(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
06 March 2025 (06.03.2025)

WIPO | PCT

(10) International Publication Number
WO 2025/045326 A1

(51) International Patent Classification:
F03D 7/00 (2006.01) *F03D 17/00* (2016.01)
F03D 1/06 (2006.01)

(21) International Application Number:
PCT/DK2024/050252

(22) International Filing Date:
16 October 2024 (16.10.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PA202370580 20 November 2023 (20.11.2023) DK

(71) Applicant: VESTAS WIND SYSTEMS A/S [DK/DK]; Hedeager 42, 8200 Aarhus N (DK).

(72) Inventor: FERNANDES LIMA, Joao Marcelo; c/o Vestas Wind Systems A/S, Hedeager 42, 8200 Aarhus N (DK).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST,

(54) Title: LEAK DETECTION IN WIND TURBINES

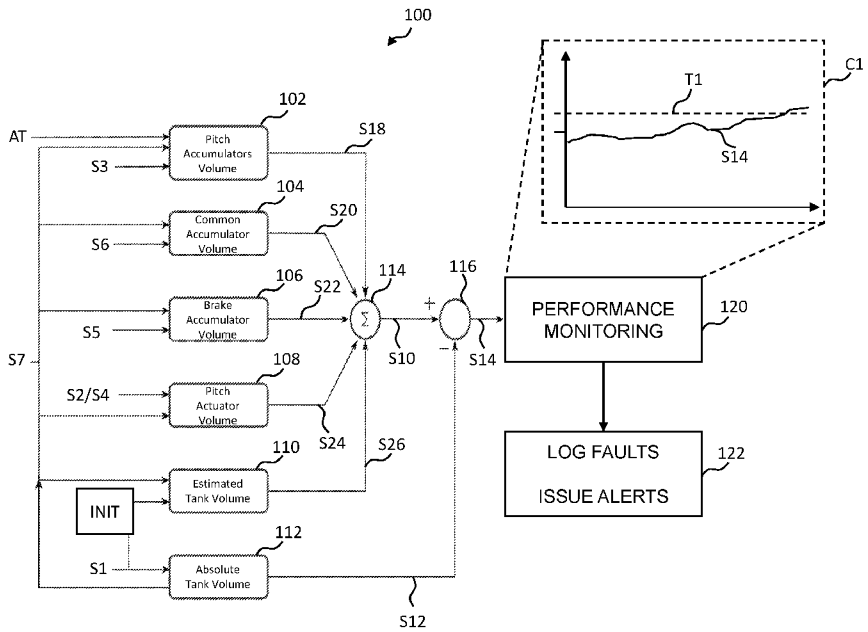

Fig. 3

(57) Abstract: A wind turbine fluid system comprising a fluid tank having a fluid level sensor that provides a tank level signal indicative of the level of fluid in the fluid tank; and a plurality of fluid-using components fluidly coupled to the fluid tank. The fluid system further comprises a processor configured to: determining an actual fluid volume of the fluid tank based at least in part on the tank level signal; using one or more models to generate an estimated fluid volume of the fluid tank based on data relating to the plurality of fluid-using components; comparing the estimated fluid volume of the fluid tank with the determined actual fluid volume of the fluid tank; triggering an alert action in the event that the result of the comparison indicates that a leak is present in the fluid system. The invention also relates to a method of detecting leakage of fluid in a system, a wind turbine comprising such a fluid system, and a computer program product. A benefit of the invention is that it provides a more accurate determination of leakage behaviour in a

WO 2025/045326 A1

[Continued on next page]

SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*
— *upon request of the applicant, before the expiration of the time limit referred to in Article 21(2)(a)*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

fluid system by monitoring the difference between an estimated volume of the fluid, for example hydraulic fluid, in the fluid tank and a measured value of fluid volume in the tank.

LEAK DETECTION IN WIND TURBINES

Technical Field

The invention relates generally to approaches for detecting fluid leaks within wind turbines, for example leaks of lubricating fluid, hydraulic fluid and coolant from associated fluid systems.

Background

Wind turbines are complex electromechanical systems which comprise various components and systems which make use of, or consume, working fluids. For example, typically a wind turbine incorporates a gearbox housed within the wind turbine nacelle which requires a lubricating oil system for efficient operation and a fluid cooling system to guard against excessively raised operating temperatures. Furthermore, it is usual for wind turbines to include a hydraulically actuated blade pitch system.

Leaks can occur wherever such lubricating fluids or hydraulic fluids are used. Typically, leak detection approaches rely on the pooling of fluids in certain locations which can then be detected by a suitable sensor, such as a float sensor. More sophisticated approaches are known, which rely generally on monitoring of stored fluid capacities during operation whereby suitable monitoring algorithms can be used to infer the presence of leaks. However, existing approaches tend to only be effective when relatively large volumes of fluid have leaked, which can be problematic.

A more effective approach to the detection of fluid leaks within a wind turbine is desirable, and it is against this background that the invention has been devised.

Summary of the Invention

Against this background, the invention provides a wind turbine fluid system, comprising a fluid tank having a fluid level sensor that provides a tank level signal indicative of the level of fluid in the fluid tank; and a plurality of fluid-using components fluidly coupled to the fluid tank. The fluid system further comprises a processor configured to: determine an actual fluid volume of the fluid tank based at least in part on the tank level signal; use one or models to generate an estimated fluid volume of the fluid tank based on data relating to the plurality of fluid-using components; compare the estimated fluid volume of the fluid tank with the determined actual fluid volume of the fluid; and trigger an alert action in the event that the result of the comparison indicates that a leak is present in the fluid system.

The invention extends to and therefore embraces a method of detecting leakage of fluid in a system, as defined above. In another aspect, the examples of the invention provide a wind turbine comprising the fluid system as defined above, a computer program product comprising instructions which, when executed in a computer, cause the computer to carry out the steps of the method as defined above, and a computer-readable carrier and/or storage medium comprising the computer program product defined above.

A benefit of the invention is that it provides a more accurate determination of leakage behaviour in a fluid system by monitoring the difference between an estimated volume of the fluid, for example hydraulic fluid, in the fluid tank and a measured value of fluid volume in the tank. The process takes into account many factors that may affect the level of fluid in the tank, such as the operating condition of the wind turbine, ambient temperatures, fluid temperatures and pressures, movement of the wind turbine, so this means that the result of the comparison is highly likely to be attributable to leakage in which case an alert system can be relied upon to highlight leakage issues reliably.

In this discussion, the parameter of fluid tank volume is considered to be indicative of the level of fluid within the tank. Moreover, the measurement of a level of fluid in the tank is also considered indicative of the volume of fluid in the tank. So, the terms ‘level’ and ‘volume’ are considered proxies for one another and conversion between the two parameters is well within the capabilities of the skilled person.

Notably, the approach described here is comparing the measured volume of fluid in the tank compared to an estimated level or volume. This is a more accurate approach than would be achievable by, for example, comparing a measured level of fluid in the tank (or even an estimated volume) with an initial value of fluid which may be calibrated at the installation of the fluid system when the system is filled with fluid. Such an approach is flawed because an initially calibrated value of hydraulic fluid in the tank may be susceptible to change, for example if some fluid-using components are added, removed or replaced. For instance, a hydraulic fluid filter may be changed which would remove hydraulic fluid from the system thereby rendering the initially calibrated value incorrect. The approach described herein may also be more effective than alternative approaches that rely on algorithms that measure the volume of fluid in a hydraulic tank and estimate the volume of fluid circulating within the system, with the aim of monitoring that the total volume of fluid in the system remains constant. In such an approach, there is a risk that failure of the tank level sensor will remove the ability of the system to have any indication of fluid level in the system.

Advantageously, the processor is further configured to generate the estimated fluid tank volume by taking into account the effect of fluid temperature on the volumes of fluid in the plurality of fluid-using components. The processor may further be configured to generate an estimate of the fluid volume variation in the fluid tank that may occur due to changes in temperature. As an enhancement to this, the process may be further configured to generate the fluid volume estimate in the fluid tank by making appropriate adjustments for components such as pumps, filters, pipework, valves and so on that are located inside the tank and immersed at least partly in the fluid. These factors ensure that the estimated fluid volumes provide an accurate evaluation of the volume of fluid within the system which results in a more reliable identification of leaks.

In triggering the alert action, the processor may be configured to compare the first and second parameter values against a predetermined threshold and trigger the alert action if the difference between the estimated tank volume and the actual tank volume exceeds the predetermined threshold. Other analysis approaches may be used to provide further data relating to the rate of leakage and the severity of the leakage. In some examples, the system may be configured to monitor the rate of change of the difference value and compare the rate of change against one or more predetermined thresholds that are indicative of certain leakage conditions. Useful, monitoring rate of change of the difference value instead of or in addition to simple threshold values provides a more powerful set of data to diagnose leakage conditions. Further, monitoring how the rate of change in the difference values behaves over certain predetermined time period provides further advantages in data analysis and problem diagnosis.

Further optional and advantageous features are referenced in the detailed description and the appended claims.

Brief Description of the Drawings

Figure 1 is a schematic view of a wind turbine including a leak detection system;

Figure 2 is a schematic view of a fluid system of the wind turbine;

Figure 3 is a block diagram illustrating an example algorithm for detecting a leak in the fluid system shown in Figure 2.

Detailed Description

With reference to Figure 1, a wind turbine 2 includes a tower 4 on which a nacelle 6 is mounted. A yaw system may be included to allow the nacelle 6 to yaw with respect to the tower 4 although such a yaw system is not shown in Figure 1 for brevity. The nacelle 6 rotatably supports a rotor 8. The rotor includes a rotor hub 10 to which a set of rotor blades 12 are attached. It will be apparent that the wind turbine 2 of Figure 1 is a horizontal-axis wind turbine, as is generally known in the art. Other types of which turbines are also known, and the invention applies also to these other types of wind turbines.

As is conventional, the rotor hub 10 is a three-bladed design, although any number of blades is possible, in principle.

Figure 1 is a schematic view and, as such, provides a general system overview of components associated with the wind turbine 2 that may be relevant to the examples of the invention that will be described here.

In overview, the rotor hub 10 is attached to a main rotor shaft 14 which rotates together with the rotor hub 10. The main rotor shaft 14 provides a low-speed input to a gearbox 16. The gearbox 16 gears up the rotational speed of the main rotor shaft 14 to a high speed output shaft which constitutes a generator drive shaft 18. The generator drive shaft 18 drives a generator 20 which converts the mechanical energy of the generator drive shaft 18 to electrical energy, which is generally known in the art. Note that some wind turbine configurations are with medium speed generators and some others do not include a gearbox and are known as ‘direct drive’ machines.

A power converter system 22 is coupled to an electrical output 24 of the generator 20. The power converter system 22 converts the AC input power from the generator 20 to a suitable output power format, as required. Typically, the output power of the converter will be three-phase AC at a selectable voltage, phase and frequency. However, the power converter 22 may also output DC power. Power is exported from the wind turbine 2 by a down conductor 25.

It should be appreciated that the wind turbine components described here have been simplified for the sake of brevity and that, in practice, a wind turbine is a complex piece of machinery which would include many other components and subsystems. However, a full discussion is not crucial for understanding the principle of the invention and so a deeper discussion will not be provided.

In addition to the main components discussed above which are concerned directly with the conversion of mechanical torque to electrical power, there are other components and systems that support operation of the wind turbine 2. One such system is a fluid system 26, which is illustrated schematically in Figure 1, and in more detail in the Figures that follow.

The fluid system 26 has the function of generating a supply of pressurised hydraulic fluid for operating various fluid sub-systems of the wind turbine 2, as would be understood by the skilled person. Figure 2 shows schematically the fluid system 26 and its associated sub-systems to which it supplies hydraulic fluid. At this point it should be noted that the fluid system 26 in this example is a hydraulic system which uses hydraulic fluid such as oil. However, this discussion also applies to fluid systems other than hydraulic system, such as cooling systems and lubrication systems, both of which use fluid and liquids. From now on, however the fluid system 26 will be discussed as being in the context of a hydraulic system.

With reference to Figure 2, in overview the hydraulic system 26 comprises a hydraulic power unit (HPU) 28 and a plurality of hydraulic fluid-using components 32. The HPU 28 includes a hydraulic fluid tank 34 provided with a hydraulic pump 36 . A common configuration is for the hydraulic pump 36 to be located within the hydraulic fluid tank 34 although other configurations are possible in which a hydraulic pump 36 is located outside of the internal tank volume. Other hydraulic components may also be located within the fluid tank, such as common accumulators and valves.

The hydraulic pump 36 is connected to a fluid circuit 38 which conveys hydraulic fluid from the fluid tank 34 to the fluid-consuming components 32 by way of a supply line 40. A return line 42 conveys hydraulic fluid from the fluid-consuming components 32 back to the hydraulic tank 34.

The plurality of fluid-using components 32 are shown as comprising four separate components or sub-systems in Figure 2, by way of example only. It should be noted that in a practical implementation there may be more fluid-using components than are presented here. At this point, it should be understood that the ‘fluid-using’ components make use of a functional fluid e.g. hydraulic fluid such as oil to perform useful work within the broader wind turbine system.

In overview, the plurality of fluid-consuming components 32 or systems comprise a pitch actuator system 44, a brake system 46, a hydraulic motor 48 and a hydraulic pump 50. The reader will appreciate these components or systems are provided by way of non-limiting example.

The pitch actuator system 44 also includes a hydraulic accumulator 52 and a proportional valve 54 for the purposes of controlling the pitch actuator system 44. As would be known to the skilled person, the pitch actuator system 44 comprises a hydraulic actuator (not shown). Other wind turbine systems may also include hydraulic actuators and so may be part of the plurality of fluid-consuming components 32.

The brake system 46 also include an associated accumulator 56 for the purposes of providing a supply of pressurised fluid to the brake system 46. Although not shown, the brake system 46 may include one or more hydraulic components such as hydraulically driven pistons. The brake system 46 may further include other components not shown here, such as control units, valves and so on, which are outside the scope of this discussion.

The hydraulic motor 48 may be used in various system of the wind turbine 2 for example as part of a yaw control system, a door system, hoisting systems, rotor turning systems, to name a few examples, as would be understood by a skilled person. Similarly, the hydraulic pump 50 may be an additional pump for supplying hydraulic fluid at a boosted pressure level or higher flow rate compared to the hydraulic pump 36 that is part of the fluid tank 34. The hydraulic pump 50 may be used in other sub-systems of the wind turbine, as would be understood by the skilled person. The hydraulic motor 48 and the hydraulic pump 50 are shown here as being supplied with hydraulic fluid from a common accumulator 59.

Also provided is a leak detection system 60. The leak detection system 60 may be considered to be a suitable processing environment that is equipped with suitable processing and memory capabilities to execute suitable algorithms to perform the functionality that will be described here. For this purpose, the leak detection system 60 comprises a processing environment or, more simply, a ‘processor’ 62 and a memory unit 64.

The processor 62 may be any suitable computing unit that has the required capabilities to execute suitable algorithms at a suitable processing speed. It is considered within the capabilities of a skilled person to specify a processing environment suitable for this task. In this context, it should be noted that the processor 62 may be a dedicated unit providing this functionality, or the functionality may be subsumed within another processing environment within the wind turbine 2 such as a wind turbine control unit, a nacelle control unit and so on.

The leak detection system 60 is also provided with a data interface 65. The data interface 65 is configured to receive signals from a number of sources. As shown in Figure 2, the data interface 65 receives a data signal S1 from the hydraulic fluid tank 34 and, more specifically, from a fluid level sensor 63 provided at the fluid tank 34. The signal S1 thus provides a measure of the level of hydraulic fluid within the fluid tank 34 and may be provided by any suitable fluid level sensor, as would be known in the art. The fluid level sensor 63 provides a high degree of discrimination of the fluid level within the fluid tank 34 and may provide a digital output at a plurality of level values or a continuous analogue output, as are sometimes known as ‘continuous level sensors’. Some examples of suitable fluid level sensing technology include electro-optical sensing technology, ultrasonic sensing technology, and float sensing technology. An example of suitable technology is available commercially from Bühler Technologies GmbH under the ‘Nivovent’ range of products.

The data interface 65 also receives further data input signals S2 to S7 In overview:

S2 provides a signal relating to the displacement of the pitch actuator in the pitch actuator system 44.

S3 provides a signal relating to the pressure of hydraulic fluid within the pitch accumulator 52.

S4 provides a signal relating to the position of the proportional valve 54 associated with the pitch actuator system 44.

S5 provides a signal relating to the pressure of hydraulic fluid in the brake accumulator 56.

S6 provides a signal relating to the pressure of hydraulic fluid in the common accumulator 59 which provides hydraulic fluid to both the hydraulic motor 48 and the hydraulic pump 50.

S7 provides a signal indicative of the temperature of the hydraulic fluid in the fluid tank 34, as generated by a suitable temperature sensor 66.

The signals described above provide an example of the main input signals that may be used by the leakage detection system to detect leakages in the hydraulic system, as will now be discussed in further detail. It should also be appreciated that other signals and data relating to the operation of the wind turbine may also be used in the detection functionality described here.

Having described the main components of the hydraulic system 26, the discussion will now focus on the functionality of the leak detection system 60.

In a broad sense, the leak detection system 60 is configured to implement one or more algorithms, models or other software constructs to monitor operation of the hydraulic system 26 and diagnose a leakage of hydraulic fluid. Such a leakage may have a high or low flow rate, so the leakage detection system 60 has the capability of detecting a wide range of leaks. To this end, the leakage detection system 60 is configured to evaluate the level of fluid within the hydraulic tank and compare this with an estimated fluid level through monitoring of the signals S2 to S7 in order to identify a statistically significant difference, delta or residual value between the measured fluid level and the estimated fluid level. The term ‘fluid level’ may be taken in its broadest sense of being the vertical height of hydraulic fluid within the tank, or, alternatively, the volume of fluid within the tank. Thus, the ‘fluid level’ is indicative of the volume of fluid in the hydraulic tank.

The ‘delta value’ or ‘difference value’ may be monitored over a time period to infer leakage information. The predetermined time period may be customisable, i.e. programmable, based on the types of leakages that are to be assessed. For example, if the delta value exceeds a predetermined threshold, then it may be inferred that an excessive volume of hydraulic fluid has leaked from the system and an appropriate action response can be taken, such as the issuance of a fault flag, or a warning message to a centralised asset management computer system. More sophisticated trend analysis can also be implemented to track the delta value over one or more predetermined time periods to evaluate absolute leakage volumes, leakage rates, and other metrics.

Further discussion about this aspect will now follow with reference to Figure 3, which shows an example implementation of an algorithm or method 100 that may be executed on the processor 62.

The method 100 comprises a plurality of estimator functions 102-110 that are configured to estimate the flow of hydraulic fluid across relevant system boundaries and how the relevant hydraulic subsystem affects the volume of hydraulic fluid tank 34. Further details of the estimator functions 102-110 will be discussed later, although it should be appreciated that the estimator functions implement suitable models of the fluid-using components which they represent. Several of such models are shown in this illustrated example, chiefly for clarity of explanation. However, it should be noted that the functionality of the individual estimator functions/models may be combined into a single more complex estimator function/model.

The method 100 also comprises actual tank volume calculation function 112 that is configured to output a value of the actual volume of hydraulic fluid in the fluid tank 34 based on known tank geometry and the signal S1 from the fluid level sensor 63. The output value from the tank volume calculation function is labelled here as S12.

The outputs of each of the estimator functions 102-110 are summed at summing junction 114 which provides an estimated value S10 of the volume of hydraulic fluid in the fluid tank 34.

The output value S12 of the tank volume calculation function 112 and the estimated tank volume value S10 are compared at summing junction 116. Here, the output value S12 of the tank volume calculation function 112 is subtracted from the estimated tank volume value S10 and thereby provides an output delta value S14, which may also be termed a ‘residual value’ or ‘error value’. The delta value S14 represents the difference or error between the actual measured volume S12 in the fluid tank 34 and the estimated tank volume S10 based on data received by the processor 62 that indicates the performance of the hydraulic system and data related thereto. Therefore, in the event that a leakage exists in the system, the actual tank volume will reduce in magnitude as compared to the estimated tank volume, which means that the delta value S14 will increase in magnitude. This is represented on the chart C1 which provides a visual representation of delta value S14 which is increasing gradually, and non-linearly, over time. It will be appreciated here that the estimator functions 102-110 provide volume estimations of the relevant fluid-using components 38 of the hydraulic system 26 in an operational scenario where no fluid leaks are present.

The discussion will now focus on the estimator functions 102-110. In general, it should be noted that the estimator functions 102-110 serve to take into account the thermal expansion of hydraulic fluid within the associated fluid-using components.

The first estimator function 102 relates to the hydraulic accumulator 52 (or several accumulators) associated with the pitch actuator system 44. The first estimator function 102 has inputs of ambient temperature AT, pitch accumulator pressure S3 and fluid temperature

S7. Ambient temperature is required since hydraulic actuators may be located in relatively cold environments such as in the nose cone of the wind turbine hub, in which case cold temperatures may have an appreciable effect on the gas in the hydraulic accumulator 52. From these values the first estimator function 102 provides an output signal S18 which represents a volumetric change based on the geometry of the hydraulic accumulator 52. It would be within the capabilities of the skilled person to define an appropriate routine to calculate this value based on the thermal expansion coefficient and other related parameters discussed here. On this basis, the estimator function may make use of the Benedict-Web-Rubin equation based on a nitrogen-filled accumulator.

The second estimator function 104 relates to the common accumulator 59. The second estimator function 104 has inputs of the pressure of the hydraulic fluid in the accumulator 59, noted here as S6, and the hydraulic fluid temperature S7. As mentioned above, the second estimator function 104 may make use of the Benedict-Web-Rubin equation. The second estimator function 104 issues an output value S20 which provides a representation a volumetric change of the common accumulator volume 59 based on its geometry and the influencing factors of pressure and temperature.

The third estimator function 106 relates to the brake system 46 and, more specifically, the brake accumulator 56 which outputs pressure signal S5, as discussed above. The third estimator function 106 has inputs of the pressure of the hydraulic fluid in the brake accumulator 56, noted here as S5, and the hydraulic fluid temperature S7. As mentioned above, the third estimator function 106 may make use of the Benedict-Web-Rubin equation as would be understood by the skilled person. The third estimator function 106 issues output S22 which provides a representation a volumetric change of the brake accumulator 56 based on its geometry and the influencing factors of pressure and temperature.

The fourth estimator function 108 relates to the pitch actuator system 44 and receives input signals of pitch actuator displacement, S2, in addition to the hydraulic fluid temperature S7. In this context, the fourth estimator function 108 may calculate the volume of fluid in each side of the actuator cylinder and then calculate the change in fluid volume within the actuator cylinder based on the displacement of the actuator rod (not shown) and taking into account thermal expansion effects of the hydraulic fluid. The fourth estimator function 108 may also receive signal S4 from the proportional valve 54, which would provide further input relating to the estimation of the fluid flow/volume through the pitch actuator and the broader pitch actuator system 44. The fourth estimator function 108 therefore provides an output signal S24 that is indicative of the total change in fluid volume given the actuator displacement and thermal expansion.

The fifth estimator function 110 relates to how the volume of the hydraulic fluid tank 34 varies due to thermal effects. The fifth estimator function 110 receives an initialisation value, labelled here as INIT, of the level of fluid within the hydraulic tank 34 and from this value the fifth estimator function 110 calculates the volume of fluid within the hydraulic tank 34. The initialisation value INIT may only be provided to the fifth estimator function 110 at the time the algorithm is initiated, for example upon start up of the wind turbine system, and may be derived from the signal S1 from the fluid level sensor 63. The fifth estimator function 110 also receives as an input the fluid temperature signal S7. Therefore, from the initialisation value INIT and the fluid temperature signal S7, the fifth estimator function 110 is operable to determine the change in volume of the hydraulic tank 34 by using known thermal expansion equations. As an enhancement, the fifth estimator function 110 may also be configured to factor in further volume changes that are due to the expansion of the hydraulic tank 34 which may affect the reading of the fluid level sensor 63.

To summarise, therefore, the fifth estimator function 110 provides an output value S26 that indicates the volume of hydraulic fluid in the hydraulic tank 34 as it is affected by the thermal expansion of the hydraulic fluid within the tank, but also (optionally) as it is affected by changes in tank geometry.

In view of the above discussion, the skilled person will appreciated that in combination the estimator functions 102-110 provide an accurate value of the volume of hydraulic fluid in the hydraulic tank 34 as it is influenced by thermal expansion effects of the fluid but also geometry changes of the tank (due to the fifth estimator function 110) but also as it may be influenced by changes in fluid volumes within the various fluid-using components 44,46,48,50 (estimator functions 102-108). This provides an accurate determination of what the fluid volume in the hydraulic tank should be in an ideal hydraulic system with no leaks.

As can be seen in the chart C1, the method 100 provides a continuous process which provides the capability to track the generated delta value S14 over time. For this purpose, delta value S14 is input into performance monitoring function 120 that is configured to implement suitable analytical processes to infer leakage characteristics due to the change in the delta value S14 and, in response, to implement appropriate actions such as logging faults within internal memory or associated fault logs and/or issuing alert messages to suitable management system (functional block 122).

It is envisaged that the delta value S14 will have inherent variability due to various factors, such as the motion of the nacelle affecting the fluid level that is picked up by the fluid level sensor 63. Therefore, suitable filtering may be implemented with an appropriate time constant to provide a delta value 14 that changes gradually over time and is not influenced unduly by transient effects. To avoid the signal from the tank level sensor 63 being obscured by normal operation of the wind turbine, different filtering techniques may be appropriate such as low pass filter, time series averaging filters (e.g Gaussian time series averaging filter), peak-to-peak smoothing filter and linear regression filters. Combination of such techniques may also be used, for example a low pass filter combined with a time-series averaging filter.

The performance monitoring function 120 may implement various approaches to detect a leak within the hydraulic system 26. A slow leak somewhere in the hydraulic system 26 will gradually cause the delta value 14 to increase over an extended period of time, for example over a few hours, days or even weeks. Alternatively, a fast leak in the hydraulic system 26 may cause the delta value to change very quickly, in the order of seconds or minutes. This may be the case for example where a valve fails catastrophically. Although such an event is unlikely, it is important to guard against such an event by providing the means to detect such an issue quickly and reliably. A simple threshold approach may be used, which is illustrated in chart C1. Here, a predetermined threshold T1 may be set that represents a value where a volume of hydraulic fluid has leaked from the system such that a suitable remedial action may be required, such as a system fluid top up. More than one threshold may also be used. For example, a first threshold (not shown in C1) may be set which, when triggered, causes a response action which may be the setting of a maintenance entry in the system. This may flag up on a suitable maintenance schedule that a system fluid top up is required, although the action is not urgent. Further thresholds may be set to issue more urgent warnings which may require specific intervention.

In terms of values for the predetermined threshold, it is envisaged that the value may be chosen to give a reliable indication when a leak may be present. For example, the threshold may be set at 2% of the nominal full capacity. So, for a tank capacity of 500 litres, a 2% threshold would represent a leakage of 10 litres. Several thresholds may also be set, so as to alert at different levels. For example a 1% threshold may be set as an advisory alert of a leak, for which action should be scheduled although it is not considered critical. Further thresholds may be set for more severe leak alerts, for example at 2%, 5% and 10% of tank capacity. In general, it is envisaged that the predetermined threshold would be set in the region of 1% to 10% of nominal tank capacity, optionally between 2% and 8%, and more optionally between

2% and 6%, or at least 2%. For a 500 litre tank, therefore, a range of between 5 litres and 50 litres may be appropriate for one or more thresholds. In this context, different thresholds may be configured to identify associated leakage conditions.

In addition to simple thresholds, trend analysis approaches may be used to monitor how the delta value S14 is changing over time. Certain characteristics may then be identified to infer leakage information. For example, gradient analysis may be performed on the data stream of delta value S14 to gain further intelligence about leakage rate. A steep gradient, therefore, will infer a higher leakage rate which may therefore trigger a response action before a predetermined absolute leakage threshold is reached. What is more, once an absolute leakage threshold has been exceeded, analysis may be performed on the gradient of the delta value to infer information about the leakage condition that is present. In this context, an example to consider is where some hydraulic fluid is removed from the fluid tank for some reason, for example due to a filter removal. The delta value may then indicate a step change due to the sudden change in fluid level. However, if there is no leakage then the delta value would be stable, albeit at a significant positive value. Combining analysis of the absolute delta value and information available from the gradient provides a more reliable approach to assessing leakages whilst avoiding false positives.

In terms of values, more than one ‘rate of change’ threshold may be implemented in order to infer information about different leakage conditions or, indeed, leakage severities. For example, as a basic level, it is currently envisaged that a leakage rate of 0.5% per hour, which equates to 3 litres per hour for a 600L tank, would be appropriate to alert to a leakage condition. However, this is considered exemplary, and other values would also be appropriate. Further, larger leakage rates may be indicative of different leakage conditions. For example a leakage rate of in excess of 5% of nominal tank capacity per hour may be considered a severe leak which could be attributable to a failed component such as a hydraulic control valve or hydraulic pipe connector. In general, it is envisaged that a range of values between 0.2% to 5% of tank capacity per hour of gradient or ‘rate of change’ would provide useful options for identifying relevant leakage conditions. As an enhancement to monitoring rate of change values that exceed thresholds, the methodology may be configured to monitor for rate of change values that exceed predetermined thresholds for specific time periods. For instance, if a monitored rate of change value exceeds a predetermined threshold for a short time period, this may be viewed as not a concern in terms of it being a significant leakage case. However, if the same predetermined rate of change threshold is exceeded for a longer time period, then the system may be responsive to issue an appropriate alert action. Note that leak detection system 60 may comprise one or more predetermined rate of change thresholds. Each of these thresholds may be configured to identify a predetermined leakage condition. Further, the one or more predetermined rate of change thresholds may be associated with a respective one or more predetermined time periods. The predetermined rate of change thresholds and the predetermined time periods may be stored in the memory unit 64. As such, the thresholds and time periods may be user configurable to ensure that the leak detection system 60 can be adapted as understanding of the system is improved. Advantageously, therefore, the leak detection system 60 can be adapted over time to adjust the effectiveness and filtering of events that are acting as noise for the system or unwanted perturbations. It is envisaged that leak detection system 60 may also be enhanced with suitable machine learning systems that is trained appropriately to assimilate the sensed data and derive diagnoses of leakage situations.

A benefit of the invention is that it provides a more accurate determination of leakage behaviour in a hydraulic system by monitoring closely the difference between an estimated volume of the hydraulic fluid in the hydraulic tank and a measured value of hydraulic fluid. The process takes into account many factors that may affect the level of fluid in the tank, as has been described above, so this means that the change in delta value S14 is highly likely to be attributable to leakage in which case an alert system can be relied upon to highlight leakage issues reliably. A significant point to note is that the system is comparing the measured volume of hydraulic fluid in the tank 34 compared to an estimated level. This is a more accurate approach than would be achievable by, for example, comparing a measured level of hydraulic fluid in the tank (or even an estimated volume value) with an initial value of hydraulic fluid which may simply be hard-coded in the control software and/or calibrated at the installation of the hydraulic system when the system is filled with hydraulic fluid. Such an approach is flawed because an initially calibrated value of hydraulic fluid in the tank may be susceptible to change for example if some fluid-using components are added, removed or replaced. For instance, a hydraulic fluid filter may be changed which would remove hydraulic fluid from the system.

In the above discussion, the method 100 is presented as deriving a delta value S14 as a result of the comparison process between the estimated volume of the tank, derived by a number of estimator functions, and the measured volume of the tank. However, although a delta value and suitable statistical analysis may be used effectively, enhancements may include the use of Kalman filters or other similar suitable modelling techniques to generate a model of the estimated fluid volume of the fluid tank under a range of operating conditions, such that the output of the model can be used to compare against the actual fluid volume of the fluid tank based at least in part of the output of the fluid level sensor 63.

The skilled person would appreciate that the illustrated example is one example of how the invention may be put into effect. Accordingly, the example described herein is provided purely for illustrative purposes and is not to be construed as limiting the scope of the invention. Some variations of the illustrated example have been described above, but the skilled person would understand that other variants are possible without departing from the invention as defined by the claims.

CLAIMS

1. A wind turbine fluid system (26), comprising:

a fluid tank (34) having a fluid level sensor (63) that provides a tank level signal (S1) indicative of the level of fluid in the fluid tank;

a plurality of fluid-using components (38) fluidly coupled to the fluid tank;

a processor (62) configured to:

determine (112) an actual fluid volume of the fluid tank based at least in part on the tank level signal;

use one or more models (102-110) to generate an estimated fluid volume (S10) of the fluid tank based on data relating to the plurality of fluid-using components;

compare (116,120) the estimated fluid volume of the fluid tank with the determined actual fluid volume (S12) of the fluid tank; and

trigger (122) an alert action in the event that the result of the comparison indicates that a leak is present in the fluid system.

2. The wind turbine fluid system of Claim 1, wherein the tank level signal (S1) provides an output indicative of a plurality of levels of fluid in the fluid tank, or provides a continuous signal indicative of the level of fluid in the fluid tank.

3. The wind turbine fluid system of Claims 1 or 2, wherein the plurality of fluid-using components includes at least two or more of the following:

a hydraulic pitch actuator (44); a pitch actuator accumulator (52); a hydraulic brake system (46); a hydraulic motor (48), a hydraulic pump (50).

4. The wind turbine fluid system of any one of the preceding claims, wherein, in generating an estimated fluid volume of the fluid tank, the processor is configured to

generate a plurality of estimated component fluid volumes (S18,S20,S22,S24,S26), each of which is associated with a respective one of the plurality of fluid-using components (38).

5. The wind turbine fluid system of any one of the preceding claims, wherein the processor is further configured to generate the estimated fluid volume of the fluid tank by taking into account the effect of fluid temperature on the volumes of fluid in the plurality of fluid-using components.

6. The wind turbine fluid system of any one of the preceding claims, wherein the processor is further configured to generate an estimate of the fluid volume variation in the fluid tank that may occur due to changes in temperature.

7. The wind turbine fluid system of any one of the preceding claims, wherein, in generating the estimated fluid volume of the fluid tank, the processor is configured to receive a signal from a proportional valve (54) associated with the hydraulic pitch actuator (44).

8. The wind turbine fluid system of any one of the preceding claims, wherein, in triggering the alert action, the processor is further configured to compare the estimated fluid volume (S10) of the fluid tank and the actual fluid volume (S12) of the fluid tank against a predetermined threshold and trigger the alert action if a difference value (S14) between the estimated fluid volume of the tank and the actual fluid volume of the tank exceeds the predetermined threshold.

9. The wind turbine fluid system of Claim 8, wherein the predetermined threshold is set at between 1% and 10% of a nominal capacity value of the fluid tank and, optionally, at least 2% of the nominal capacity value.

10. The wind turbine fluid system of Claim 8 or 9, wherein the predetermined threshold is one of a plurality of predetermined thresholds configured to alert leakage conditions in respect of associated parts of the fluid system.

11. The wind turbine fluid system of Claim 8, wherein the processor is configured to trigger the alert action if the result of the comparison indicates a rate of change in excess of a rate of change threshold.

12. The wind turbine fluid system of Claim 11, wherein the processor is configured to trigger the alert action when the rate of change threshold exceeds a predetermined time period.

13. The wind turbine fluid system of Claims 11 or 12, wherein the rate of change threshold is set at a value between 0.2% to 5% of nominal tank capacity per hour.

14. The wind turbine fluid system of Claim 13, wherein the rate of change threshold is one of a plurality of rate of change thresholds configured to alert leakage conditions in respect of associated parts of the fluid system.

15. A method (100) of detecting leakage of fluid in a fluid system (26) comprising a fluid tank (34) having a fluid level sensor (63) that provides a tank level signal (S1) indicative of the level of fluid in the fluid tank; and a plurality of fluid-using components (38) fluidly coupled to the fluid tank, wherein the method comprises:

determining (112) an actual fluid volume of the fluid tank based at least in part on the tank level signal;

using one or more models (102-110) to generate an estimated fluid volume (S10) of the fluid tank based on data relating to the plurality of fluid-using components;

comparing (116,120) the estimated fluid volume of the fluid tank with the determined actual fluid volume (S12) of the fluid tank;

triggering (122) an alert action in the event that the result of the comparison indicates that a leak is present in the fluid system.

16. A wind turbine comprising the fluid system of Claims 1 to 15.

17. A computer program product comprising instructions which, when executed in a computer, cause the computer to carry out the steps of the method of Claim 15.

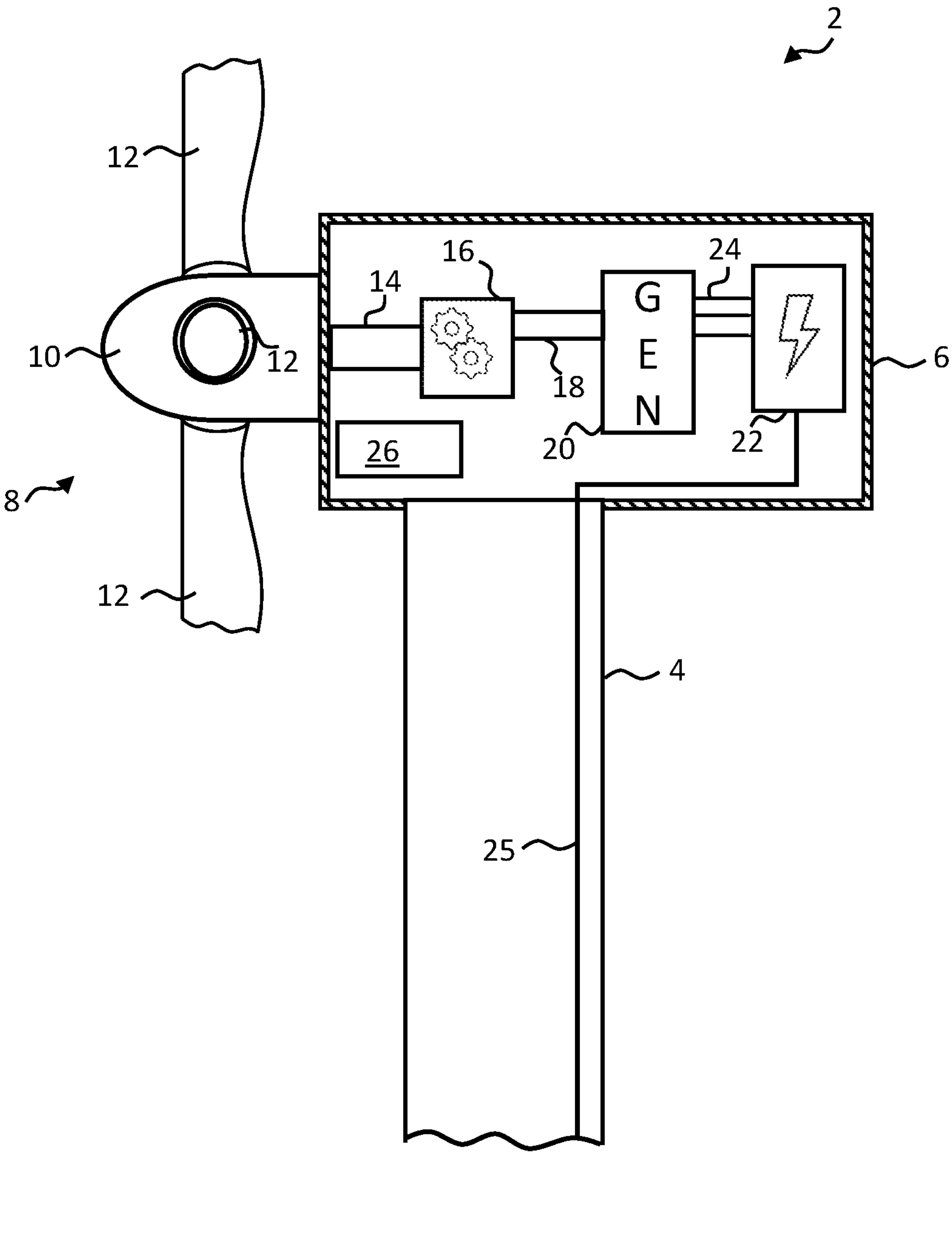

Fig. 1

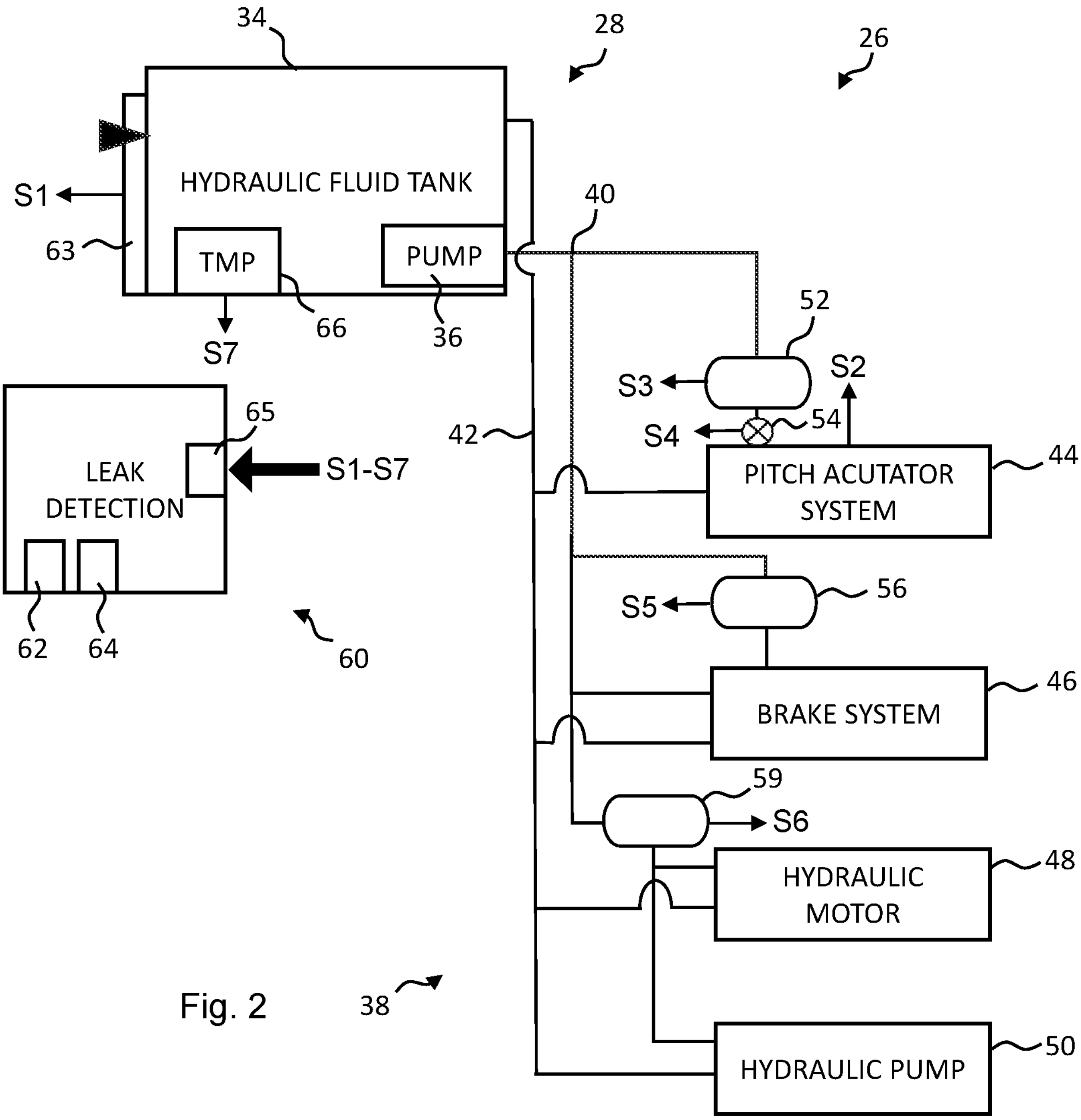
34
28
26
HYDRAULIC FLUID TANK
S1
63
TMP
PUMP
40
66
36
S7
52
S3
S2
54
S4
65
42
LEAK
DETECTION
S1-S7
PITCH ACUTATOR
SYSTEM
44
S5
56
62
64
60
BRAKE SYSTEM
46
59
S6
HYDRAULIC
MOTOR
48
38
HYDRAULIC PUMP
50

Fig. 2

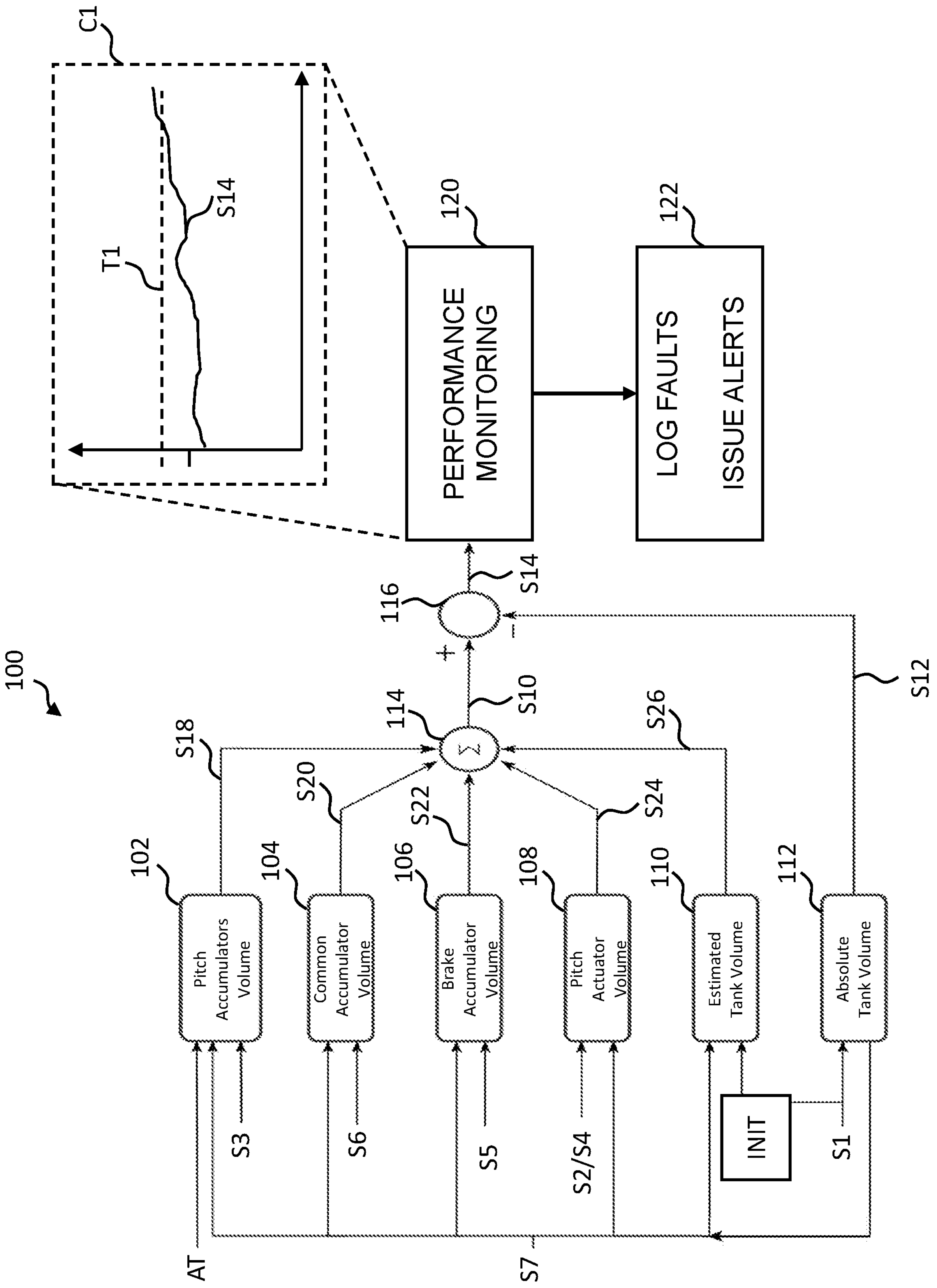
C1
T1
S14
120
PERFORMANCE MONITORING
122
LOG FAULTS
ISSUE ALERTS
100
116
+
−
S14
114
S10
S12
S18
S20
S22
S24
S26
102
Pitch Accumulators Volume
104
Common Accumulator Volume
106
Brake Accumulator Volume
108
Pitch Actuator Volume
110
Estimated Tank Volume
112
Absolute Tank Volume
INIT
AT
S3
S6
S5
S2/S4
S1
S7

Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2024/050252

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D7/00 F03D1/06 F03D17/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 270 342 A1 (SIEMENS AG [DE]) 5 January 2011 (2011-01-05) paragraphs [0014], [0026], [0027] - [0029], [0034], [0036], [0041], [0044] figures 1,2; compounds 100,101, 102, 103, 104, 106, 107, 108 -----	1-17
X	EP 0 748 437 B1 (FLUID POWER IND INC [US]) 10 May 2000 (2000-05-10) paragraphs [0018] - [0023]; figure 1 -----	15,17
A	CN 110 566 540 B (SHANGHAI ELECTRIC WIND POWER GROUP CO LTD) 19 January 2021 (2021-01-19) paragraphs [0040], [0042], [0044] - [0046], [0065], [0069] figure 1 -----	1-17

-/--

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 January 2025	27/01/2025

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Pasquet, Pierre

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2024/050252

C(Continuation). **DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 112 879 388 A (CHINA RAILWAY ENGINEERING EQUIPMENT GROUP CO LTD) 1 June 2021 (2021-06-01) claims 1-5 -----	15,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/DK2024/050252

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 2270342	A1	05-01-2011	CA	2708002	A1	22-12-2010
			CN	101929490	A	29-12-2010
			DK	2270342	T3	13-05-2013
			EP	2270342	A1	05-01-2011
			ES	2411385	T3	05-07-2013
			US	2010319336	A1	23-12-2010
EP 0748437	B1	10-05-2000	AU	696727	B2	17-09-1998
			CA	2184689	A1	08-09-1995
			DE	69516858	T2	07-12-2000
			EP	0748437	A1	18-12-1996
			FI	963409	A	02-09-1996
			JP	3380558	B2	24-02-2003
			JP	H09510291	A	14-10-1997
			NO	313475	B1	07-10-2002
			US	5461903	A	31-10-1995
			WO	9523958	A1	08-09-1995
CN 110566540	B	19-01-2021	NONE			
CN 112879388	A	01-06-2021	NONE			