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(54) **Method of operating a fluid working machine**

(57) The invention relates to a method (32) of operating a fluid working machine (1), comprising at least one working chamber (4) of cyclically changing volume, a high pressure fluid connection (19), a low pressure fluid connection (18) and at least one electrically actuated valve (10, 11), connecting said working chamber (4) to said high pressure fluid connection (19) and/or said low pressure fluid connection (18). The actuation of the electrically actuated valve (10, 11) is varied depending on the fluid flow demand (34) and/or on the mechanical power demand (34). For the actuation of the electrically actuated valves (10, 11), an actuation sequence (14) is calculated, covering a plurality of working cycles (15) of the cyclically changing volume (4).

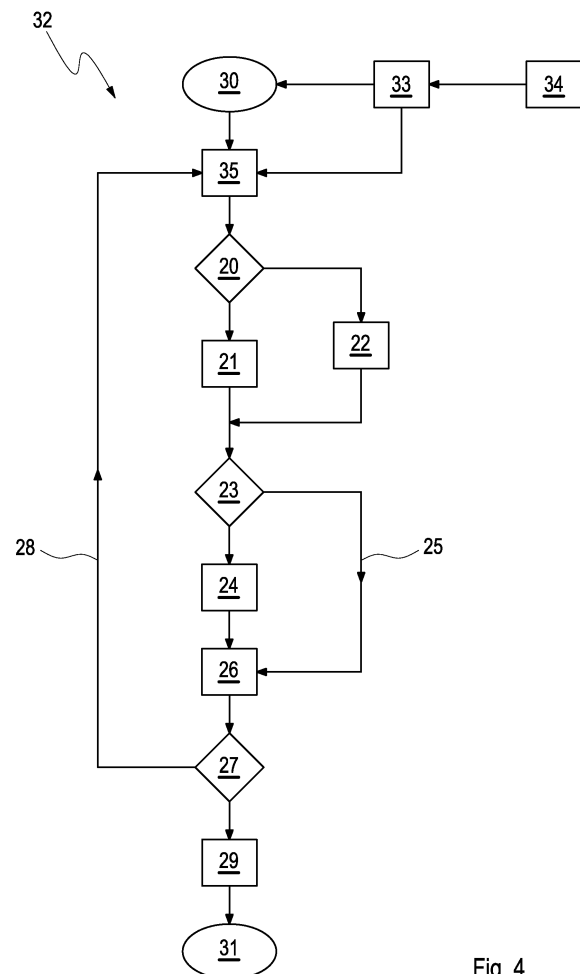


Fig. 4

Description

[0001] The invention relates to a method of operating a fluid working machine, comprising at least one working chamber of cyclically changing volume, a high pressure fluid connection, a low pressure fluid connection and at least one electrically actuated valve, connecting said working chamber to said high-pressure fluid connection and/or said low pressure fluid connection, wherein the actuation of said electrically actuated valve is varied depending on the fluid flow demand and/or on the mechanical power demand. Additionally, the invention relates to an electronic controlling unit for the actuation of a fluid working machine, comprising at least one actuated valve. Furthermore, the invention relates to a fluid working machine, comprising at least one working chamber of cyclically changing volume, a high pressure fluid connection, a low pressure fluid connection and at least one electrically actuated valve, connecting said working chamber to said high pressure fluid connection and/or said low pressure fluid connection and at least one electronic controller unit.

[0002] Fluid working machines are generally used, when fluids are to be pumped or fluids are used to drive the fluid working machine in a motoring mode. The word "fluid" can relate to both gases and liquids. Of course, "fluid" can even relate to a mixture of a gas and a liquid and furthermore to a supercritical fluid, where no distinction between gas and liquid can be made anymore.

[0003] Very often, such fluid working machines are used, if the pressure level of a fluid has to be increased. For example, such a fluid working machine could be an air compressor, a hydraulic pump, a pneumatic motor or a hydraulic motor.

[0004] Usually, fluid working machines comprise one or more working chambers of a cyclically changing volume. Usually, for each cyclically changing volume, a fluid inlet valve and the fluid outlet valve is provided.

[0005] Traditionally, the fluid inlet valves and the fluid outlet valves, which are used for fluid working machines, are passive valves, particularly when pumps are considered. When the volume of a certain working chamber increases, its fluid inlet valve opens, while its fluid outlet valve closes under the pressure differences, caused by the volume increase of the working chamber. During the phase, in which the volume of the working chamber decreases again, the fluid inlet valve closes, while the fluid outlet valve opens under the changed pressure differences.

[0006] A relatively new and promising approach for improving fluid working machines are the so-called synthetically commutated hydraulic machines (synthetically commutated hydraulic pumps), also known as digital displacement pumps. Such synthetically commutated hydraulic machines are a unique subset of variable displacement machines. Such synthetically commutated hydraulic machines are known as such, for example from EP 0 494 236 B1 or WO 91/05163 A1. In synthetically

commutated hydraulic pumps, the passive inlet valves are replaced by electrically actuated inlet valves. Preferably the passive fluid outlet valves are also replaced by electrically actuated outlet valves. By appropriately controlling the valves, a full stroke pumping mode, an empty cycle pumping mode (idle mode) and a part stroke pumping mode can be achieved. Furthermore, if both inlet valves and outlet valves are electrically actuated, the pump can be used as a hydraulic motor as well. If the pump is run as a hydraulic motor, a full stroke motoring mode, a part stroke motoring mode and an idle motoring mode are possible as well.

[0007] A major advantage of such synthetically commutated hydraulic machines is their higher efficiency, as compared to traditional hydraulic pumps. Furthermore, since the valves are electrically actuated, the output characteristics of synthetically commutated hydraulic machines can be changed very quickly. In particular, it is possible to completely change the output characteristics of the synthetically commutated hydraulic machine from one working cycle to another (for example from zero fluid output flow to full fluid output flow).

[0008] For adapting the fluid flow output of a synthetically commutated hydraulic pump according to a certain requested fluid flow demand (which can vary over time, of course), several approaches are known in the state of the art.

[0009] The perhaps simplest possibility is to switch the synthetically commutated hydraulic pump to full stroke pumping mode for a certain time. When the synthetically commutated pump runs in the (full) pumping mode, a high-pressure fluid reservoir is filled with pressurised fluid. Once a certain pressure level is reached in the high pressure fluid reservoir, the synthetically commutated hydraulic pump is switched to an idle mode and the fluid flow demands is supplied by the high pressure fluid reservoir. As soon as the high pressure fluid reservoir reaches a certain lower threshold level, the synthetically commutated hydraulic pump is switched on again.

[0010] This approach, however, necessitates a relatively large high-pressure fluid reservoir. Such a high-pressure fluid reservoir is expensive, occupies a large volume and is quite heavy. Furthermore, a certain variation in the output pressure will inevitably occur.

[0011] Another approach for adapting the fluid output flow of a synthetically commutated hydraulic pump according to a different fluid flow demand is described in EP 1 537 333 B1. Here, it is proposed to use idle modes, part stroke pumping modes and full stroke pumping modes for realising a fluid flow output, whose time average is equal to given fluid flow demand. In the idle mode, no fluid is pumped by the respective working chamber to the high pressure manifold. In the full stroke mode, all of the usable volume of the working chamber is used for pumping fluid to the high pressure side in the respective cycle. In the part stroke mode, only a part of the usable volume is used for pumping fluid to the high pressure side in the respective cycle. The different modes are dis-

tributed among several chambers and/or among several successive cycles in a way that the time averaged effective fluid flow rate of the machine satisfies the requested demand. The decision, on what kind of stroke has to be triggered is made by the use of a so-called accumulator variable. The accumulator variable is increased in certain time intervals by a value, which is representative of the fluid flow demand. Depending on the value of the accumulator variable, an idle mode, a part stroke mode or a full stroke mode is performed. Consequently, the accumulator is deducted by a value, which is representative of the volume, pumped by the pumping mode performed.

[0012] This controlling method performs the necessary calculations "online", i.e. during the actual use of the fluid working machine. Furthermore, the decision on whether to perform a pumping stroke or not, as well as the decision on whether a part stroke pumping mode or a full stroke pumping mode has to be performed, is made on a cycle-by-cycle basis and only for the very next cycle could be performed in line. In other words, the respective decision is only made for the very next possible actuation. Other (future) actuations of the actuated valve(s) are not taken into consideration.

[0013] While such "online" controlling methods are relatively easy to implement, they suffer from certain limitations and drawbacks. A major issue is the problem of pressure pulsations. In particular under certain working conditions of the synthetically commutated hydraulic machine, strong pressure pulsations on the high pressure side can occur. Such pressure pulsations can be noticed in the behaviour of a hydraulic consumer (e.g. a hydraulic piston or a hydraulic motor). As an example, the pulsations can be noticed as a start-stop-like movement (a "stiction" behaviour). The pressure pulsations can even lead to the destruction of certain parts of the hydraulic system. Furthermore, the "online" controlling methods according to the state of the art are usually susceptible to numerical artefacts (i.e. some kind of a "Moiré"-effect occurs). Certainly, such erratic fluid flow output characteristics are not desirable.

[0014] A different approach was followed in the not yet published European patent application, application number 07 254 331. Here, it is suggested to completely abandon "online" calculations. This is done by calculating actuation patterns in advance. The thus calculated actuation patterns are stored in a memory device. The thus stored actuation patterns can be read out by an electronic controlling unit of the synthetically commutated hydraulic machine. Usually, the pre-calculated actuation patterns are generated before the respective fluid working machine is even assembled.

[0015] Although this approach can yield a very smooth fluid flow output characteristics with relatively small pressure pulsations, a lot of effort has to be put into the calculation of the actuation patterns. Furthermore, relatively elaborate electronics and memory devices have to be used. Another problem can occur, if the fluid flow demand changes. This is because the actuation patterns, as de-

scribed in said European patent application, can be of considerable length. If the fluid flow demands changes in between, this could lead to a long delay between changing fluid flow demands and actual fluid output flow, generated by the synthetically commutated hydraulic machine. To avoid such delays, an elaborate algorithm for transitioning between different actuation patterns is suggested in said application. However, this transitioning algorithm is rather complicated.

[0016] It is therefore the object of the invention to suggest an improved method for operating a fluid working machine of the synthetically commutated type. Another object of the invention is to suggest an improved electronic controller unit for a synthetically commutated fluid working machine. Yet another object of the invention is to suggest an improved fluid working machine.

[0017] Therefore, a method of operating a fluid working machine, comprising at least one working chamber of cyclically changing volume, a high pressure fluid connection, a low pressure fluid connection and at least one electrically actuated valve, connecting said working chamber to said high pressure fluid connection and/or said low pressure fluid connection, is suggested, wherein the actuation of said electrically actuated valve is varied depending on the fluid flow demand and/or on the mechanical power demand, and wherein for said electrically actuated valve at least in part and/or at least at times an actuation sequence, covering a plurality of working cycles of said cyclically changing volume, is calculated. Surprisingly, by "looking some actuations into the future", it is possible to achieve a much better fluid output characteristics, showing in particular fewer and less predominant pressure pulsations. Put in other words, by using the suggested method, multiples of future actuations can be considered at the same time (i.e. usually at the time of the calculation of the actuation sequence). Furthermore, the already described occurrence of numerical artefacts can usually be decreased. The actuation sequence, however, is still calculated "online", i.e. usually during the operation of said fluid working machine. Because of this "online" calculation, it can be avoided to spend extensive time on developing pre-calculated actuation sequences, which have to be stored in a memory device of a sufficient size. In particular, if several parameters have to be considered, in case of pre-calculated actuation sequences the number of actuation sequences, which have to be pre-calculated and stored can increase exponentially, thus requiring a huge memory and extensive calculation efforts. As an example: the pressure, the speed and/or the temperature of the hydraulic fluid can be parameters, which can influence the operation of the fluid working machine quite significantly, and hence should be considered. Thus, the suggested method is still relatively easy to implement, and can be adapted to changing situations and/or to different fluid working machines easily. It is possible to calculate the next actuation sequence shortly before the end of the active actuation sequence is reached. This way, sufficient time

can be provided for calculating the next actuation sequence. The exact timing for the start of the calculation of the next actuation sequence can depend on the available calculation means (for example the speed of an electronic controller on which the algorithm is run) and/or the method in which the algorithm is implemented. Generally, the timing should be chosen in a way that even under disadvantageous situations (i.e. the calculation of the actuation sequence takes very long) the calculation is finished before the actual actuation sequence is completed. With nowadays available computer hardware, the necessary time margin can usually be kept quite short. Another possibility is to calculate a new actuation sequence, as soon as the current fluid flow demand changes (if applicable, after filtering). The newly calculated actuation sequence will be applied, as soon as possible. This will usually happen, when the currently actuated actuation sequence is finished. However, if the calculation of the new actuation sequence cannot be completed before the current actuation sequence is finished, the "old" actuation sequence can simply be reapplied. Of course, it is even possible to generally reapply the current ("old") actuation sequence over and over again, if the fluid flow demand does not change (if applicable, after filtering). Although the suggested method will usually yield an actuation sequence, covering a plurality of working cycles of the at least one cyclically changing volume (for example two, three, four, five, six, seven, eight, nine and/or ten working cycles) it is possible that under certain conditions, particularly at certain fluid flow demands and/or mechanical power demands, a preferred (or even the optimum) actuation sequence will be reached with an actuation sequence, having a length of only one working cycle. As a rather obvious example: if the fluid flow demand is zero, the suggested method will yield an optimum actuation sequence of a single actuation with a zero pumping mode to be performed. The fluid flow demand and/or the mechanical power demand can be calculated, at least in part and/or at least at times, from the fluid pressure (in particular from the fluid pressure in the high-pressure manifold), from the speed of the fluid working machine and/or from the torque of the fluid working machine. Of course, the actuation sequence should be set up in a way that its time averaged fluid output flow will correspond to the actual fluid flow demand.

[0018] Preferably, the length of said actuation sequence is minimised. This way it is possible that the calculated actuation sequence can be finished without causing any undue delays, even if the fluid flow demand and/or the mechanical power demand changes. Preferably, the actuation sequence should be as short as possible, without increasing the number and/or the amount of the pressure pulsations at all, noticeably and/or significantly. The method can be performed in a way that a balance between short actuation sequences and low pressure pulsations will be reached. In other words, if the length of the actuation sequence would become too long, a certain deterioration of the quality and/or the accuracy of the

generated fluid output flow will be tolerated, to limit the length of the actuation sequence. Also, the "allowed" regions could be expanded in such a case (see the following description). It is even possible to make the length of the actuation sequence (in units of working cycles) dependent on the speed of the fluid working machine. This way, a certain limit for the maximum delay (in units of time) between a change in the fluid flow demand and a change in the fluid flow output can be set. Furthermore, the limitation and/or avoidance of excessive "gear-shifting" behaviour of the synthetically commutated hydraulic pump might be another operational consideration, which can influence the choice of the actuation sequence length. As an example: if shorter actuation sequences are only available for a very limited region of the fluid flow demand, it may be desirable to keep using a preferably slightly longer actuation sequence, which conforms to the lengths of the actuation sequences of the rest of the region of fluid flow demand. Hence, the amount of transition between different actuation sequences and/or different lengths of actuation sequences can be reduced.

[0019] A preferred embodiment of the suggested method can be achieved, if at least one filtering function for said fluid flow demand and/or said mechanical power demand is applied at least in part and/or at least at times. In particular, a hysteresis function, a peak filtering function and/or a derivative consideration function can be used. This way, unnecessary transitions between different actuation sequences can be largely avoided. This way, particularly numerical artefacts in the output behaviour of the fluid working machine can be avoided. By way of example, if the fluid flow demand is increased from 35% to 36%, the fluid output flow will consequently be increased to 36% as well (the given numbers indicate the fraction of the maximum pumping capability of the respective working chamber and/or of the fluid working machine). If the fluid flow demand drops to 35% again, the fluid output flow will be kept on 36%, by virtue of the hysteresis function. Only when the fluid flow demand will drop to 34% (or even lower), the actuation sequence will be changed according to the changing fluid flow demand. The peak filtering function can be set up in a way that not only "positive" peaks are filtered out (i.e. a sudden and very short increase in fluid flow demand), but also "negative" peaks are filtered out. Furthermore, said derivative consideration function can take into account the "size" of the change in fluid flow demand. For example, if an operator quickly increases and/or decreases the speed of a hydraulic consumer, said derivative consideration function can stress this increase and/or a decrease even more. For a more detailed example: if the operator is performing an emergency stop, this can be noted by a sudden decrease in fluid flow demand for the respective hydraulic consumer. The derivative consideration function can then decrease the fluid flow output even more, resulting in an even faster emergency stop. Although the gain in time will usually be only fractions of a second, these fractions of a second can be deciding in

such a situation.

[0020] It is possible to perform the method in a way that an actuation of said electrically actuated valve is at least in part and/or at least at times limited to at least one allowed actuation range, preferably to a plurality of allowed actuation ranges. It has been found that for part stroke pulses at or around 50%, the speed of the fluid leaving the working chamber of the fluid working machine can be very high, because of the usually sinusoidal shape of the volume change of the working chamber. If the electrically actuated inlet valve is closed in this region (to initiate a part stroke pumping cycle of approximately 50% pumping fraction, for example), the actuation of the actuated valve can result in the generation of noise and/or in a higher wear of the valve. Therefore, it is preferred to exclude such fractional values. The "forbidden" interval can start at 16.7%, 20%, 25%, 30%, 33.3%, 40% and/or 45% and can end at 55%, 60%, 65%, 66.7%, 70%, 75%, 80% and/or 86.1%. In particular, the limits of the "forbidden" interval can be changed in dependence of external parameters, in particular in dependence of the speed of the fluid working machine. This way, the "forbidden" interval can at least in part and/or at least at times be defined using the speed of the fluid flowing through the respective actuated valve.

[0021] Preferably, at least one of said allowed actuation ranges is taken from the group, comprising zero stroke pulses, small part stroke pulses, large part stroke pulses and/or full stroke pulses. Usually, zero stroke pulses have a pumping fraction of zero. Small part stroke passes are usually chosen from an interval with the lower end at 0%, 1%, 2%, 3%, 4% and/or 5% and the upper end at the already mentioned 16.7%, 20%, 25%, 30%, 33.3%, 40% and/or 45% (presumably taking into account external parameters). The lower limit of the small part stroke pulses - if present - can come from compressibility effects of the fluid used. Of course, the exact numbers can depend on the nature and condition of the fluid. The indicated values are typical for liquids, in particular hydraulic oil. Large part stroke pulses can be chosen from an interval starting at the already mentioned 55%, 60%, 65%, 66.7%, 70%, 75%, 80% and/or 86.1% (presumably varying with external parameters) and can go up to 100% (or almost 100%). Full stroke pulses are usually chosen from the 100% range.

[0022] Preferably, said allowed actuation ranges, in particular said small part stroke pulses and/or said large part stroke pulses depend at least in part and/or at least at times on at least one working condition of said fluid working machine, in particular on the viscosity of the fluid and/or on the pressure of the fluid and/or on the temperature of the fluid and/or on the speed of said fluid working machine. As already mentioned, a high speed of the fluid, flowing through the actuated valve, can lead to the generation of unnecessary noise and/or to an increased wear of the actuated valve. The same can apply to highly viscous fluids, because such fluids can generate high frictional forces. This, of course, is not desired.

[0023] Preferably, the method is performed in a way that at least in part and/or at least at times said actuation sequence comprises zero stroke pulses, full stroke pulses and part stroke pulses. Experiments have shown that a mixture of all three types of pumping pulses (or of even more types) can lead to a particularly advantageous fluid output flow characteristics. In particular, the part stroke pulses can be small part stroke pulses and/or large part stroke pulses.

[0024] Experiments have shown that a particularly advantageous fluid output flow characteristics can be achieved, if within said actuation sequence, at least in part and/or at least at times pulses of a larger size, in particular large part stroke pulses and/or full stroke pulses are preferred. As an example, instead of performing several zero stroke pulses and/or small part stroke pulses, these pulses (or at least some of them) should be combined to one or a few large stroke pulses and/or full stroke pulses, whenever this is possible. Pulses of a larger size are usually defined as pulses having a pumping fraction of at least 40%, 45%, 50%, 55% and/or 60%. Of course, it is also possible that said pulses of a larger size are large part stroke pulses and/or full stroke pulses.

[0025] Furthermore, it is preferred that within said actuation sequence at least in part and/or at least at times pulses of a smaller size, in particular zero stroke pulses and/or a small part stroke pulses, are used for replacing at least one pulse of a larger size. Under different working conditions, it can prove to be advantageous to split one or several pulses of a larger size into several zero stroke pulses and/or small part stroke pulses, for generating an advantageous fluid output flow characteristics. This "splitting up" of pulses of a larger size can preferably be performed, if otherwise the length of the actuation sequence would become too long and/or an actuation sequence, generating the demanded fluid output flow would not be possible at all.

[0026] A particularly smooth fluid flow output characteristics can be achieved if the actuations within said actuation sequence are arranged at least in part and/or at least at times in a way that pulses of a smaller size, in particular zero stroke pulses and/or small part stroke pulses, precede pulses of larger size, in particular large part stroke pulses and/or full stroke pulses. Experiments have shown that by placing pulses of smaller size in the "leading gap" of pulses of larger size usually a very smooth fluid output flow characteristics can be generated. Pulses of a smaller size are usually pulses with a pumping fraction of up to 40%, 45%, 50%, 55%, 55% and/or 60% (and can have a lower end as well, if necessary).

[0027] Yet another embodiment can be achieved if the actuations within said actuation sequence are at least in part and/or at least at times arranged in a way that within subgroups of pulses of a larger size, in particular within subgroups of large part stroke pulses and/or full stroke pulses, pulses with a larger size precede pulses with a smaller size. Experiments have shown that this way of

arranging the actuation sequence can lead to a particularly smooth fluid output flow characteristics as well.

[0028] Furthermore, it is possible that the actuations within said actuation sequence are at least in part and/or at least at times arranged in a way that within subgroups of pulses of smaller size, in particular within subgroups of zero stroke pulses and/or small part stroke pulses, pulses with a larger size precede pulses with a smaller size. Once again, this can lead to particularly smooth fluid output flow characteristics as well.

[0029] Another preferred embodiment can be achieved if the actuations within said actuation sequence are arranged at least in part and/or at least at times in a way that pulses of a smaller size, in particular zero stroke pulses and/or small part stroke pulses, and pulses of a larger size, in particular large part stroke pulses and/or full stroke pulses, are distributed over said actuation sequence. This again can lead to a very smooth fluid output flow characteristics. In particular, pulses of a smaller size can be placed in the leading "gaps" of the pulses of a larger size and/or between two pulses of a larger size, which are spaced apart from each other.

[0030] Furthermore an electronic controller unit for the actuation of a fluid working machine, comprising at least one actuated valve, is suggested, wherein said electronic controller unit is designed and arranged in a way that said electronic controller unit actuates said at least one electrically actuated valve at least in part and/or at least at times according to the previously suggested method. This way fluid working machines, comprising such an electronic controller unit, can show the previously described features and advantages in analogy.

[0031] Furthermore a fluid working machine, comprising at least one working chamber of cyclically changing volume, a high-pressure fluid connection, a low pressure fluid connection, at least one electrically actuated valve, connecting said working chamber to said high pressure fluid connection and/or said low pressure fluid connection and at least one electronic controller unit, is suggested, wherein said electronic controller unit is designed and arranged in a way that said electronic controller unit actuates at least one of said electrically actuated valves at least in part and/or at least at times according to the previously described method. This way, the resulting fluid working machine can show the previously described features and embodiments in analogy.

[0032] For understanding the previously given explanations, it is important to understand that usually a "rotation" of the single actuations within an actuation sequence will not change the fluid output flow characteristics of the respective actuation sequence. Therefore, usually all "rotations" of an actuation sequence have to be considered to be equivalent to each other. As an example, an actuation sequence (A-B-C-D) is usually equivalent to an actuation sequence (B-C-D-A), to an actuation sequence (C-D-A-B), and to an actuation sequence (D-A-B-C). This equivalency can be particularly understood, when considering that usually the fluid flow

demand will not change for relatively long time intervals within typical applications. The respective actuation sequence will therefore usually be repeated for numerous times.

[0033] Furthermore, when talking about actuations to be performed, the actuations usually refer to the phase, in which the respective actuation cycle performs an "active" fluid flow, leaving the working chamber towards the high-pressure side of the fluid working machine (in case of a pump) and/or performs useful work (in the case of a hydraulic motor). Of course, different definitions are possible as well. For example, the actuation could correspond to the beginning of the contraction phase of the respective working chamber.

[0034] Further advantages, features, and objects of the invention will be apparent from the following detailed description of the invention in conjunction with the associated drawings, wherein the drawings show:

Fig. 1: shows a schematic diagram of a synthetically commutated hydraulic pump with six cylinders;

Fig. 2: illustrates the part stroke pumping concept;

Fig. 3: illustrates, how an output fluid flow is generated by the individual output flow of several cylinders;

Fig. 4: a flow chart, illustrating a possible embodiment of an algorithm for the calculation of an actuation sequence.

[0035] In Fig. 1, an example of a synthetically commutated hydraulic pump 1, with one bank 2, having six cylinders 3 is shown. Each cylinder has a working space 4 of a cyclically changing volume. The working spaces 4 are essentially defined by a cylinder part 5 and a piston 6. A spring 7 pushes the cylinder part 5 and the piston 6 apart from each other. The pistons 6 are supported by the eccentrics 8, which are attached off-centre of the rotating axis of the same rotatable shaft 9. In the case of a conventional radial piston pump ("wedding-cake" type pump), multiple pistons 6 can also share the same eccentric 8. The orbiting movement of the eccentrics 8 causes the pistons 6 to reciprocally move in and out of their respective cylinder parts 5. By this movement of the pistons 6 within their respective cylinder parts 5, the volume of the working spaces 4 is cyclically changing.

[0036] In the example shown in Fig. 1, the synthetically commutated hydraulic pump 1 is of a type with electrically actuated inlet valves 10 and electrically actuated outlet valves 11. Both inlet valves 10 and outlet valves 11 are fluidly connected to the working chambers 4 of the cylinders 3 on one side. On their other side, the valves are fluidly connected to a low pressure fluid manifold 18 and a high pressure fluid manifold 19, respectively. The actuations of the inlet valves 10 are controlled by an electronic controller 16, for example by a printed circuit board

computer. The electronic controller 16 receives input signals from one or several sensors 17.

[0037] Because the synthetically commutated hydraulic pump 1 comprises electrically actuated outlet valves 11, it can also be used as a hydraulic motor. Of course, the valves, which are inlet valves during the pumping mode, will become outlet valves during the motoring mode and vice-versa.

[0038] Of course, the design could be different from the example shown in Fig. 1, as well. For example, several banks of cylinders could be provided for. It's also possible that one or several banks 2 show a different number of cylinders, for example four, five, seven and eight cylinders. Although in the example shown in Fig. 1, the cylinders 3 are equally spaced within a full revolution of the rotatable shaft 9, i. e. 60° out of phase from each other, the cylinders 3 could be spaced unevenly, as well. Another possible modification is achieved, if the number of cylinders in different banks 2 of the synthetically commutated hydraulic pump 1 differ from each other. For example, one bank 2 might comprise six cylinders 3, while a second bank 2 of the synthetically commutated hydraulic pump 1 comprises just three cylinders 3. Furthermore, different cylinders can show different displacements. For example, the cylinders of one bank could show a higher displacement, as compared to the displacement of the cylinders of another bank.

[0039] Of course, not only piston and cylinder pumps are possible. Instead, other types of pumps can take advantage of the invention as well.

[0040] In Fig. 2 the fluid output flow 12 of a single cylinder 3 is illustrated. In Fig. 2, a tick on the abscissa indicates a turning angle of 30° of the rotatable shaft 9. At 0° (and of course at 360° , 720° and so on) the working chamber 4 of the respective cylinder 3 starts to decrease in volume. In the beginning, the electrically actuated inlet valve 10 remains in its open position. Therefore, the fluid, being forced outwards of the working chamber 4 will leave the cylinder 3 through the still open inlet valve 10 towards the low pressure fluid manifold. Therefore, in time interval I, a "passive pumping" is done, i.e. the fluid, entering and leaving the working chamber 4 is simply moved back to the low pressure fluid manifold 18 and no effective pumping towards the high pressure side of the hydraulic pump 1 is performed. In the example shown in Fig. 2, the firing angle 13 is chosen to be at 120° rotation angle of the rotatable shaft 9 (and likewise 480° , 840° , etc.). At firing angle 13, the electrically commutated valve 10 is closed by an appropriate signal. Therefore, the remaining fluid in working chamber 4 cannot leave the cylinder 3 via the inlet valve 10 anymore. Therefore, pressure builds up, which will eventually open the outlet valve 11 and push the fluid towards the high pressure manifold. Therefore, time interval II can be expressed as an "active pumping" interval, i.e., the hydraulic fluid leaving the working chamber 4 will leave the cylinder 3 towards the high pressure fluid manifold. Hence, effective pumping is performed by the hydraulic pump 1. Once the piston 6 has reached its

top dead center (or slightly afterwards) at 180° (540° , 900° etc.), outlet valve 11 will close automatically under the force of the closing spring, and inlet valve 10 will be opened by the underpressure, created in the working chamber 4, when the piston 6 moves downwards. Now the expanding working chamber 4 will suck in hydraulic fluid via inlet valve 10. In the example of Fig. 2, an effective pumping of 25 % of the available volume of working chamber 4 is performed.

[0041] Fig. 3 illustrates how a series of single pulses 15 of different volume fractions (including full stroke cycles and idle stroke cycles) can be combined to generate a certain total output flow 14. By choosing an actuation sequence, wherein the number of pumping cycles as well as the pumping volume fraction of each individual pumping stroke 15 can be varied, an unlimited number of output fluid flow rates can be achieved on the time average. The total fluid output flow 14 of Fig. 3 is not necessarily of a shape that is likely to be used as an actuation sequence for real applications. However, it is a good example, on how the fluid output flow 15 of individual cylinders sums up to the total fluid output flow of the hydraulic pump.

[0042] In Fig. 4, a flowchart 32 is shown, illustrating an embodiment of the algorithm for generating an actuation sequence for actuating the fluid inlet valves 10 (and the fluid outlet valves 11 as well, if applicable) of the synthetically commutated hydraulic pump 1. The algorithm can be implemented as a software program in an electronic controller 16 of the synthetically commutated hydraulic pump 1. The electronic controller 16 can be a printed circuit board computer or the like.

[0043] The algorithm, shown in the flowchart 32 of Fig. 4 starts at the starting point 30. The algorithm is initiated as soon as in starting step 30 it is noticed that a change in fluid flow demand has occurred. The information about the actual fluid flow demand comes from an input unit 34. The input unit 34 can be, for example, a sensor, which is connected to a control lever or the like. The (unmodified) input value from the input unit 34 is first modified by a filtering unit 33, which applies a hysteresis function, as well as a short peak filtering function on the incoming data. This modified data is used in starting step 30 for checking, whether a change in fluid flow demand has occurred.

[0044] Once the algorithm has started, first of all, the accumulator variable is updated 35, i.e. the previous value of the accumulator variable is increased by the current fluid flow demand. The fluid flow demand is interrogated from the same source as described above, i.e. from an input unit 34, whose data is modified by a filtering unit 33.

[0045] Once the accumulator variable has been updated in step 35, it is checked in step 20, whether the updated accumulator is larger than or equal to a certain minimum decision value. Usually, this minimum decision value is the lower limit of pumping strokes of a larger size and/or the lower limit of the large part stroke pulses. In other words, the minimum decision value can be the upper value of the "forbidden" interval.

[0046] If the accumulator value is larger than or equal to the minimum decision value, then a variable, indicating the number of pulses of a larger size within the actuation pattern to be calculated is incremented in step 21. Furthermore, the accumulator value is decreased by the minimum decision value in step 21.

[0047] If, however, the accumulator value is smaller than the minimum decision value, a variable, indicating the number of pulses of smaller size is incremented in step 22, while the accumulator remains unmodified.

[0048] Now, in step 23, a check is performed, whether there exists an actuation sequence, having the actual provisional sequence length, and which satisfies the accumulator totally. For this, it is checked whether the accumulator can be satisfied by one or several of the following modifications to the previously determined provisional actuation sequence: a) one or several of the zero stroke pulses are expanded to pulses of a smaller size (e.g. small part stroke pulses); b) pulses of a larger size (e.g. large part stroke pulses) are expanded by increasing the respective pumping fraction and c) pulses of a larger size (e.g. large part stroke pulses) are reduced in size (without reducing them into the "forbidden" interval; however a reduction to a pulse of a smaller size is possible) and steps a) and/or b) are performed additionally.

[0049] If it is found that no actuation sequence of the actual length exists which fulfils the actual fluid flow demand, the algorithm jumps directly to step 26, where the length of the provisional actuation sequence is incremented.

[0050] If, however, the check 23 yields a positive result, a rearrangement sequence 24 is performed. In this rearrangement sequence, pulses of a smaller size are arranged in front of pulses of a larger size. Within the respective subgroups of pulses with a larger size and/or pulses with a smaller size, the respective pulses are arranged in order of decreasing value. After this rearrangement procedure 24 has been performed, the length of the actuation sequence is incremented in step 26 as well.

[0051] In step 27, a check is performed, whether the accumulator indeed has a value of zero. If this is not the case, the algorithm jumps back to step 35, where the accumulator value 35 is updated by the current fluid flow demand.

[0052] If, however, the accumulator value is zero, the correct actuation sequence has been found. This actuation sequence is commanded 29 to the electronic controller 16, and the respective actuated valves 10 are actuated accordingly. The calculation algorithm has been finished and stops at 31. Now the algorithm rests in hibernation, until in starting step 30 it is noticed that the (modified) fluid flow demand has changed. If such a change is noticed, the algorithm starts again at starting point 35.

[0053] The previously calculated actuation sequence that has been commanded 29 to the electronic controller 16 will be stored in a buffer within the electronic controller 16. Therefore, the actuation sequence will be repeated

over and over again, until a new (modified) actuation sequence is commanded 29 to the electronic controller 16. In case the fluid flow demand has changed and the calculation of the new actuation sequence is underway, but not yet finished when the actually performed actuation sequence (as stored in the buffer) is completed, the actual actuation sequence (as stored in the buffer) is repeated once again.

[0054] By way of example, in the following two explicit examples are given. both examples are given with respect to the synthetically commutated hydraulic pump 1, as shown in Fig. 1.

[0055] For the first example, the "forbidden" interval is chosen to be 5% to 95%. In other words, only pumping strokes with a pumping fraction between 0% and 5% and between 95% and 100% are allowed. The fluid flow demand is chosen to be 74% in this example.

[0056] In the first iteration (iteration 0), the accumulator is updated to 74%. This value is smaller than the minimum decision value of 95% (in this example). Hence, the number of pulses with a smaller size is incremented and reads "1". The accumulator remains to be 74% and the provisional sequence reads "0". Hence, another iteration will be performed.

[0057] In iteration 1, the accumulator is updated to $74\% + 74\% = 148\%$. Now the accumulator is larger than the minimum decision value of 95%. Therefore, the number of pulses with a larger size within the actuation sequence is increased by one. Furthermore, the accumulator is modified to $148\% - 95\% = 53\%$ in step 21. The provisional sequence now reads (0;95). This provisional sequence cannot be modified by backward correction so that the remaining accumulator will be 0. Hence, another iteration will be performed.

[0058] In the next iteration 2, the accumulator is updated to $53\% + 74\% = 127\%$. Again, this value is above the minimum decision value of 95%. The number of pulses with a larger size and the length of the actuation sequence is increased by one again, and the accumulator is modified to $127\% - 95\% = 32\%$. The provisional sequence now reads (0;95;95). Again, this provisional sequence cannot be modified by backward correction so that the remaining accumulator will be 0. Hence, another iteration will be performed.

[0059] In iteration 3, the accumulator is updated to $32\% + 74\% = 106\%$. Again, the number of pulses with a larger size is incremented and the accumulator is modified to be $106\% - 95\% = 11\%$. The provisional actuation pattern now reads (0;95;95;95). Finally, backward correction is possible. In other words, the remaining accumulator value of 11 % can be dispensed with by updating actuation pulses within the (previous) provisional actuation sequence. The rule for getting the best values is to place the pulses with a smaller size (i.e. the zero stroke pulse) in front of the pulses with a larger size (i.e. the pulses with more than 95%). Within the subgroup of pulses with a larger size, the pulses are preferably arranged in decreasing order. Furthermore, it is preferred to modify

(enlarge) pulses of a larger size instead of pulses with a smaller size. Therefore, the final sequence will eventually read (0;100;100;96). The actuation sequences (100;100;96;0), (100;96;0;100) and (96;0;100;100) are equivalent to the actuation sequence (0;100;100;96).

[0060] Now, a second example will be presented. For the second example, three different ranges of pumping strokes are allowed: zero stroke pulses (pumping fraction of 0%), small part stroke pulses (with a pumping fraction between 5% and 20%, including the limits) and large part stroke pulses (with a pumping fraction between 80% and 100%, including the limits). The fluid flow demand is chosen to be 67% in this example.

[0061] In the first iteration (iteration 0), the accumulator is updated to 67%. This value is smaller than the minimum decision value of 80% (according to this example). Hence, the number of pulses with a smaller size is incremented and reads "1". The accumulator remains to be 67% and the provisional sequence reads "0".

[0062] In iteration 1, the accumulator is updated to $67\%+67\%=134\%$. Now the accumulator is larger than the minimum decision value of 80%. Therefore, the number of pulses with a larger size within the actuation pattern this increased by one. Furthermore, the accumulator is modified to $134\%-80\%=54\%$ in step 21. The provisional sequence now reads (0;80). This provisional sequence cannot be modified by backward correction so that the remaining accumulator will be 0. Hence, another iteration will be performed.

[0063] In the next iteration 2, the accumulator is updated to $54\%+67\%=121\%$. Again, this value is above the minimum decision value of 80%. The number of pulses with a larger size and the length of the actuation sequence is increased by one again, and the accumulator is modified to $121\%-80\%=41\%$. The provisional sequence now reads (0;80;80). Now the provisional sequence can already be modified by backward correction in a way that the remaining accumulator will be 0.

[0064] Applying the usual rules (placing pulses with a smaller size in front of the pulses with a larger size; arranging the single actuations within the respective subgroup in decreasing order; preferably modifying (enlarging) pulses of a larger size instead of pulses with a smaller size), the final sequence will eventually read (20;100;81). Of course, the actuation sequences (100;81;20) and (81;20;100) are equivalent to the actuation sequence (20;100;81).

[0065] Additional information can be taken from European patent applications number 07 254 331, 07 254 332, 07 254 333, 07 254 337, all filed on November 1, 2007. The content of said application is fully incorporated into the present application by reference.

Claims

1. Method (32) of operating a fluid working machine (1), comprising at least one working chamber (4) of

cyclically changing volume, a high pressure fluid connection (19), a low pressure fluid connection (18) and at least one electrically actuated valve (10, 11), connecting said working chamber (4) to said high pressure fluid connection (19) and/or said low pressure fluid connection (18), wherein the actuation of said electrically actuated valve (10, 11) is varied depending on the fluid flow demand (34) and/or on the mechanical power demand (34), **characterised in that** for said electrically actuated valves (10, 11), at least in part and/or at least at times an actuation sequence (14), covering a plurality of working cycles (15) of said cyclically changing volume (4), is calculated.

2. Method (32) according to claim 1, **characterised in that** the length of said actuation sequence (14) is minimised.

3. Method (32) according to claim 1 or 2, **characterised in that** at least one filtering function (33) for said fluid flow demand (34) and/or said mechanical power demand (34) is applied at least in part and/or at least at times, in particular a hysteresis function, a peak filtering function and/or a derivative consideration function.

4. Method (32) according to any of the preceding claims, **characterised in that** an actuation of said electrically actuated valves (10, 11) is at least in part and/or at least at times limited to at least one allowed actuation range, preferably to a plurality of allowed actuation ranges.

5. Method (32) according to claim 4, **characterised in that** said at least one of said allowed actuation ranges is taken from the group, comprising zero stroke pulses, small part stroke pulses, large part stroke pulses and/or full stroke pulses.

6. Method (32) according to claim 4 or 5, **characterised in that** at least one of said allowed actuation ranges, in particular said small part stroke pulses and/or said large part stroke pulses depend at least in part and/or at least at times on at least one working condition of said fluid working machine (1), in particular on the viscosity of the fluid and/or on the pressure of the fluid and/or on the temperature of the fluid and/or on the speed of said fluid working machine (1).

7. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 6, **characterised in that** at least in part and/or at least at times said actuation sequence (14) comprises zero stroke pulses, full stroke pulses and part stroke pulses.

8. Method (32) according to any of the preceding

claims, in particular according to any of claims 4 to 7, **characterised in that** within said actuation sequence (14), at least in part and/or at least at times pulses of a larger size, in particular large part stroke pulses and/or full stroke pulses, are preferred.

9. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 8, **characterised in that** within said actuation sequence (14), at least in part and/or at least at times pulses of a smaller size, in particular zero stroke pulses and/or small part stroke pulses, are used for replacing at least one pulse of a larger size.
10. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 9, **characterised in that** the actuations (15) within said actuation sequence (14) are arranged at least in part and/or at least at times in a way that pulses of a smaller size, in particular zero stroke pulses and/or small part stroke pulses, precede pulses of a larger size, in particular large part stroke pulses and/or full stroke pulses.
11. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 10, **characterised in that** the actuations (15) within said actuation sequence (14) are at least in part and/or at least at times arranged in a way that within subgroups of pulses of larger size, in particular within subgroups of large part stroke pulses and/or full stroke pulses, pulses with a larger size precede pulses with a smaller size.
12. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 11, **characterised in that** the actuations (15) within said actuation sequence (14) are at least in part and/or at least at times arranged in a way that within subgroups of pulses of smaller size, in particular within subgroups of zero stroke pulses and/or small part stroke pulses, pulses with a larger size precede pulses with a smaller size.
13. Method (32) according to any of the preceding claims, in particular according to any of claims 4 to 12, **characterised in that** the actuations (15) within said actuation sequence (14) are arranged at least in part and/or at least at times in a way that pulses of a smaller size, in particular zero stroke pulses and/or small part stroke pulses, and pulses of a larger size, in particular large part stroke pulses and/or full stroke pulses, are distributed over said actuation sequence (14).
14. Electronic controller unit (16) for the actuation of a fluid working machine (1), comprising at least one actuated valve (10, 11), **characterised in that** said

electronic controller unit (16) is designed and arranged in a way that the electronic controller unit (16) actuates said at least one electrically actuated valve (10, 11) at least in part and/or at least at times according to the method (32) according to any of claims 1 to 13.

15. Fluid working machine (1), comprising at least one working chamber (4) of cyclically changing volume, a high pressure fluid connection (19), a low pressure fluid connection (18), at least one electrically actuated valve (10, 11), connecting said working chamber (4) to said high pressure fluid connection (19) and/or said low pressure fluid connection (18) and at least one electronic controller unit (16), **characterised in that** said electronic controller unit (16) is designed and arranged in a way that said electronic controller unit (16) actuates at least one of said electrically actuated valves (10, 11) at least in part and/or at least at times according to the method (32) according to any of claims 1 to 13

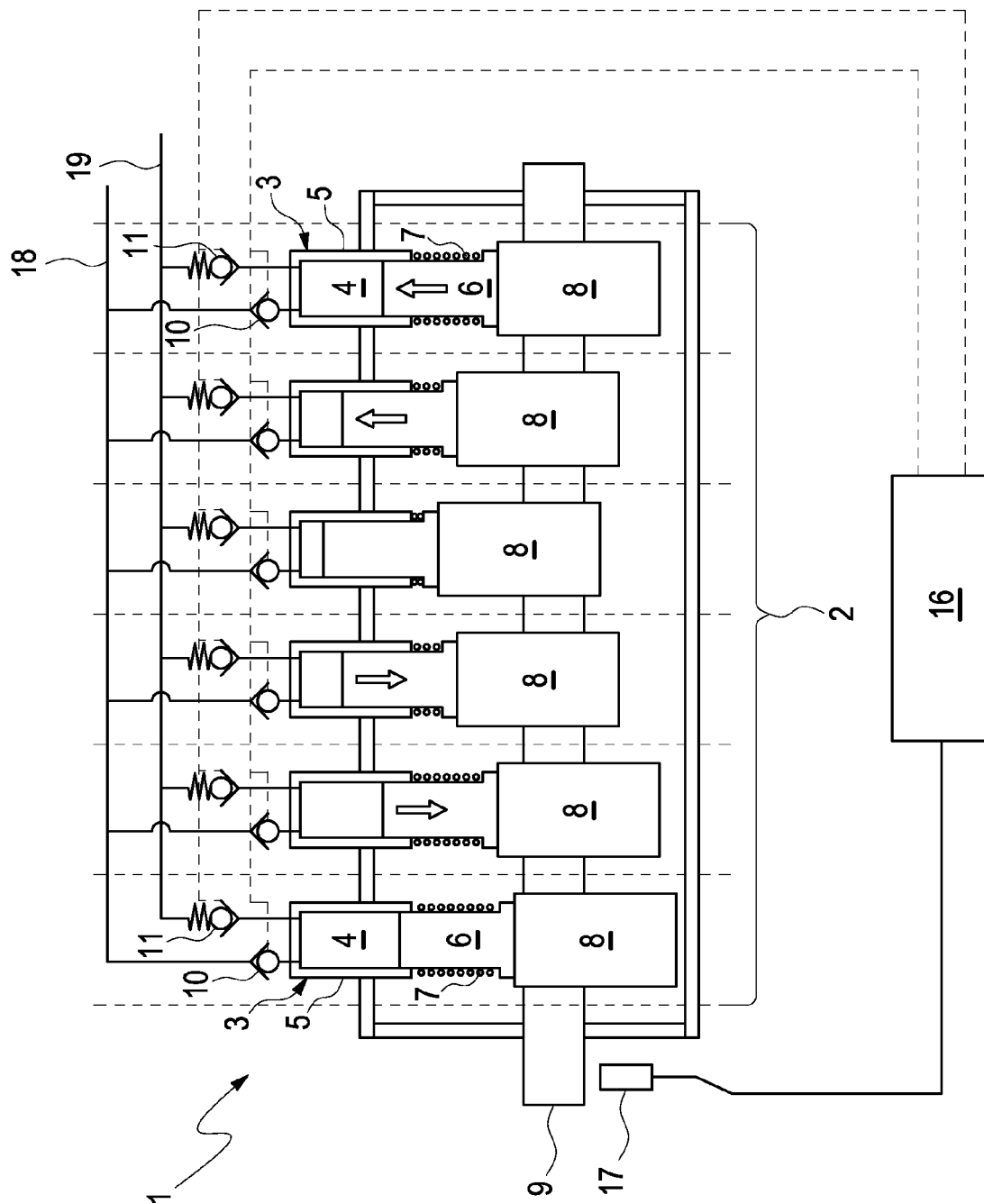


Fig. 1

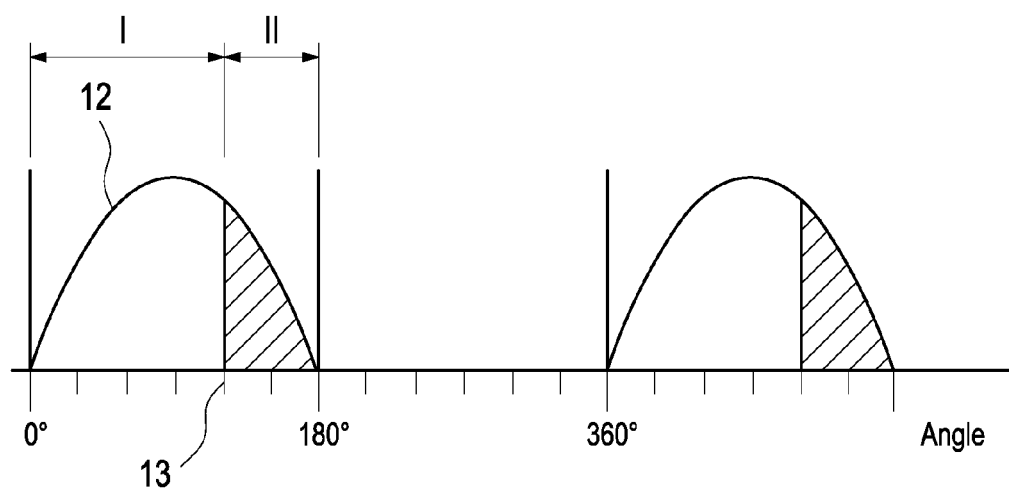


Fig. 2

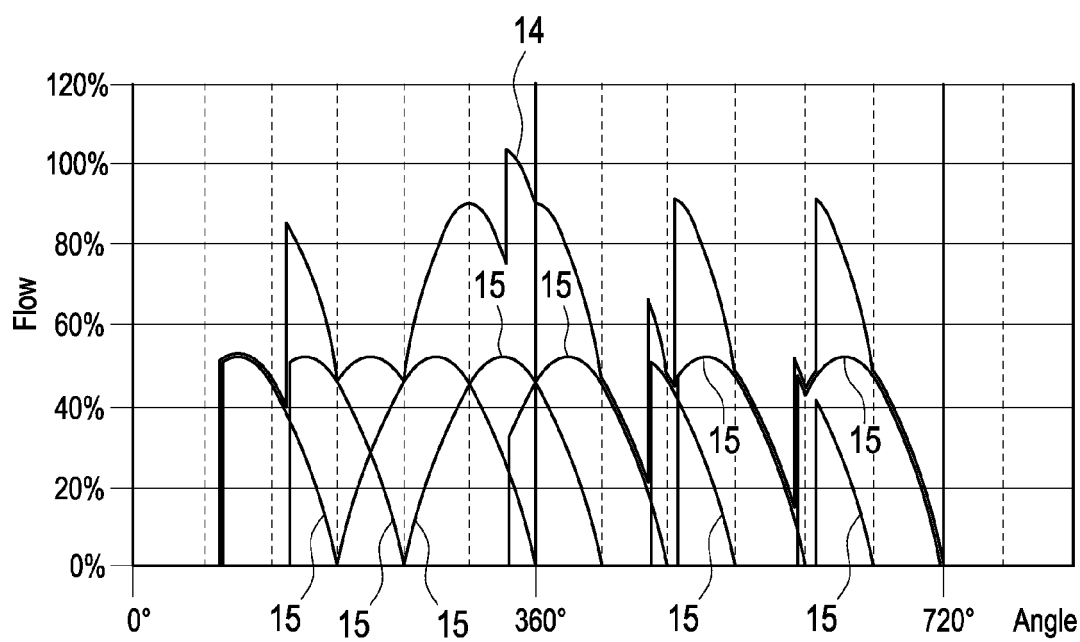


Fig. 3

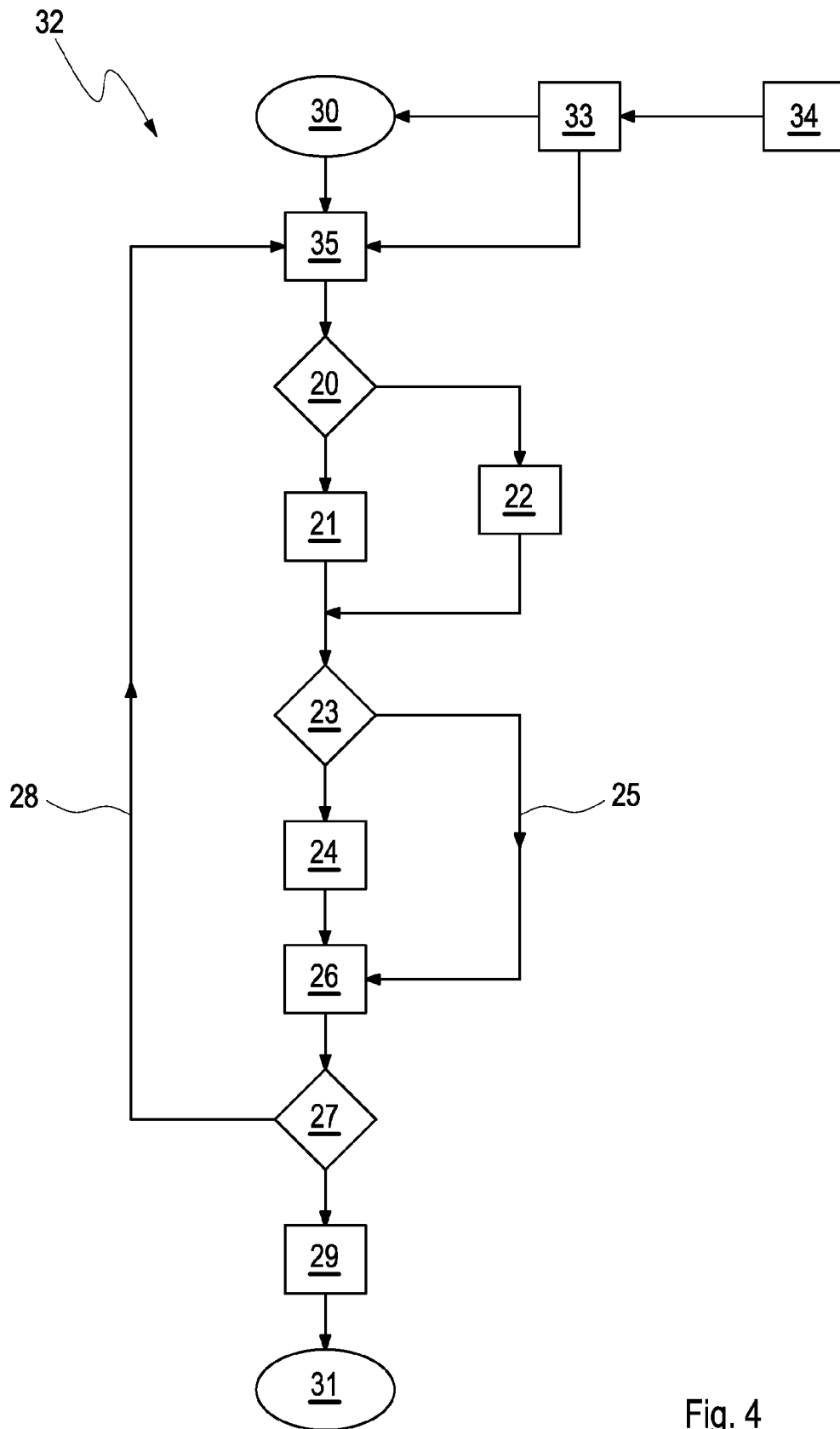


Fig. 4



EUROPEAN SEARCH REPORT

Application Number
EP 09 15 8933

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X,D	EP 1 537 333 B1 (ARTEMIS INTELLIGENT POWER LTD [GB]) 14 June 2006 (2006-06-14) * paragraph [0006] - paragraph [0012] * * paragraph [0039] * * figure 1 *	1-2,4-15	INV. F04B1/14 F04B7/00 F04B49/06 F04B49/22 F04B53/10
A	----- EP 0 494 236 B1 (UNIV EDINBURGH [GB] ARTEMIS INTELLIGENT POWER LTD [GB]) 13 December 1995 (1995-12-13) * column 6, line 43 - column 8, line 26 * * abstract; figures 1-4 *	1-15	
A	----- EP 0 361 927 A1 (UNIVERSITY OF EDINBURGH [GB]) 4 April 1990 (1990-04-04) * column 1, line 54 - column 2, line 30 * * column 5, line 49 - column 7, line 24 *	1-15	
			TECHNICAL FIELDS SEARCHED (IPC)
			F04B
The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
Munich		26 November 2009	Gnächtel, Frank
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 09 15 8933

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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26-11-2009

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 1537333	B1	14-06-2006	AT 330123 T	15-07-2006
			AU 2003263356 A1	30-04-2004
			DE 60306169 T2	31-05-2007
			EP 1537333 A1	08-06-2005
			WO 2004025122 A1	25-03-2004
			JP 2005538299 T	15-12-2005
			US 2006039795 A1	23-02-2006

EP 0494236	B1	13-12-1995	EP 0494236 A1	15-07-1992

EP 0361927	A1	04-04-1990	AU 639213 B2	22-07-1993
			AU 4499089 A	18-04-1990
			AU 641438 B2	23-09-1993
			DE 68917066 D1	01-09-1994
			DE 68917066 T2	19-01-1995
			WO 9003519 A1	05-04-1990
			WO 9105163 A1	18-04-1991
			JP 4501294 T	05-03-1992
			JP 5503335 T	03-06-1993
			NZ 230801 A	25-06-1992
			US 5190446 A	02-03-1993
			US 5259738 A	09-11-1993
			ZA 8907398 A	29-05-1991

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- EP 0494236 B1 **[0006]**
- WO 9105163 A1 **[0006]**
- EP 1537333 B1 **[0011]**
- JP 07254331 A **[0014]**
- EP 07254331 A **[0065]**
- EP 07254332 A **[0065]**
- EP 07254333 A **[0065]**
- EP 07254337 A **[0065]**