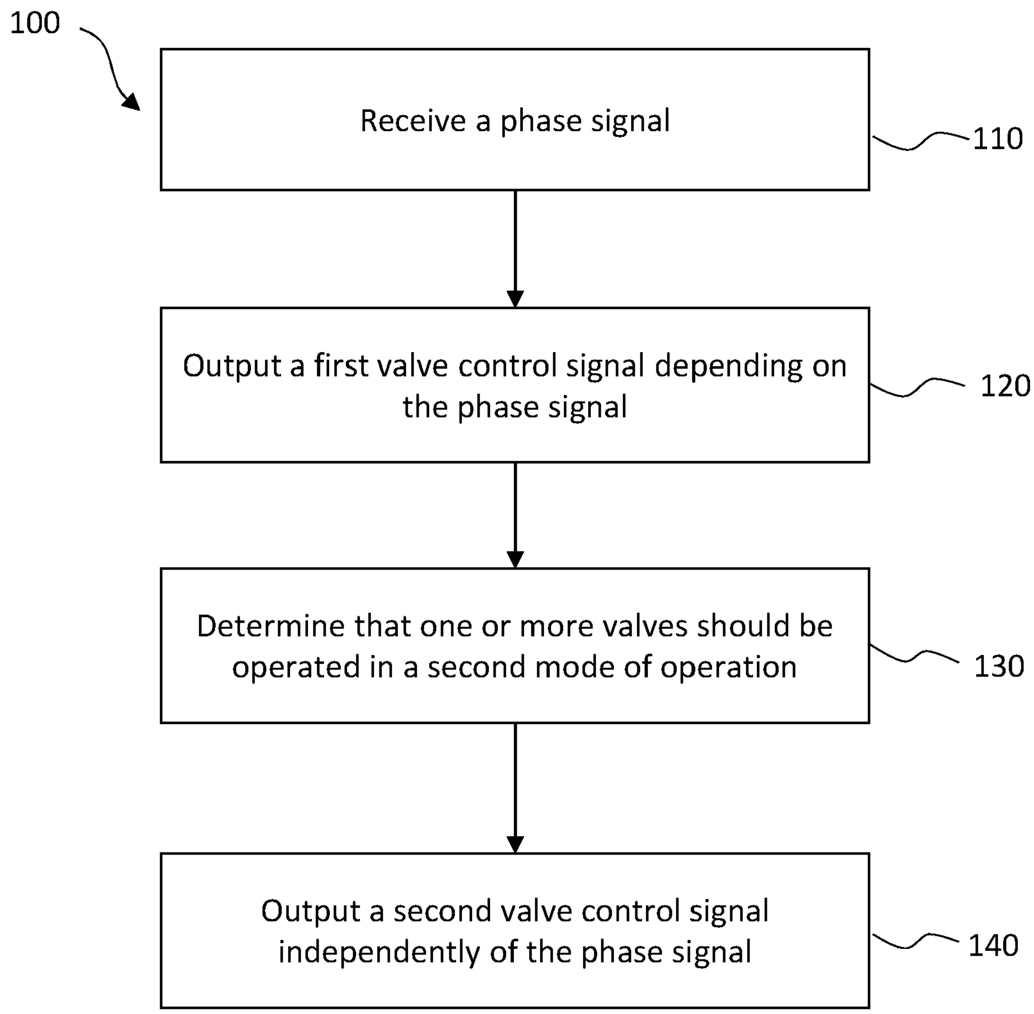
the controller is configured to:
determine whether to:

output the second valve control signal of claim 9 or claim 10; or
output the second valve control signal of claim 11 or claim 12, optionally depending on fault information.

14. The method or apparatus of any preceding claim, wherein either the method comprises:
determining that the one or more electronically actuated valves should be operated in the second mode of operation depending on measured data from one or more components of a second sensor assembly, optionally wherein the hydraulic apparatus comprises the second sensor assembly, or
the controller is configured to:
determine that the one or more electronically actuated valves should be operated in the second mode of operation depending on measured data from one or more components of a second sensor assembly, optionally wherein the hydraulic apparatus comprises the second sensor assembly.

15. A controller configured to control operation of at least one of one or more electronically actuated valves of a hydraulic machine; and
the controller being further configured to:

receive a phase signal from a first sensor assembly of the hydraulic machine;
in a first mode of operation, output a first valve control signal depending on the phase signal, the first valve control signal configured to cause the at least one of the one or more electronically actuated valves to operate in accordance with the first mode;
determine that the at least one of the one or more electronically actuated valves should be operated in a second mode of operation of the hydraulic machine depending on a trigger; and
in response to determination that the at least one of the one or more electronically actuated valves should be operated in the second mode of operation, in the second mode of operation, output a second valve control signal independently of the phase signal, the second valve control signal to cause the at least one of the one or more electronically actuated valves to operate in accordance with the second mode.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Receive a phase signal
110
Output a first valve control signal depending on the phase signal
120
Determine that one or more valves should be operated in a second mode of operation
130
Output a second valve control signal independently of the phase signal
140

Fig. 1

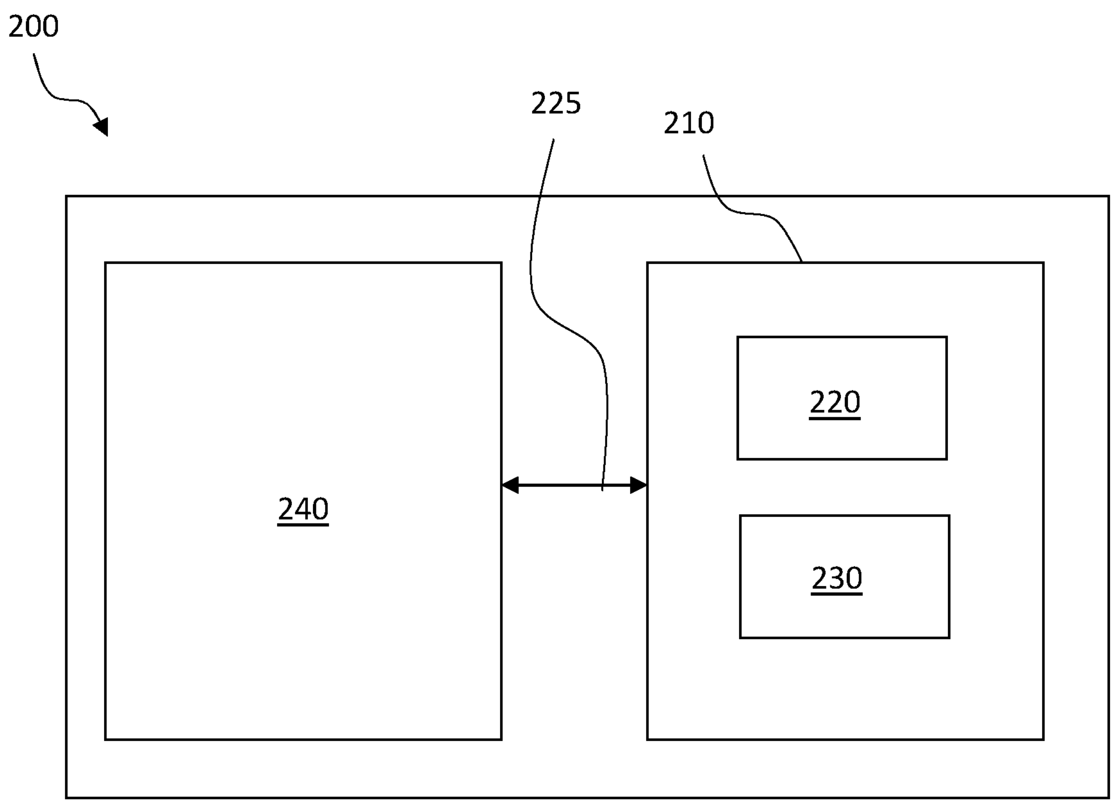
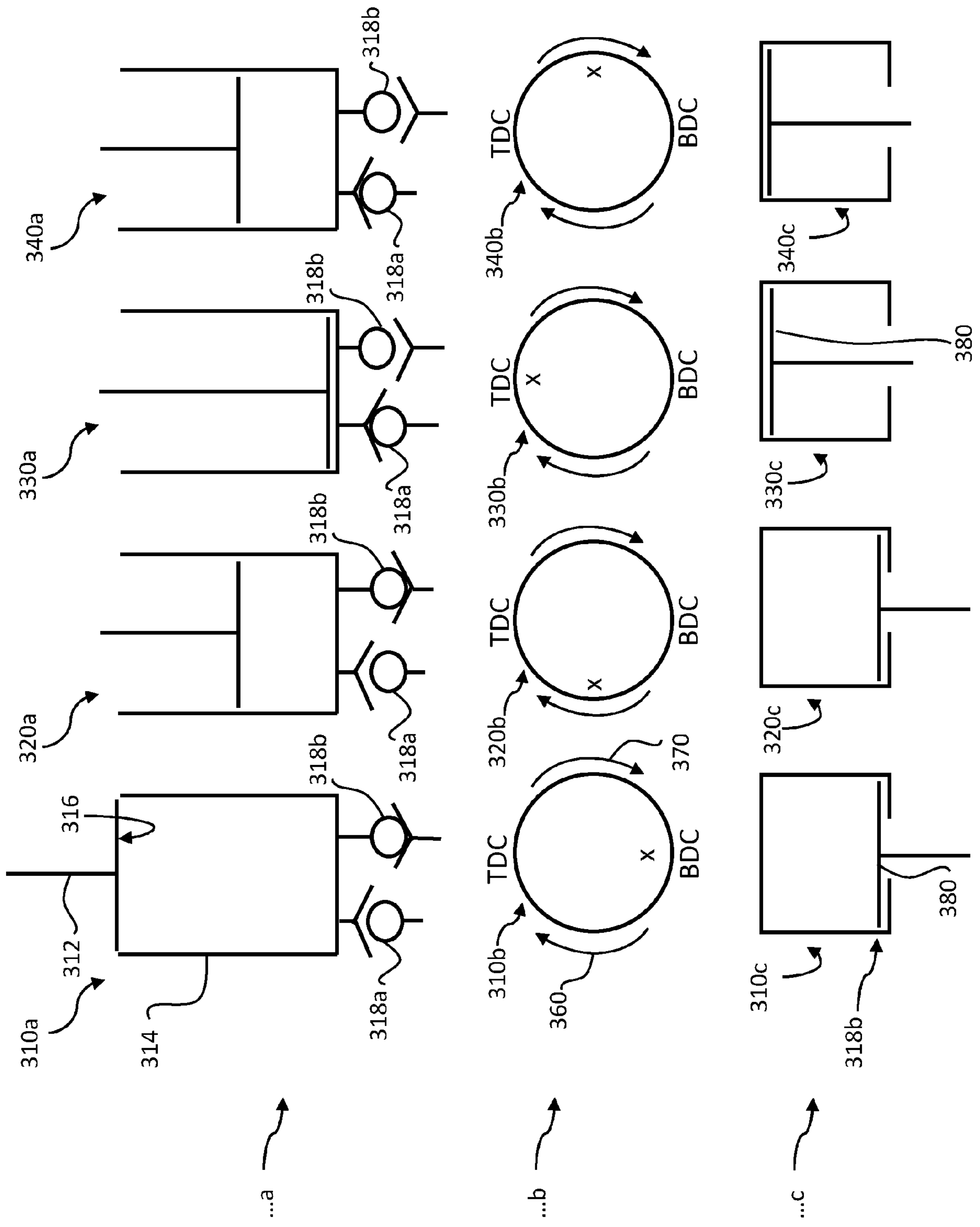


Fig. 2


310a
312
314
316
318a
318b
320a
330a
340a
TDC
BDC
310b
320b
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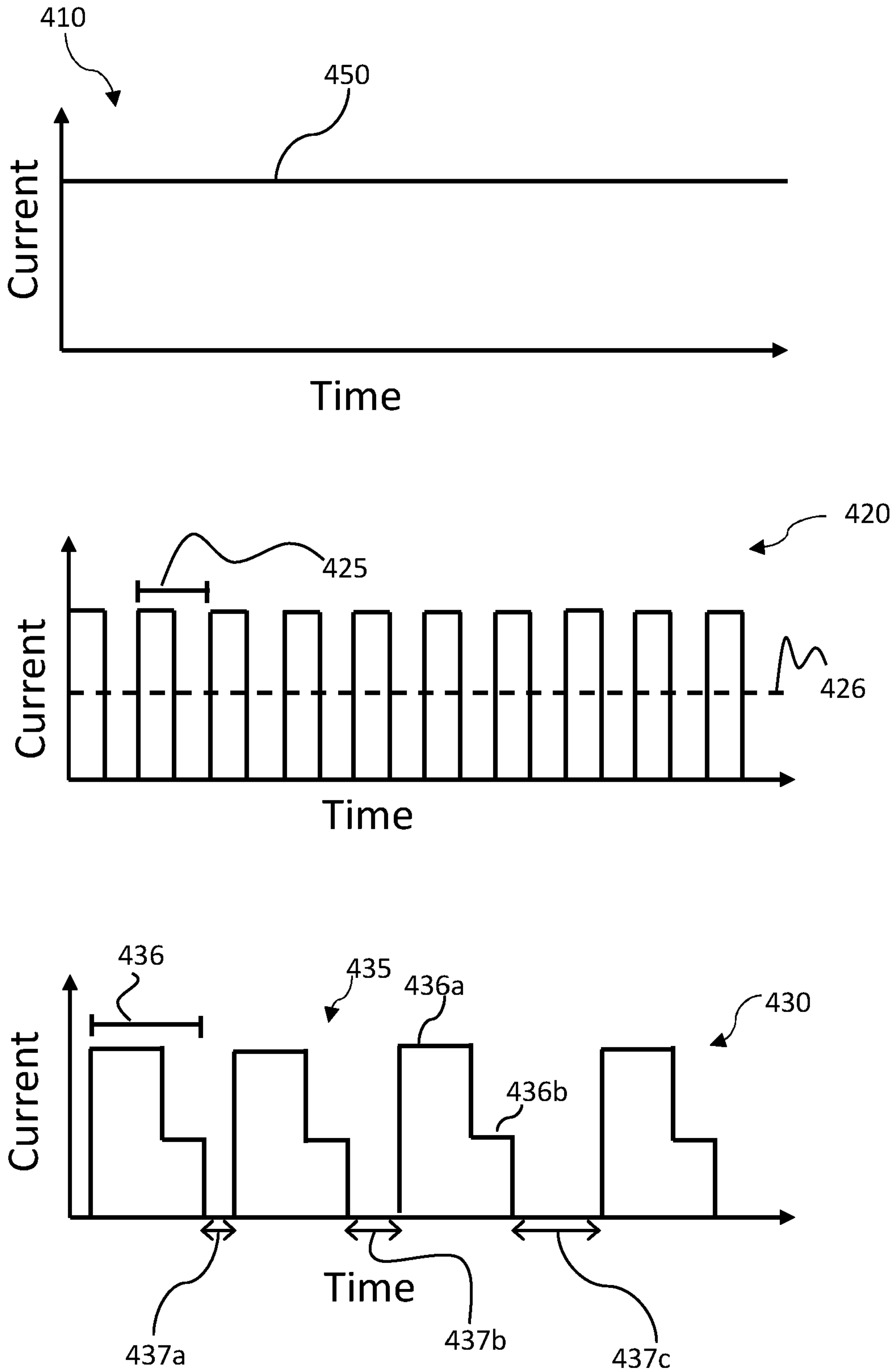
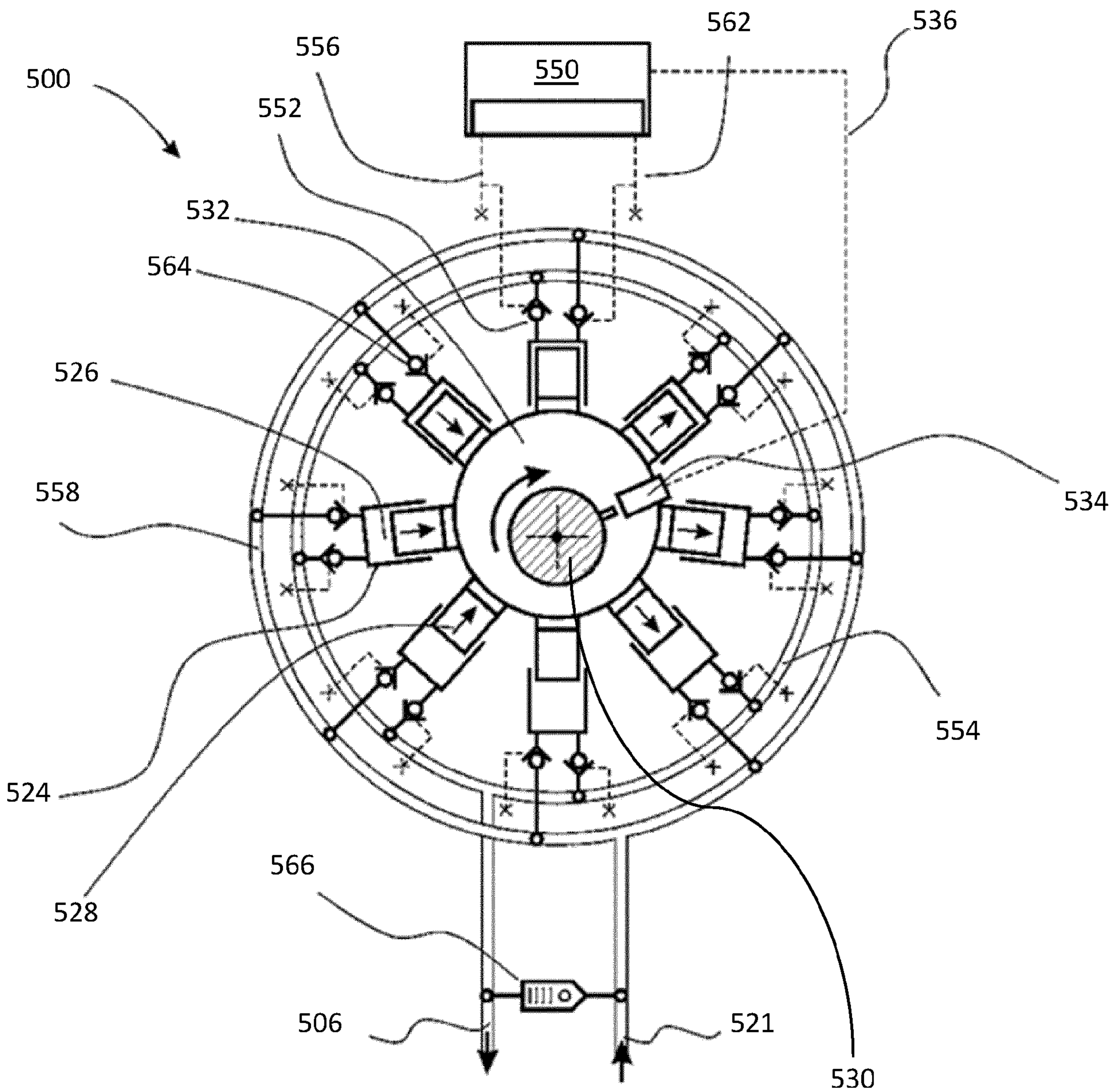
360
370
310c
320c
330c
340c
380
...a
...b
...c

Fig. 3



410
450
Current
Time
420
425
426
Current
Time
436
435
436a
430
436b
Current
Time
437a
437b
437c

Fig. 4


500
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532
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526
558
534
554
524
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566
506
521
530

Fig. 5

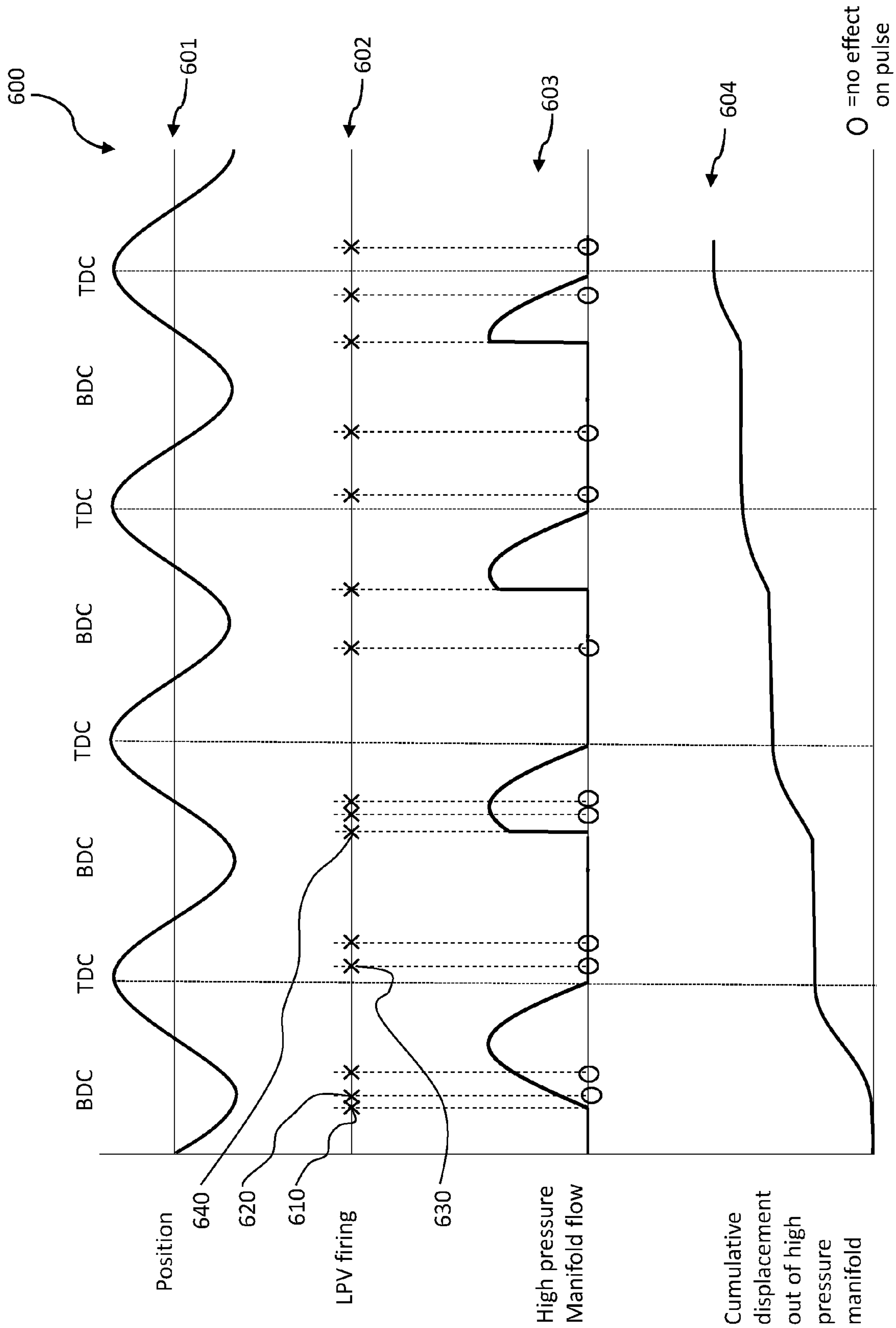
600
601
602
603
604
O =no effect on pulse
BDC
TDC
BDC
TDC
BDC
TDC
BDC
TDC
Position
640
620
610
LPV firing
630
High pressure Manifold flow
Cumulative displacement out of high pressure manifold

Fig. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 22 18 8617

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	EP 3 674 546 A1 (ARTEMIS INTELLIGENT POWER LTD [GB]) 1 July 2020 (2020-07-01) * paragraphs [0061], [0131] - [0139], [0153] *	1-15	INV. F04B1/053 F04B1/06 F04B7/00 F03C1/00
A	US 10 180 135 B2 (ARTEMIS INTELLIGENT POWER LTD [GB]) 15 January 2019 (2019-01-15) * the whole document *	1-15	
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TECHNICAL FIELDS SEARCHED (IPC)

F04B
F03C

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	8 February 2023	Ziegler, Hans-Jürgen

CATEGORY OF CITED DOCUMENTS

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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 22 18 8617

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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08-02-2023

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