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(54) **FAULT DIAGNOSTICS IN HYDRAULIC MACHINES**

(57) A method of determining a state of an electronically commutated hydraulic machine (10), the machine (10) having a machine shaft (12) that is connected to a set of piston assemblies (18), each piston assembly (18) comprising a respective electromechanical actuator (56). The method comprises performing a diagnostic routine while the machine shaft (12) is stationary. The diagnostic routine comprises: operating each of the actuators (56) of the set of piston assemblies (18); detecting, for each actuator (56), a signal indicative of a response of the actuator (56) as the actuator (56) is operated; and analysing each of the detected actuator response signals to determine the state of the machine (10).

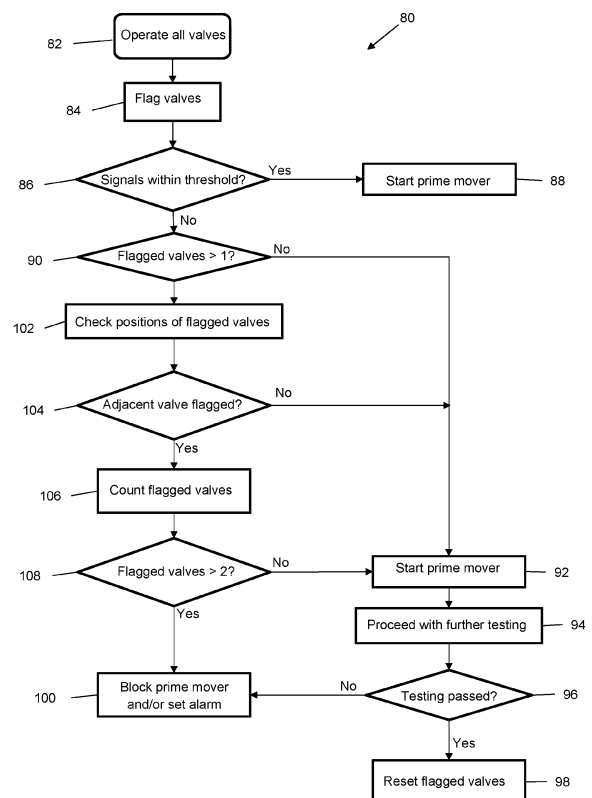


Fig. 6

Description

Field of the Invention

[0001] The invention relates to methods and control arrangements for determining a state of a hydraulic machine. In particular, the invention relates to fault diagnostics for electronically commutated hydraulic machines.

Background to the Invention

[0002] Hydraulic machines such as hydraulic pumps or motors are typically complex devices involving several moving parts and interacting sub-assemblies, with the associated potential for various fault states to arise.

[0003] For example, in an electronically commutated hydraulic machine (ECM) such as an electronically commutated pump, also referred to as a 'digital displacement pump', faults of varying degrees of severity may arise. Some faults, such as a broken return spring in an electromechanical valve used to control flow of hydraulic fluid through the machine, are local to individual components. Other faults are more global in nature, in that the fault affects multiple components of the ECM, and such faults tend to present a greater risk of damage to the machine.

[0004] A particular source of potential fault states in an ECM is the lubrication arrangement that facilitates relative movement between components to minimise wear. In this respect, in ECMs the hydraulic fluid to be displaced is often also used for lubrication. For example, a crankcase housing a machine shaft, piston cylinder units (PCUs) and the associated valves may be flooded with the hydraulic fluid to immerse the components requiring lubrication.

[0005] Occasionally, an air pocket may form around a component and therefore deprive that component of lubricating fluid. For the case of a valve, this may be referred to as a 'dry valve' scenario. Such faults can be identified and remedied in various ways, although if not addressed can lead to failure of the associated component, such as a PCU of the ECM. A PCU may become airlocked due to incorrect purging of fluid, during initial filling or fluid replacement, for example.

[0006] A more severe problem arises if the overall level of lubricating fluid in the crankcase is low, for example if the ECM is inadvertently disconnected from the source of hydraulic fluid, if there is a leak, or if the ECM is not filled correctly during commissioning. The hydraulic fluid may alternatively be overly aerated or otherwise contaminated. Such faults can become more global in nature, in that multiple components within the crankcase may be inadequately lubricated. In particular, if the machine shaft is rotated without sufficient lubrication, referred to as 'dry running', a critical fault state may arise that threatens damage to the running surfaces of the shaft and failure of the ECM.

[0007] Distinguishing between the different possible faults that may emerge and applying appropriate correc-

tive action in a timely manner to prevent damage to the machine is therefore a challenge.

[0008] It is against this background that the present invention has been devised.

Summary of the Invention

[0009] An aspect of the invention provides a method of determining a state of an electronically commutated hydraulic machine. The machine has a machine shaft that is connected to a set of piston assemblies. The piston assemblies may be piston cylinder units or pump modules, for example. Each piston assembly comprises a respective electromechanical actuator, such as a solenoid actuator. The method comprises performing a diagnostic routine while the machine shaft is stationary, the diagnostic routine comprising: operating each of the actuators of the set of piston assemblies; detecting, for each actuator, a signal indicative of a response of the actuator as the actuator is operated; and analysing each of the detected actuator response signals to determine the state of the machine.

[0010] Performing the diagnostic routine while the machine shaft is stationary enables the state of the machine to be determined before operating the machine. If the state of the machine includes one or more faults, discovering this before operating the machine enables preventative action to be taken to avoid incurring a risk of damage by operating the machine shaft when a fault exists.

[0011] The diagnostic routine may be performed at any suitable time. For example, the routine may be performed automatically each time the machine is to be operated, to validate the state of the machine before commencing operation. The diagnostic routine may also be performed on command. In some circumstances, the machine may be stopped to perform the diagnostic routine, and then the machine may be restarted once the routine completes.

[0012] A response of an actuator may comprise movement of a component of the actuator. For example, if the actuator comprises a solenoid actuator, the moving component may be an armature. Each signal indicative of a response of an actuator may comprise a signal corresponding to a back-electromotive force generated by movement of a component of the actuator.

[0013] Analysing a detected actuator response signal optionally comprises identifying any abnormalities in the actuator response signal. Identifying abnormalities in a detected actuator response signal may comprise comparing the detected actuator response signal with a reference response and/or with one or more threshold values.

[0014] The method may comprise analysing two or more of the detected actuator response signals collectively to determine the state of the machine.

[0015] The method may comprise analysing the detected actuator response signals in accordance with the respective positions of the actuators with respect to the

machine and/or with respect to each other. Such methods may comprise determining whether the respective responses of adjacent actuators are anomalous. The position of an actuator having an anomalous response may be taken into account to determine the likely cause of the anomaly.

[0016] The method may comprise commencing rotation of the machine shaft in dependence on the determined state of the machine, and optionally preventing rotation of the machine shaft and/or generating an alarm if the state of the machine comprises a fault. This advantageously enables the method to identify faults before incurring a risk of damage to the machine shaft by operating the shaft when a fault state exists. The fault may affect two or more of the actuators and therefore potentially be indicative of a fault that affects various parts of machine, such as a low fluid level in a crankcase of the machine.

[0017] Operating an actuator may comprise issuing a control signal to a drive circuit associated with the actuator. Operating an actuator may comprise energising and then de-energising the actuator, in which case each signal indicative of a response of an actuator may comprise an indication of movement of a component of the actuator following de-energisation.

[0018] Operating an actuator may comprise progressively increasing an electrical current supplied to the actuator. In such embodiments, analysing the detected actuator response signal may comprise determining a value of the electrical current at which the actuator began to move. This may provide information that enables a fault to be characterised, for example if the value of the electrical current at which the actuator began to move deviates from an expected value.

[0019] Each actuator may be operable to open and close a respective fluid valve of the machine, for example a low-pressure valve. Each actuator may be integrated with its respective valve.

[0020] Determining the state of the machine may comprise detecting one or more faults. Such faults may include, for example, any of: a low fluid level; an airlocked actuator or valve; a broken actuator spring; a detached component associated with an actuator, such as a valve member associated with the actuator; resistance to actuator movement; or an erroneous state of fluid in the machine, for example if the fluid is overly aerated or otherwise contaminated, or more generally the fluid being other than it should be.

[0021] Another aspect of the invention provides a controller for an electronically commutated hydraulic machine, the controller being configured to perform the method of the above aspect.

[0022] Another aspect of the invention provides a controller for an electronically commutated hydraulic machine. The machine has a machine shaft that is connected to a set of piston assemblies. The piston assemblies may be piston cylinder units or pump modules, for example. Each piston assembly comprises a respective elec-

tromechanical actuator, such as a solenoid actuator. The controller comprises: an output configured to issue control signals for operating the actuators of the set of piston assemblies; an input configured to receive signals indicative of responses of the actuators as the actuators are operated; and a processing module or processor configured to analyse the detected actuator response signals. The controller is configured to perform a diagnostic routine while the machine shaft is stationary, the diagnostic routine comprising: operating each of the actuators of the set of piston assemblies; detecting, for each actuator, a signal indicative of a response of the actuator as the actuator is operated; and analysing each of the detected actuator response signals to determine the state of the machine. The diagnostic routine may be performed by the processing module, for example, using signals received by the input.

[0023] The invention also extends to an electronically commutated hydraulic machine comprising a controller of either of the above aspects.

[0024] It will be appreciated that preferred and/or optional features of each aspect of the invention may be incorporated alone or in appropriate combination in the other aspects of the invention also.

Brief Description of the Drawings

[0025] In order that the invention may be more readily understood, preferred non-limiting embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings, in which like features are assigned like reference numerals, and in which:

Figure 1 shows an ECM in transverse cross section;

Figure 2 shows a PCU of the ECM of Figure 1 schematically;

Figure 3 shows an electrical arrangement for the PCU of Figure 2;

Figure 4 shows a normal response of a low-pressure valve of the PCU of Figure 2;

Figure 5 corresponds to Figure 4 but shows an abnormal response of the low-pressure valve; and

Figure 6 is a flow diagram showing a diagnostic routine for identifying faults in the ECM of Figure 1.

Detailed Description of Embodiments of the Invention

[0026] In general terms, embodiments of the invention provide diagnostic routines for hydraulic machines to identify and characterise faults that have the potential to damage the machine. The diagnostic routines are advantageously performed before commencing operation

of the machine, and in particular before allowing a machine shaft of the machine to rotate. This allows faults to be identified and corrective and/or preventative action to be taken before any damage is incurred.

[0027] In embodiments described below, the diagnostic routines involve operating electromechanical actuators of valves of an ECM while a machine shaft is stationary, and monitoring how the valves respond. A 'response' of a valve may refer to the time that the valve takes to transition between closed and open states, for example. Any abnormalities in the responses are identified, for example through a comparison with a reference, expected response. In turn, such abnormalities are indicative of the existence of a fault. The nature of the fault can be characterised, at least to some extent, by analysing the characteristics of the or each anomalous response and by taking the positions of the valves indicating faults into account.

[0028] Embodiments of the invention are therefore predicated on the insight that diagnosing faults before commencing operation of the machine enables some situations in which the machine is damaged to be avoided.

[0029] The responses of the valves may be monitored by detecting back-EMF generated by transitional movement of the valve members, which beneficially enables the diagnostic routine to be implemented with existing hardware and without requiring dedicated sensors for monitoring valve movement.

[0030] Figure 1 shows a portion of an ECM 10 in which fault diagnostic routines may be implemented to identify and characterise faults before running the ECM 10, which faults may otherwise incur a risk of damage. In this example, the ECM 10 is configured to operate as a hydraulic pump, but it should be appreciated that embodiments of the invention are equally applicable to ECMs configured as a hydraulic motor or as a pump/motor. More generally, diagnostic routines according to the invention may be implemented in any type of hydraulic machine.

[0031] The ECM includes a machine shaft defining a driveshaft 12 that is driven by a prime mover (not shown) such as an internal combustion engine or an electric motor, for example. The driveshaft 12 is housed within a crankcase 14 that has a circular cross-section in Figure 1, with the driveshaft 12 having a central axis defining a shaft axis that is aligned with the centre of the crankcase 14. The driveshaft 12 carries an eccentric cam 16, which may be fixed to or integral with the driveshaft 12.

[0032] In the simplified example shown in Figure 1, a set of six identical PCUs 18 are arranged in a circular array around the cam 16. Each PCU 18 has a longitudinal axis 20 that extends radially within the crankcase 14 and therefore orthogonally to the shaft axis. The PCUs 18 are equiangularly spaced around the driveshaft 12, and hence the respective longitudinal axes 20 of the PCUs 18 are spaced in a common plane at 60° intervals around the shaft axis.

[0033] As shown, and as is conventional, the top-most PCU 18 is labelled as 0° in Figure 1. In some instances

where the alignment of the pump body is such that the valve cavity doesn't align with vertical, the top-most cylinder is correspondingly in an off-vertical orientation.

[0034] Each PCU 18 comprises a piston slipper 22 that engages a tubular outer face of the cam 16 to form a running interface with the cam 16 and therefore act as a cam follower. As is conventional, as the driveshaft 12 rotates in operation the eccentricity of the cam 16 causes the cam 16 to drive the PCUs 18 in angular succession, via their respective piston slippers 22.

[0035] The interior of the crankcase 14 is designed to be flooded with hydraulic liquid at low pressure, typically the same fluid that is displaced in the PCUs 18, which fluid serves as lubricating fluid for the components of the ECM 10. As shall become clear from the description that follows, a diagnostic routine may be used to determine whether the crankcase 14 is fully flooded as intended, or whether the level of fluid in the crankcase 14 is low such that a fault state exists.

[0036] Figure 2 shows an individual PCU 18 in more detail. This reveals that the PCU 18 comprises a piston 24 received within a cylinder 26, defining a working chamber 28 therebetween. On an opposite side of the piston 24 to the working chamber 28, a piston rod 30 extends towards the cam 16, a distal end of the piston rod 30 carrying or defining the piston slipper 22 that engages the cam 16. Reciprocating movement of the piston slipper 22 as the cam 16 rotates during pumping drives corresponding linear reciprocating movement of the piston 24 relative to and within the cylinder 26, causing pressurisation of hydraulic fluid in the working chamber 28.

[0037] The working chamber 28 comprises two fluid ports, namely a low-pressure port 32 and a high-pressure port 34. Hydraulic fluid is drawn into the working chamber 28 through the low-pressure port 32 at relatively low pressure, for example from a low-pressure manifold. The hydraulic fluid is then pressurised and discharged from the working chamber 28 at elevated pressure through the high-pressure port 34. When the respective PCU 18 is operating in a pumping mode, the low-pressure port 32 therefore defines an inlet of the PCU, and the high-pressure port 34 defines an outlet of the PCU.

[0038] Flow of hydraulic fluid through each of the ports is governed by a respective valve of a valve arrangement 36. Accordingly, the valve arrangement 36 includes a low-pressure valve (LPV) 38 that acts to open and close the low-pressure port 32, and a high-pressure valve (HPV) 40 that acts to open and close the high-pressure port 34.

[0039] Accordingly, the LPV 38 opens while the piston 24 undergoes a filling or intake stroke, corresponding to downward movement in Figure 2, and closes as the piston 24 undergoes a pumping stroke to displace the hydraulic fluid at elevated pressure, corresponding to upward movement in Figure 2. Conversely, the HPV 40 operates in a complementary manner and so opens during the pumping stroke to permit the pressurised fluid to be discharged, and closes during the intake stroke.

[0040] The LPV 38 is shown schematically in Figure 2, in a left portion of the valve arrangement 36. The LPV 38 is configured as a face-sealing poppet valve that acts as a check valve. The LPV 38 comprises a valve member defining a low-pressure poppet (LPP) 42, which is configured to engage a low-pressure valve seat 44 to close the low-pressure port 32 when required, and correspondingly to lift from the low-pressure valve seat 44 to open the low-pressure port 32. The LPP 42 is biased away from the low-pressure valve seat 44 by an LPV return spring 46, and so the LPV 38 is configured as a normally-open valve.

[0041] In the arrangement shown in Figure 2, the LPV 38 is configured to be normally open, and is thus open during intake strokes, primarily under the action of a spring force provided by the LPV return spring 46. During intake stroke flow via the LPV 38, hydrodynamic forces acting on the LPP 42 generally align and compound with the respective spring force. Closing movement of the LPV 38 is controlled by a solenoid actuator (shown in Figure 3) that is integrated with the LPV 38, as described further below. The LPV 38 can therefore be closed selectively, enabling the volume of fluid admitted to the working chamber 28 on each cycle to be regulated. This, in turn, controls the extent to which the fluid is pressurised in each pumping stroke. Accordingly, the output of the PCU 18 is independently controllable from the output of other PCUs.

[0042] As the LPP 42 is disposed between its valve seat 44 and the working chamber 28, closing movement of the LPP 42 is assisted during pumping strokes by high pressure fluid acting on the LPP 42, which acts to press the LPP 42 into engagement with the low-pressure valve seat 44 to close the LPV 38. This arrangement helps to prevent backflow of high-pressure fluid through the low-pressure port 32.

[0043] The HPV 40 is shown to the right of the valve arrangement 36 in Figure 2, and is also configured as a face-sealing poppet valve that acts as a check valve. The HPV 40 therefore comprises a high-pressure valve member defining a high-pressure poppet (HPP) 48. The HPP 48 is configured to engage a high-pressure valve seat 50 to close the high-pressure port 34 when required, and correspondingly to lift from the high-pressure valve seat 50 to open the high-pressure port 34. The HPP 48 is biased into engagement with the high-pressure valve seat 50 by an HPV return spring 52, and so the HPV 40 is configured as a normally-closed valve.

[0044] The HPP 48 is on an opposite side of its valve seat 50 to the working chamber 28, and so the HPV 40 is configured to open passively during pumping strokes when the fluid pressure in the working chamber 28 overcomes the opposing force provided both by the spring force of the HPV return spring 50, and the pressure force acting on the other side of the HPP 48 connected to the high-pressure manifold, to allow high-pressure fluid to be discharged. In the example of a motor or pump/motor, the HPV 40 is also solenoid-actuated to enable the HPV

40 to be opened selectively.

[0045] Figure 3 shows an electrical arrangement 54 for operating the LPV 38, although it is noted that the HPV 40 may be configured in a similar manner when applied to a motor or pump/motor. Figure 3 shows that the LPV 38 comprises a solenoid actuator 56 having an armature 58 that is arranged within a coil defining a solenoid 60, so that energising the solenoid with an electrical current induces downward linear movement of the armature 58 in the orientation shown in Figure 3. Correspondingly, when the solenoid 60 is de-energised the armature 58 moves upwardly under the action of the LPV return spring 46.

[0046] The LPP 42 is mounted to the upper end of the armature 58 so that the LPP 42 and the armature 58 define an armature assembly. Thus, the LPP 42 is carried by the armature 58 when the armature assembly moves on energisation and de-energisation of the solenoid 60. Accordingly, energising the solenoid 60 moves the LPP 42 downwardly to engage the low-pressure valve seat 44, compressing the LPV return spring 46 in the process, and transitioning the LPV 38 to a closed state in which the LPP 42 closes the low-pressure port 32. Conversely, when the solenoid 60 is de-energised the armature assembly is returned by the LPV return spring 46 to an open position in which the LPP 42 is lifted away from the low-pressure valve seat 44 to open the LPV 38 and the low-pressure port 32. The LPV 38 therefore has an energise-to-close configuration in this example.

[0047] Figure 3 also shows that the electrical arrangement 54 further includes a controller 62, a drive circuit 64, and a sensing circuit 66. These are known electrical components and so are described only in overview here.

[0048] The controller 62 is configured to issue control signals to the drive circuit 64 in accordance with measurements received from the sensing circuit 66, to control energising and de-energising of the solenoid 60 and, in turn, operation of the LPV 38. In this respect, the controller 62 includes an input 68 for receiving feedback signals from the sensing circuit 66, a processor or processing module 70 for analysing the feedback signals and generating control signals accordingly, and an output 72 for issuing the control signals to the drive circuit 64.

[0049] Correspondingly, the drive circuit 64 selectively energises and de-energises the solenoid 60, to close and open the LPV 38 respectively, in response to control signals received from the controller 62.

[0050] The sensing circuit 66 is configured to produce a signal that is indicative of an electrical current in the solenoid 60, although in other examples the sensing circuit 66 may alternatively be configured to detect a voltage in the solenoid 60, or both a current and a voltage. Notably, the ability of the sensing circuit 66 to detect an electrical current and/or voltage in the solenoid 60 entails that it will also detect any back-electromotive force, also referred to as 'counter-electromotive force' or 'back-EMF', that is induced in the solenoid 60 by movement of the armature 58 within the solenoid 60 under the action

of the LPV return spring 46 as the LPV 38 opens following de-energisation.

[0051] It is noted that each LPV 38 of the ECM 10 comprises a respective drive circuit 64 and sensing circuit 66 in this embodiment, whereas the controller 62 is common to all of the LPVs 38 to enable the control of the LPVs 38 to be coordinated. The controller 62 may correspond to a main controller 62 of the ECM 10, for example. It is also possible for each LPV 38 to have a dedicated controller, however. Conversely, in other arrangements a single drive circuit may drive all of the LPVs 38, and correspondingly a single sensing circuit may monitor responses of all of the LPVs 38.

[0052] The hardware of the ECM 10 described thus far is known, and may broadly correspond to the ECM described in the Applicant's earlier application, WO 2021/044148, for example. This hardware provides context for diagnostic routines for identifying faults that shall now be described. It is reiterated that diagnostic routines and corresponding control arrangements for diagnosing faults according to the invention may be implemented in different hydraulic machines, however.

[0053] In this example, the diagnostic routine involves operating the LPV 38 of each PCU 18 while the driveshaft 12 is stationary, and monitoring the response of the LPV 38 to check for anomalies. In this respect, operating an LPV 38 entails energising the associated solenoid 60 to close the LPV 38, and then de-energising the solenoid 60 to allow the LPV 38 to open passively. Correspondingly, the response of an LPV 38 to being operated refers to its behaviour when operated, particularly in terms of transitional movement between open and closed states.

[0054] As the LPV 38 opens, the movement of the armature 58 generates back-EMF in the solenoid 60 of the LPV 38 that can be detected by the sensor circuit. The characteristics of the back-EMF reading, particularly its amplitude, delay, and duration, are indicative of the movement of the armature 58 and so can be analysed to infer the state of the LPV 38 and to identify anomalies.

[0055] In this respect, Figure 4 illustrates a normal response of an LPV 38 as indicated by the back-EMF in the solenoid 60 as measured by the sensor circuit. The response profile shown in Figure 4 therefore defines a reference response, against which measured responses may be compared to identify anomalies indicative of a fault.

[0056] Figure 4 shows the profile of the current measured by the sensor circuit over the course of a single operation of the LPV 38, that operation comprising energising the LPV 38 to close and then de-energising the LPV 38 to allow it to re-open.

[0057] Accordingly, Figure 4 shows an initial static phase in which the measured current is constant, corresponding to a period during which the solenoid 60 is energised by the drive circuit 64 and thus closed. At a time labelled ' $t_{\text{switch_off}}$ ', the solenoid 60 is de-energised and the electromagnetic field acting on the armature 58 begins to decay. This manifests as a downward curve in

Figure 4, as the current measured by the sensor circuit falls.

[0058] The armature assembly does not begin to move immediately when the solenoid 60 is de-energised. Instead, the armature assembly remains stationary until the residual electromotive force created by the decaying magnetic field, combined with a stiction force holding the armature assembly in place, falls below the spring force provided by the return spring 46, such that a net force acts to lift the LPP 42 from its seat 44.

[0059] It is noted that, as the driveshaft 12 is stationary during the diagnostic routine, all fluid within the ECM 10 can be expected to be at substantially the same pressure. So, during the diagnostic routine opening of the LPV 38 is not assisted by hydrodynamic forces as it would be when the ECM 10 is operating.

[0060] Movement of the armature assembly initiates a dynamic phase. The moment at which the LPP 42 lifts and the dynamic phase commences manifests as an increase in the measured current shown in Figure 4, which corresponds to the back-EMF that is induced in the solenoid 60 by the movement of the armature 58. The current continues to increase for a short period, reflecting acceleration of the armature 58 and a corresponding increase in the induced back-EMF. Acceleration of the armature 58 is opposed by a range of forces that arise in the dynamic phase, including hydrodynamic, frictional and eddy-making resistance forces.

[0061] The current then reaches a peak, 'back-EMF_max', corresponding to an amplitude of the back-EMF, beyond which the current falls again sharply to resume the original trajectory of the decaying magnetic field. The peak current corresponds to termination of the movement of the armature 58, which in turn ceases the induction of back-EMF in the solenoid 60. Accordingly, the peak current measurement defines the moment at which the LPV 38 reaches its open state and so defines a reopening time, ' $t_{\text{reopening}}$ '.

[0062] The period between de-energising the solenoid 60 and completion of reopening of the LPV 38 defines a response time, ' T_{response} ', of the LPV 38. The response time therefore reflects the total time for the LPV 38 to reopen fully after de-energisation.

[0063] Various factors may influence the response time of an LPV 38. For example, the response time in part reflects of the medium through which the armature 58 and LPP 42 move through while opening. Figure 4 reflects the normal situation, in which the LPP 42 and the armature 58 are immersed in hydraulic fluid. The hydraulic fluid is relatively dense and viscous, and so presents significant resistance to movement of the armature assembly.

[0064] As a comparison, Figure 5 shows the response of an LPV 38 that is 'dry', in that there is no hydraulic fluid around the armature assembly, which is instead surrounded by air. This may be because the LPV 38 is encased by an air bubble, or because the level of hydraulic fluid in the crankcase 14 is low, for example. Air has a

lower density and viscosity compared to hydraulic fluid and so presents less resistance to movement of the armature assembly. It follows that the armature assembly moves faster in this situation, and so the LPV response time is reduced. This is reflected in Figure 5, in that the upward curve during the dynamic phase corresponding to back-EMF in the solenoid 60 is steeper, reaches a higher amplitude, and is of reduced duration compared to the corresponding curve in Figure 4. This, in turn, reflects the different characteristics of the back-EMF generated by the faster armature movement, noting that the amplitude of the back-EMF is proportional to the velocity of the armature 58.

[0065] It follows from the above that the response of an LPV 38 to being operated when the driveshaft 12 is stationary can be used to infer whether the LPV 38 is functioning properly. In particular, a response that differs from the expected response shown in Figure 4 is indicative of a fault. More specifically, either or both of the response time T_{response} of the LPV 38 and the amplitude of the response may be analysed to detect an abnormality with respect to the expected response of the LPV 38.

[0066] There are various faults that may cause the response to deviate from the expected response. Some of these faults are local in nature, including a dry valve state as represented in Figure 5, a broken return spring 46 or detachment of the LPP 42 from the armature 58, for example. Other faults are more global, including a low fluid level in the crankcase 14 and the physical state of the hydraulic fluid being other than it should be, for example due to being overly aerated or otherwise contaminated, for example with air, water or diesel.

[0067] It may not be possible to determine the precise nature of a fault from the response of an LPV 38 alone, although it may be possible for certain faults. However, the respective responses of the different LPVs 38 of the ECM 10 can be analysed collectively to provide further insight. If a fault is found to be isolated to a single valve, the fault may be deemed to be local in nature and so may not threaten damage to the ECM 10. In this scenario, it may be considered safe to activate the ECM 10 and to rotate the driveshaft 12, which enables further tests to be conducted to determine the nature of the local fault.

[0068] If multiple LPVs 38 are exhibiting anomalous responses that deviate from the reference response, however, a more global fault may be present, such as a low fluid level in the crankcase 14 or a poor physical state of the hydraulic fluid. In either case, it is preferable not to activate the ECM 10 until the fault has been remedied. To assess this, the positions of the faulty LPVs 38, both relative to the other LPVs 38 and spatially within the crankcase 14, can be taken into account. There are various ways to do so, one of which is shown in Figure 6.

[0069] In this respect, Figure 6 shows a process defining a diagnostic routine 80 for detecting faults in the ECM 10, which routine 80 involves operating the LPVs 38 while the ECM 10 is otherwise inactive and the driveshaft 12 is stationary. It is envisaged that the routine 80 may be

performed at start-up of the ECM 10 as part of an initialisation procedure, although the routine 80 may be performed at other times and at different frequencies. The diagnostic routine 80 may also be used as part of a commissioning process to confirm proper configuration of the ECM 10.

[0070] The routine 80 starts by operating, at step 82, each of the LPVs 38 of the ECM 10. The LPVs 38 may be operated simultaneously or at different times, for example in succession. In this example, operating an LPV 38 entails energising the LPV 38 to close the LPV 38 for a short period, and then de-energising the LPV 38 to allow it to open. A complete cycle of energisation followed by de-energisation therefore represents a single operation of the LPV.

[0071] The response of each LPV 38 as it is operated is detected by its respective sensing circuit 66. As noted above, in this example the sensing circuits 66 detect signals indicative of the electrical current in the solenoid 60 of the LPV. These signals are transmitted to the controller 62 as response signals, which are analysed by the controller 62 to determine whether the amplitude and/or the response time T_{response} of the response signals are as expected. In this respect, the controller 62 applies threshold values to the characteristics of the response signals, based on the reference response shown in Figure 4, to determine whether the measured values are within expected threshold ranges.

[0072] If an LPV 38 exhibits a response within the threshold values, the diagnostic routine 80 finds that LPV 38 to be operating correctly. If an LPV 38 exhibits a response that lies outside the threshold values, that LPV 38 is flagged at step 84 as indicating a fault.

[0073] If all of the LPVs 38 are determined at step 86 to have response signals within the thresholds and so are operating correctly, such that none are flagged, the prime mover is started at step 88, to commence rotation of the driveshaft 12 and the diagnostic routine 80 terminates.

[0074] The controller 62 then checks whether more than one LPV is flagged at step 90. If only one LPV 38 is found to be flagged, the fault can be assumed to be localised to that LPV 38. In this example, the prime mover is allowed to start at step 92, subject to further testing. Once the driveshaft 12 begins to rotate, further tests can be performed at step 94 to characterise the fault in the flagged LPV 38. Once the nature of the fault has been assessed at step 96, either the flag can be cleared at step 98 or, if a fault is verified and requires corrective action, the prime mover can be stopped and/or an alarm can be generated for an operator at step 100.

[0075] However, in other examples the ECM 10 may not be allowed to start if even a single LPV 38 is flagged.

[0076] If multiple LPVs 38 are flagged at step 90 as indicating a fault, the diagnostic routine 80 continues to assess the nature of the faults further, in particular to determine whether the indicated faults are localised, or if they collectively suggest a global fault such as a low

fluid level in the crankcase 14.

[0077] In this respect, the next step of the routine 80 is to identify at step 102 the position of each flagged LPV 38. In this example, the LPVs 38 can be identified with reference to the angular positions of their respective PCUs 18 with respect to the shaft axis, as shown in Figure 1. Accordingly, references below to an LPV 38 at a particular angle refers to the LPV 38 of the PCU 18 at that angle.

[0078] The positions of each flagged LPV 38 can then be used to evaluate the likelihood that the indicated faults relate to a global fault. In this example, the proximity of flagged LPVs 38 to each other is used as an indicator of a global fault. In particular, the controller 62 checks at step 104 whether flagged LPVs 38 are adjacent to each other, meaning that the flagged LPVs 38 are at 60° to each other with respect to the shaft axis in this example.

[0079] If no two flagged LPVs 38 are adjacent to each other, the flagged LPVs 38 are assumed to be subject to separate localised faults. For example, if the LPVs 38 at 60° and 180° are flagged but the remaining LPVs 38 are not flagged, the fault indicated for the LPV 38 at 60° can be assumed to be localised and different to the fault indicated for the LPV 38 at 180°. In this situation, the routine proceeds to steps 92, 94 and 96 and so the prime mover is activated to commence rotation of the driveshaft 12. Further tests can then be performed at step 94 to characterise the faults in the flagged LPVs 38. The outcome of these further tests may require an individual PCU 18 to be deactivated, or the ECM 10 to be stopped entirely at step 100 so that the fault can be remedied. Alternatively, the further testing may reveal one or more of the faults to be minor or even false positives, such that the associated flags can be cleared at step 98.

[0080] If two or more flagged LPVs 38 are adjacent to one another, it is likely that the responses of those LPVs 38 are anomalous due to a global fault such as a low fluid level in the crankcase 14. For example, if the LPVs 38 at 0°, 60° and 300° are all flagged while the remaining LPVs 38 are not flagged, this is suggestive of a fluid level in the crankcase 14 that is between the flagged and unflagged LPVs 38, and therefore low and potentially below the level of the driveshaft 12.

[0081] The controller 62 also takes into account the spatial orientation of the flagged LPVs 38 as an additional or alternative way to characterise faults. For example, if the fluid level in the crankcase 14 is low, it would be expected that all LPVs 38 above the fluid level would be flagged, whereas LPVs 38 below the fluid level would not be expected to be flagged. So, for example, if the LPVs 38 at 0° and 60° are flagged but the LPV 38 at 300° is not flagged, this suggests that something other than a low fluid level is the cause of the problems in the flagged LPVs 38.

[0082] More generally, if the LPV 38 at 0° is not flagged, this may be taken as indicative that the crankcase 14 is filled correctly and therefore a low fluid level cannot be the cause of flagging for any of the other LPVs 38. The

risk of a false negative, namely a response that is within the threshold range when a fault is actually present, can be taken into account in this respect.

[0083] Conversely, flagging of the LPV 38 at 0° could in itself indicate a low crankcase 14 fluid level, even if no other LPVs 38 are flagged, since the fluid level could be between the LPV 38 at 0° and those at 60° and 300°. However, in that situation the fluid level would nonetheless be sufficient to immerse the driveshaft 12 and the rolling interfaces between the cam 16 and the piston sliders 22 of the PCUs 18, and so the risk of damage if the ECM 10 is started is low. It may therefore be considered safe to proceed with activating the ECM 10 even if the LPV 38 at 0° is flagged.

[0084] The above principles are taken into account in the routine 80 shown in Figure 6 in that the controller 62 applies a criterion that more than two LPVs 38 must be flagged and adjacent to indicate a global fault. In this respect, as flagging of the LPV 38 at 0° alone is deemed acceptable, in all other low fluid level situations at least three adjacent LPVs 38 will be flagged, since the LPVs 38 at 60° and 300° are at the same vertical level (in the instance the 0° top-most cylinder is at or very close to vertical).

[0085] Accordingly, the flagged, adjacent LPVs 38 are counted at step 106. If no more than two adjacent LPVs 38 are found to be flagged at step 108, the faults are assumed to be local to the flagged LPVs 38 such that it is safe to operate the ECM 10 without risking damage, and so the prime mover is started at step 92. Once the ECM 10 is operating, other tests can be performed to determine the precise nature of the faults in the flagged LPVs 38. These tests may reveal the flagged LPVs 38 to be operating correctly, such that the controller 62 flagged the LPVs 38 incorrectly, in which case the flags are removed and the ECM 10 continues to operate. Otherwise, if a fault is confirmed then the ECM 10 can be deactivated and the fault can be reported to an operator of the ECM 10.

[0086] Alternatively, if the number of flagged, adjacent LPVs 38 exceeds two then the controller 62 determines that a global fault is likely to exist that threatens damage to the ECM 10 if it is activated. The controller 62 therefore takes preventative action by prohibiting operation of the prime mover and/or generating an alarm that is indicated to an operator of the ECM 10 at step 100. The fault can then be investigated further without ever having risked damage to the ECM 10 by operating whilst in a fault state.

[0087] In a variant of the process shown in Figure 6, if the diagnostic routine 80 is performed during commissioning or servicing, the prime mover may not be started on identifying a localised fault in one or more LPVs 38. Instead, if an air bubble around an LPV 38 is suggested, the machine can be bled of air or refilled as necessary to remove the bubble. The diagnostic routine 80 can then be repeated to confirm whether the fault is resolved.

[0088] It should be appreciated that the logic and criteria applied in the diagnostic routine 80 for characteris-

ing faults based on the readings of the LPV responses may vary, for example based on operating experience or to represent varying degrees of caution. For example, the prime mover may be prohibited from operating if a single LPV 38 is flagged. Specific spatial patterns for flagged valves may be defined that are deemed to indicate global faults or to be otherwise unacceptable. In another option, two or three non-adjacent flagged LPVs 38 may be sufficient to trigger prohibiting of the prime mover.

[0089] In general terms, whichever specific criteria are used in the diagnostic routine 80 to judge the state of the ECM 10, the routine 80 helps to identify fault states that could cause severe damage to the ECM 10 if it is allowed to operate, and therefore prevents that damage from arising. This is achieved without requiring any sensors or other additional hardware to be fitted to the ECM 10, and so does not contribute unwanted complexity.

[0090] It is noted that characterisation of local faults may be possible at least to some extent while the ECM 10 remains inactive. In this respect, an air bubble or a detached LPP 42 will cause the LPV 38 to close faster than usual due to the reduced resistance to movement of the armature assembly. Conversely, a broken return spring 46 that provides a reduced spring force will result in an LPV 38 that opens more slowly than is normally expected, and which potentially does not open at all. In this respect, it is noted that opening of the LPV 38 is not aided by fluid flow when the ECM 10 is inactive, and so the spring force is the only force available to open the LPV. Accordingly, an LPV response that exhibits a response time that is longer than for the reference response may indicate a broken return spring 46.

[0091] In addition, or as an alternative, to provide further information from which to ascertain the presence and nature of faults a second diagnostic test can be used before allowing the driveshaft 12 to rotate. The second diagnostic test may be applied to each LPV 38 or, if used in combination with the diagnostic routine 80 described above, only to flagged LPVs 38.

[0092] In the second diagnostic test, for each LPV 38 that is tested, the drive circuit 64 of the LPV 38 is controlled to increase an electrical current supplied to the solenoid 60 of the LPV 38 gradually, and the feedback received from the sensing circuit 66 is analysed to find the current at which the armature assembly begins to move to close the LPV. Similarly to the diagnostic routine 80 of Figure 6, in the second diagnostic test the expected response is known and so a threshold range for the current required to close the LPV 38 can be applied to determine whether the LPV response is normal.

[0093] Increasing the current supplied to a solenoid 60 may be implemented by increasing a duty cycle of a pulse-width modulated (PWM) signal used to control the LPV, for example.

[0094] If the LPV return spring 46 is faulty so that it provides only a partial spring force, the electromagnetic force necessary to overcome the spring force to move

the armature assembly towards the associated valve seat 44 will be lower than if the return spring 46 were functioning normally. In turn, the current required to close the LPV 38 will be correspondingly lower and so below the threshold range. Hence, this test can be used to identify whether an LPV 38 has a broken return spring 46 and therefore supplement the information provided by the diagnostic routine 80.

[0095] Conversely, if the LPP rod, or armature plunger suffers from unexpected friction, the current required to close the LPV 38 will be correspondingly higher and so above the threshold range. Hence, this test can be used to identify whether an LPV 38 has a 'sticky' moving component and therefore supplement the information provided by the diagnostic routine 80.

[0096] The two diagnostic tests described above can be combined, by energising each LPV 38 with a gradually increasing current to close the LPV, and then de-energising the LPV. The current or voltage in the solenoid 60 measured by the sensor circuit throughout the operation can then be analysed to determine both the current at which the LPV 38 closed, and therefore whether the return spring 46 is faulty, and the response of the LPV 38 during reopening and therefore whether any other abnormalities are indicated.

[0097] It will be appreciated by a person skilled in the art that the invention could be modified to take many alternative forms to that described herein, without departing from the scope of the appended claims.

Claims

1. A method of determining a state of an electronically commutated hydraulic machine (10), the machine (10) having a machine shaft (12) that is connected to a set of piston assemblies (18), each piston assembly (18) comprising a respective electromechanical actuator (56), the method comprising performing a diagnostic routine while the machine shaft (12) is stationary, the diagnostic routine comprising:

operating each of the actuators (56) of the set of piston assemblies (18);
detecting, for each actuator (56), a signal indicative of a response of the actuator (56) as the actuator (56) is operated; and
analysing each of the detected actuator response signals to determine the state of the machine (10).

2. The method of claim 1, wherein a response of an actuator (56) comprises movement of a component of the actuator (56).
3. The method of claim 2, wherein each signal indicative of a response of an actuator (56) comprises a signal corresponding to a back-electromotive force

generated by movement of a component of the actuator (56).

4. The method of any preceding claim, wherein analysing a detected actuator response signal comprises identifying any abnormalities in the actuator response signal. 5
5. The method of claim 4, wherein identifying abnormalities in a detected actuator response signal comprises comparing the detected actuator response signal with a reference response and/or with one or more threshold values. 10
6. The method of any preceding claim, comprising analysing two or more of the detected actuator response signals collectively to determine the state of the machine (10). 15
7. The method of any preceding claim, comprising analysing the detected actuator response signals in accordance with the respective positions of the actuators (56) with respect to the machine. 20
8. The method of claim 7 when dependent on claim 4, comprising determining whether the respective responses of adjacent actuators (56) are anomalous. 25
9. The method of any preceding claim, comprising commencing rotation of the machine shaft (12) in dependence on the determined the state of the machine (10). 30
10. The method of claim 9, comprising preventing rotation of the machine shaft (12) and/or generating an alarm if the state of the machine (10) comprises a fault. 35
11. The method of any preceding claim, wherein operating an actuator (56) comprises energising and then de-energising the actuator (56). 40
12. The method of any preceding claim, wherein operating an actuator (56) comprises progressively increasing an electrical current supplied to the actuator (56). 45
13. The method of claim 12, wherein analysing the detected actuator response signal comprises determining a value of the electrical current at which the actuator (56) began to move. 50
14. The method of any preceding claim, wherein determining the state of the machine (10) comprises detecting one or more faults. 55
15. The method of claim 14, wherein a fault may comprise any of: a low fluid level; an airlocked actuator;

a broken actuator spring; a detached component associated with an actuator; resistance to actuator movement; or an erroneous state of fluid in the machine.

16. A controller (62) for an electronically commutated hydraulic machine (10), the machine (10) having a machine shaft (12) that is connected to a set of piston assemblies (18), each piston assembly (18) comprising a respective electromechanical actuator (56), the controller (62) comprising:

an output (72) configured to issue control signals for operating the actuators (56) of the set of piston assemblies (18);
 an input (68) configured to receive signals indicative of responses of the actuators (56) as the actuators (56) are operated; and
 a processing module (70) configured to analyse the detected actuator response signals;

wherein the controller (62) is configured to perform a diagnostic routine while the machine shaft (12) is stationary, the diagnostic routine comprising:

operating each of the actuators (56) of the set of piston assemblies (18);
 detecting, for each actuator (56), a signal indicative of a response of the actuator (56) as the actuator (56) is operated; and
 analysing each of the detected actuator response signals to determine the state of the machine (10).

17. An electronically commutated hydraulic machine (10) comprising the controller (62) of claim 16.

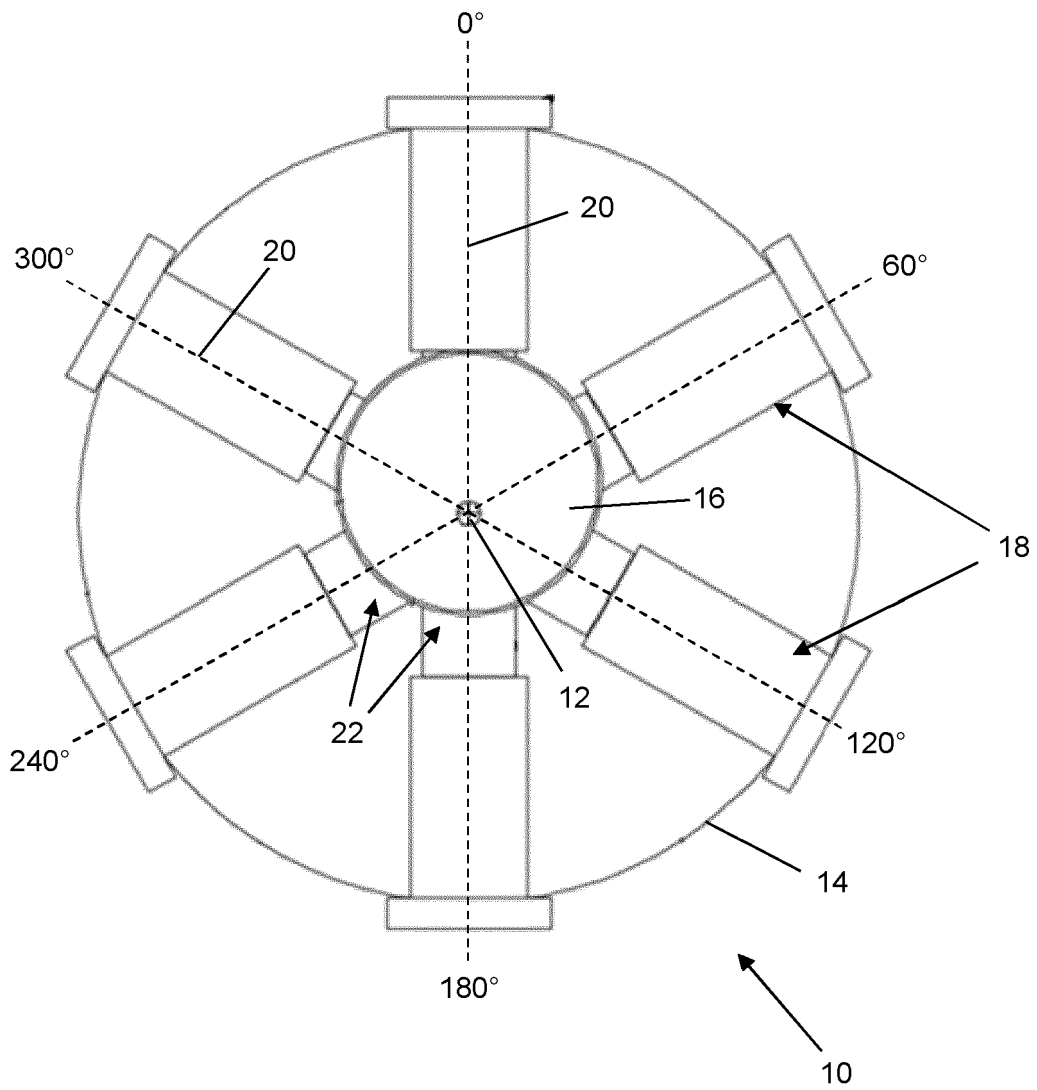


Fig. 1

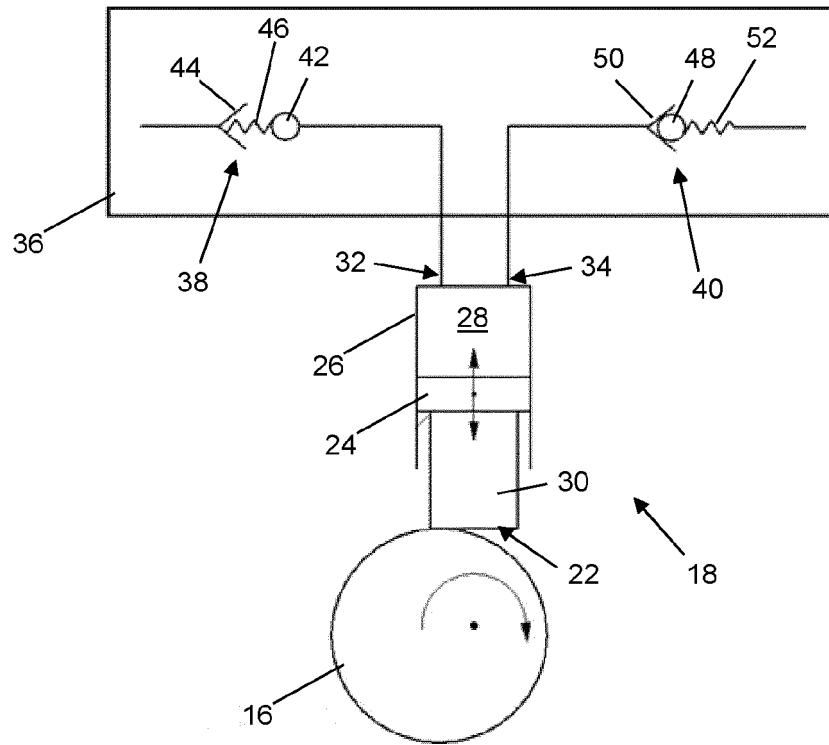


Fig. 2

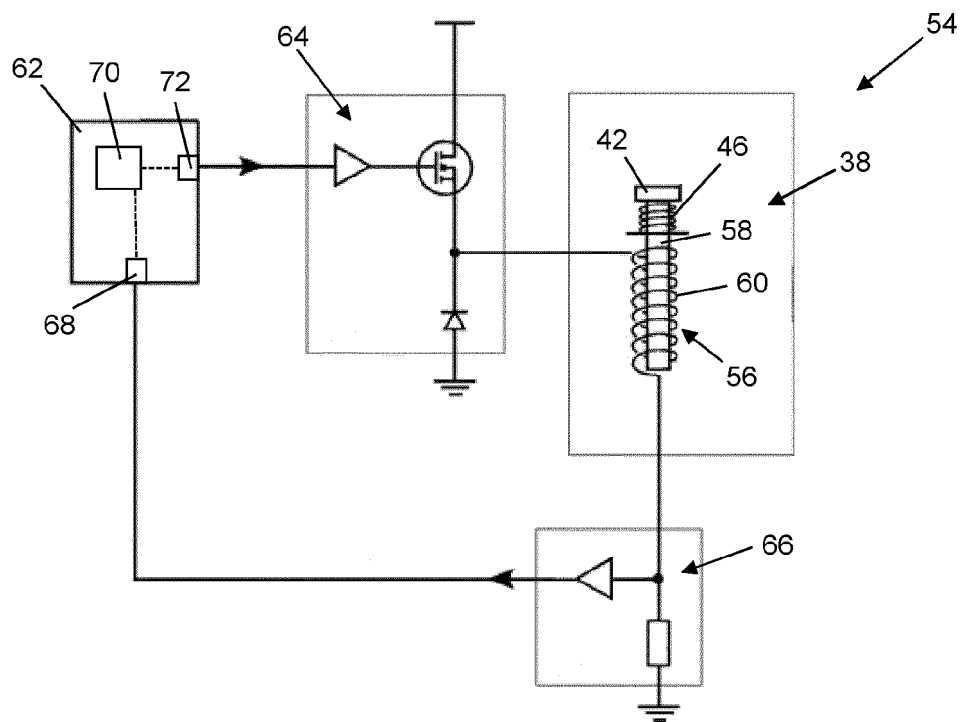


Fig. 3

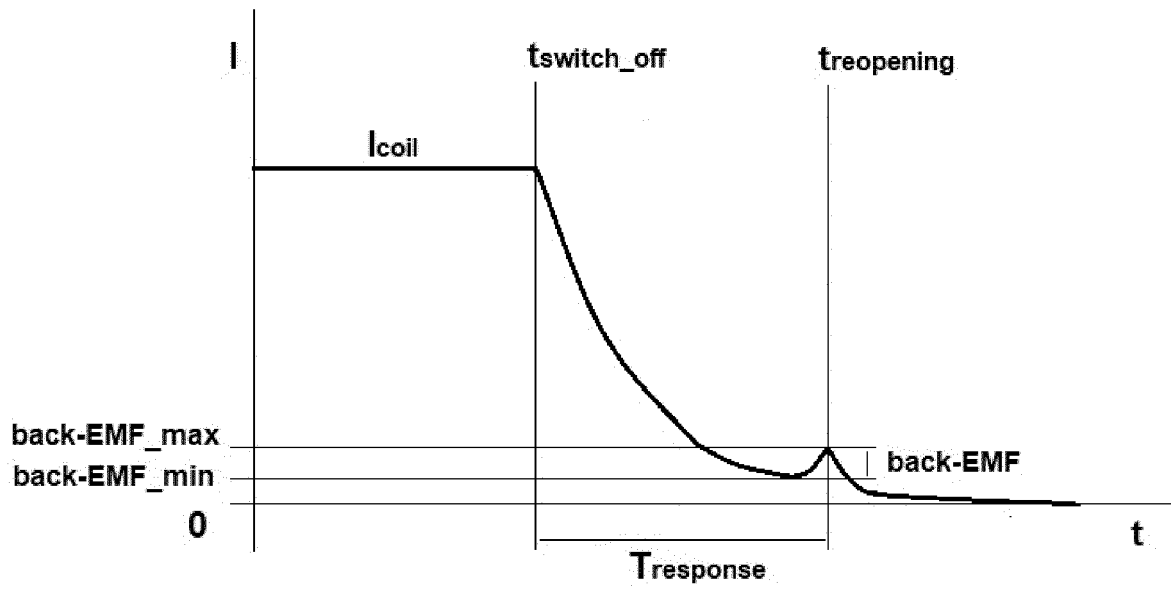


Fig. 4

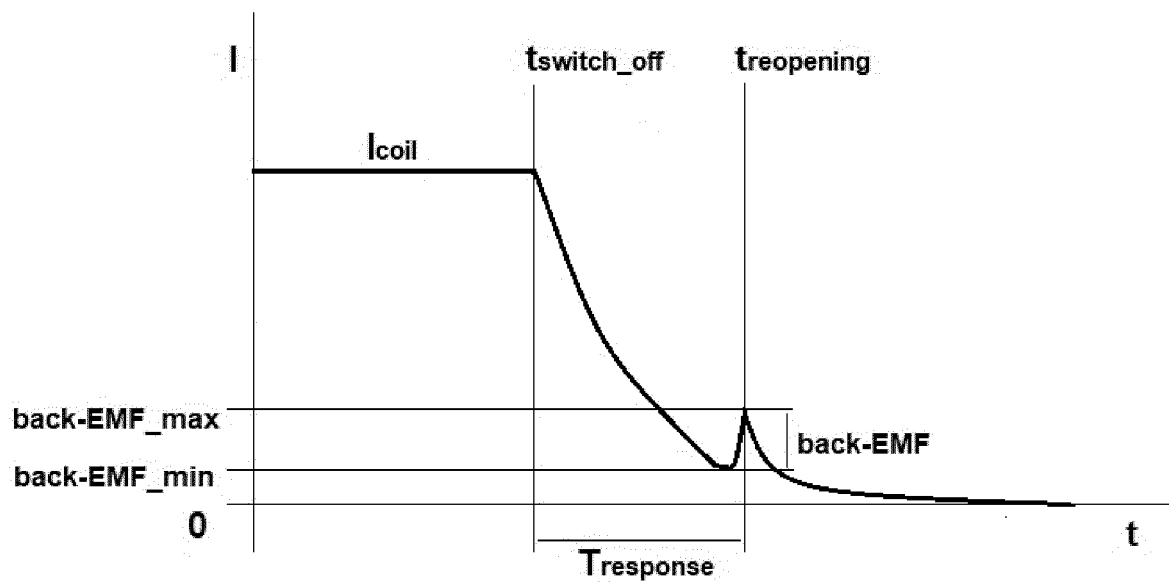


Fig. 5

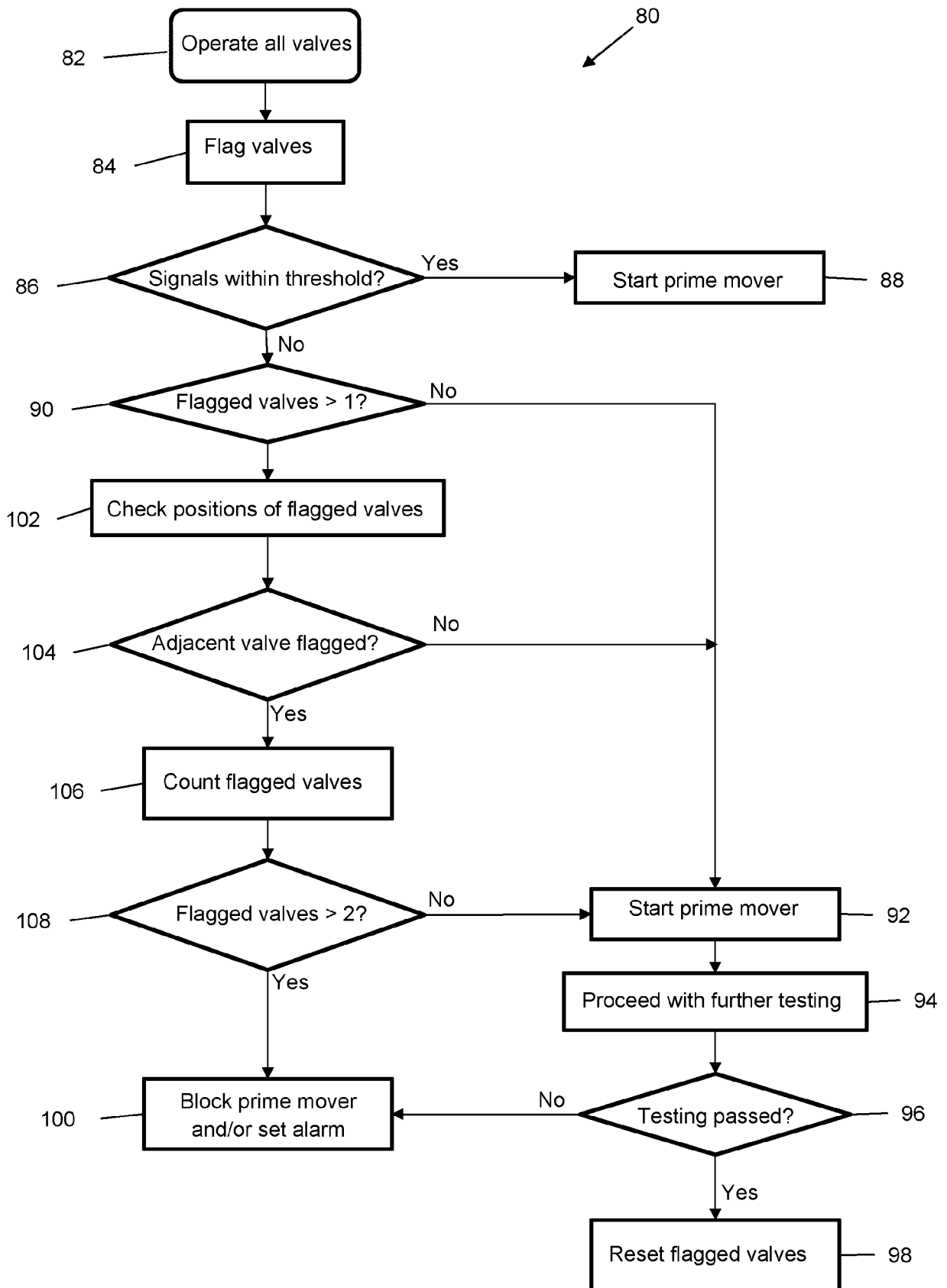


Fig. 6



EUROPEAN SEARCH REPORT

Application Number

EP 22 18 7973

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