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Scaled Wind Farm Technology Hydraulic System Failure Modes and Effects Analysis

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Abstract

The purpose of this Failure Modes and Effects Analysis (FMEA) is chosen to examine the potential failures of the systems which could result in an overspeed event with a potential for flying debris from the wind turbine blades. The FMEA method was chosen to examine the turbine hydraulic system because two important turbine protective features use hydraulic pressure to function: the blade pitching system, and the brake. The objective of the FMEA was to determine if the two safety features have a likely common failure point, or if the safety systems can be individually credited for protection of the turbine.

1.0 Introduction

The Scaled Wind Farm Technology (SWiFT) project is a joint-operated Sandia and Texas Tech University research project located on the Reese Technology Center near Lubbock, Texas. The facility studies wind turbine design and wake effects using Vestas V-27 wind turbines.

On May 6, 2014, one of three turbines at The Sandia SWiFT test facility in Lubbock, TX, was destroyed when the entire rotor and nacelle assembly separated from the tower and fell to the ground, lofting composite blade debris 30 m (98 ft.) to the North and 170 m (558 ft.) to the East of the tower. Although no one was injured in this incident, there was the potential for a serious injury or a fatality due to the collapse of the 8 metric ton (8.8 ton) rotor/nacelle and flying debris from the turbine. This event resulted in a re-evaluation of the SWiFT safety basis and subsequent update to the PHS as a moderate hazard facility because of the debris that impacted outside of the Sandia controlled area. A moderate hazard facility is a facility in which the hazard(s) have the potential for significant onsite impact.

The purpose of this Failure Modes and Effects Analysis (FMEA) is chosen to examine the potential failures of the systems which could result in an overspeed event with a potential for flying debris from the wind turbine blades. The FMEA method was chosen to examine the turbine hydraulic system because two important turbine protective features use hydraulic pressure to function: the blade pitching system, and the brake. The objective of the FMEA was to determine if the two safety features have a likely common failure point, or if the safety systems can be individually credited for protection of the turbine.

2.0 Vestas Hydraulic System

The SWiFT Facility turbines are equipped with the manufacturer installed (Vestas) hydraulic system as a function of the turbine design basis. The Vestas hydraulic system serves two important safety functions for the wind turbine: hydraulic pressure operates the blade pitching system (controls speed of the rotor) and the turbine brake (quickly slows down and stops the turbine, or holds it in a stopped position). A brief description of the four SWiFT turbine operating states can be found in **Table 1**. Detailed information on the turbine operating states, blades, pitching system, and turbine operating states can be found in the SWiFT Facility Safety Analysis, Revision 0 (July 2015).

Table 1: SWiFT Turbing Operating States

Turbine State	Description
Run	The turbine must be in *Run* to initiate and maintain rotor motion and power generation. In *Run*, the nacelle controller operates the pitching system via the pitch proportional valve to reach and maintain optimum rotor speed, and allow the generator to produce and send power to the grid.
Pause	In *Pause*, the generator is disconnected from the grid, and the rotor and blades are allowed to slow to a stop. *Pause* is a useful state to slow or stop the turbine without initiating more extreme modes of stopping (which expose the turbines to high loads), or to disconnect the generator and slow the rotor for a short time. *Pause* is also used for many of the system service modes, allowing the turbine or individual systems to be tested and maintained.
Stop	*Stop* is activated by the operators, the hardwired Stop Circuit, or the nacelle controller to quickly slow the turbine by pushing the blades to the "full feather" position. *Stop* is activated by a set of alarming sensors that do not require the immediate (and high-stress) stop of an *E-Stop*, such as the acceleration switch, where the application of a high energy impulse of the brakes may induce negative effects. *Stop* is also used as part of the normal turbine shutdown process.
E-Stop	*E-Stop* is activated when the turbine enters an unstable or unsafe condition, such as rotor over-speed, brake disk over-heat, or power failure. In *E-Stop*, the blades are pushed to full feather, and the brake is applied to stop the turbine immediately. *E-Stop* is also used as part of the normal turbine shutdown process, because it holds the turbine in a safe, stationary position. *E-Stop* is used during many maintenance procedures when personnel need to enter the nacelle.

When the E-Circuit is opened and then re-closed, the turbine will stay in *E-Stop* until the operator gives a command to raise the state of the turbine to *Stop*. As described, the SWiFT Facility emergency procedures require an incident report, notifications of an emergency stop, and a tour/inspection of the turbine prior to raising the state of the turbine following an unplanned *E-Stop*.

2.1 Supply

The hydraulic system is supplied with fluid by a 30 liter tank and the hydraulic pump motor. The pump supplies 4.5 l/min at 100 bar (the pump ranges 4.3 – 5.0 l/min according to changes in system pressure). The pump is started and stopped with input from pressure sensor 12 and the turbine controller to maintain the pitching hydraulic system between 75 – 90 bar. The tank is equipped with an air/filling filter that vents the tank to atmospheric pressure via a filter to avoid contamination to the fluid, and filters hydraulic fluid as operators fill the system. Tank level is monitored by an on/off tank level switch that sends a signal to the nacelle controller. If the nacelle controller loses the signal from the tank level switch because the switch turns off or loses power, the controller initiates an *Emergency Stop* (*E-Stop*). Temperature of the hydraulic fluid is monitored by the tank resistance temperature detector (RTD), which sends a signal to the nacelle controller. The nacelle controller initiates protective actions if the temperature signal reads <-20^{o}C for longer than 20 seconds (to prevent system damage) or <65^{o}C for longer than 20 seconds (prevents system damage and could indicate an over-cycled pump).

Upstream of the pump is the high-pressure filter (HPF 10), a secondary protection against system contamination. HPF 10 is equipped with an on/off filter sensor that sends a signal to the nacelle controller. The sensor turns off at a differential pressure of 5 bar, indicating a dirty or clogged filter. If the sensor turns off for 2 seconds, the nacelle controller alerts the operators that the filter/sensor needs maintenance. If sensor turns off or the nacelle controller otherwise loses the sensor signal, filter alarm 164 sends the turbine to *Stop*. HPF 10 is also equipped with a pressure-activated bypass valve. The bypass valve opens automatically to allow fluid/pressure flow at a differential pressure of 7 bar, to avoid destroying a clogged filter and contaminating the system.

2.2 Pitching

The pitching portion of the hydraulic system applies hydraulic pressure to the pitching ram. The pitching linkage system translates the movement of the ram to rotate the blades along their longitudinal axis. A fully contracted ram translates to 0^{o} (perpendicular to the oncoming wind), or “run” position. A fully extended ram translates to 90^{o} (parallel to the oncoming wind) or “feathered” position. Solenoid valves 19.1 and 19.2 supply pressure to the pitching ram, and are energized during *Run* and *Pause*. The solenoid valves are deenergized during *Stop* and *E-Stop*, aligning pressure directly to the “feather” side of the ram. These valves fail safe, so pressure cannot be applied to move the pitching ram toward “run” when power is lost.

Small adjustments to the pitching ram are made via the three-way pitch proportional valve (PPV 20). PPV 20 directs pressure toward the “run” side of the ram (via the straight flow paths through the valve) or “feather” side of the ram (via the crossed flow paths through the valve) as needed to adjust the speed of the rotor and maintain a nominal rpm. PPV 20 is monitored and controlled by the Vickers card (position 21). The Vickers card receives inputs from pitch sensors and the nacelle controller. PPV 20 is energized in *Run* and *Pause* to allow flow of fluid/pressure, and deenergized in *Stop* and *E-Stop* to close the valve and stop fluid/pressure flow.

The pitch ram position sensor (not pictured on system schematics) tracks the pitch angle by measuring the linear position of the pitch ram. Pitch alarm 190 (pitch error) sends the turbine to *Stop* if desired pitch position and measured pitch position are >10% different for >10 seconds. Pitch alarm 191 (pitch velocity alarm) sends turbine to *Stop* if desired pitch velocity (rate of change of the pitch angle) and measured pitch velocity do not match.

The safety block (position 31) is positioned on the hydraulic line supplying the “feather” side of the pitching ram, and consists of a parallel solenoid valve and check valve. In *Run* and *Pause*, the solenoid valve is energized, and open, allowing two-way flow into and out of the “feather” side of the ram. In

Stop and *E-Stop*, the solenoid valve is deenergized, and shut, only allowing one-way flow through the check valve. The purpose of the safety block is to allow pressure in or out of the "feather" side of the ram during *Run* and *Pause* (to allow for adjustments in pitch and rotor speed), but to only allow pressure in (and to hold pressure against) the "feather" side of the ram during *Stop* and *E-Stop*. This keeps the blades pitched to "feather" even if upstream hydraulic pressure degrades. If the safety block solenoid valve loses power, it fails shut, to hold pressure against the "feather" side of the ram.

2.3 Brake

The brake portion of the hydraulic system aligns the brake calipers either to pressure to apply the brake, or to the drain to release the brake. The solenoid valve that supplies pressure to the brake from the braking accumulator is energized when the brake is disengaged (all turbine states except *E-Stop*), and deenergized to supply break pressure during *E-Stop*. The braking solenoid valve fails safe, so that pressure is applied to the braking system when power is lost.

The pitch and brake nodes are separated by a spring-activated pressure reduction valve (PRV 24). PRV 24 is pre-set to allow enough hydraulic fluid into the downstream brake node to maintain it at 19 +- 1.5 bar, regardless of fluctuations in upstream pressure. PRV 24 also has a pressure relief function. If pressure in the brake nodes increases, PRV 24 will bleed off excess pressure to the drain line, and back to the system tank.

2.4 Protective Components

The hydraulic system pitch nodes are protected from high pressure by relief valve 13, set to relieve pressure at 100 bar (normal pressure 75 – 90 bar). The brake nodes are equipped with relief valve 29, set to relieve pressure at 25 bar (normal pressure 17.5 – 20.1 bar). Both relief valves feed into the drain line, so hydraulic fluid is returned back to the tank.

The pitching and the brake portions of the hydraulic system are each supplied with an accumulator to build up and store reserve pressure to operate the system. The hydraulic accumulators store hydraulic energy as a reserve to operate the active pitch control in *Run* and *Pause*, the active pitch-to-feather function in *Stop* and *E-Stop*, and the brake in *E-Stop*. The accumulators are equipped with a needle valve to release pressure into the system drain line (and return hydraulic fluid into the tank) prior to repair or maintenance.

The safety block and high-pressure filter are discussed above.

A functioning pitch system is expected to slow down and stop the turbine, independent of the brake. A functioning brake is expected to slow down and stop the turbine, independent of the pitching system. The purpose of the FMEA is to determine whether the two systems have a common failure point, or if the two can reasonably be credited as two separate controls in the hazard analysis of the entire turbine.

2.5 Passive Pitch Design

The SWiFT turbine design includes an engineered safety system called passive pitch design. Passive pitch ensures that the turbine blades cannot be pitched to increase or maintain rotor speed without active hydraulic pressure. If the pitching system loses the hydraulic pressure that holds the ram extended and the blades in the “run” position, the blades passively pitch toward “feather” via the aerodynamic pitching moments acting on the rotating blades. This slows down and stops the rotor, even at high wind speeds. The blades cannot move toward or maintain a “run” position without hydraulic pressure.

Passive pitch design does not depend on a functioning hydraulic system; however, there are certain failures of the hydraulic system that could disable the passive pitch function. In order for the blades to passively pitch toward “feather” via aerodynamic forces, the pitching ram must be able to move in that direction, which requires an unobstructed path into the “feather” side of the ram, and an unobstructed path out of the “run” side of the ram to allow the transfer of hydraulic fluid. The system is designed to allow passive pitch, but if a failure in the hydraulic system obstructed either flow path, passive pitch could be disabled.

3.0 Hazard Analysis Process and Method

The purpose of an FMEA is to identify single equipment and system failure modes and each failure mode’s potential effects(s) on the system. An FMEA tabulates failure modes of equipment and the corresponding effects on the system [CCPS 2008]. Single equipment and system failures may result in or contribute to an incident.

The SWiFT Hudraulic System FMEA team held three FMEA workshops; 4-1-15, 4-9-15, and 5-6-15. The requsite attendees included aworkshop facilitator, scribe, and subject matter experts (SMEs) from SWiFT, Safety Engineering, and Safety Basis. The sign-in sheets from the workshops are included in Appendix A. From the workshop, the resulting FMEA table was peer-reviewed by SWiFT and Industrial Facilities Safety Basis SMEs.

The first step in an FMEA is to define the scope and determine the level of detail of the analysis. The FMEA can have a broad to narrow scope (i.e., entire facility,individual system, etc.), and a general or in-depth level of detail (i.e., examining system interactions, components within a system, etc.).It is important for the team to discuss and understand the scope boundaries and level of detail prior to initiating the FMEA process.

The FMEA was performed in a deliberate, systematic manner to reduce the possibility of omissions and to enhance the completeness of the FMEA. For the SWiFT hydraulic system, each component and each possible failure mode was listed in tabular form. For completeness, the normal mode for the component was listed and identified, as well as any failure mode, regardless of whether or not it resulted in adverse effects on the system. Before the analysis, uniform failure mode language was selected to describe the failure modes of the components in consistent terms. The table listing each examined component and associated failure modes is included in Appendix B.

For each failure mode of each component, systemic effects, possible causes, and controls were identified and documented on the FMEA tables. Questions, action items, and notes relevant to the analysis were also recorded during the FMEA workshop.

4.0 Hydraulic System FMEA

4.1 Scope and Level of Detail

The SWiFT hydraulic system interfaces with three other systems in the Vestas V-27 turbines: the pitching linkage system, the shaft system, and the nacelle controller. For the purposes of the FMEA, only the hydraulic system was evaluated, up to and including the pitching ram (the ram interfaces with the linkage system that translates ram movement into blade rotation—the linkage system is outside the FMEA scope), the brake (the brake interfaces with the high-speed shaft; the high-speed shaft is outside the FMEA scope), and any hydraulic system components that send signals to or receive signals from the nacelle controller (the nacelle controller, software, and logic are outside the FMEA scope).

Generally, for a system-level analysis, the FMEA should focus on the failure modes and effects of individual components. For the SWiFT hydraulic system, whole components were analyzed (such as a valve), but pieces and parts of individual components (such as a valve seat or fitting) were not broken down for analysis. Some components in the hydraulic system are more complex than others, but were still analyzed as whole component, rather than as individual parts. For example, the safety block (position 31) was analyzed as a unit, rather than as an individual check valve and solenoid valve. HPF 10 was also analyzed as a unit, rather than as a filter, bypass valve, and sensor.

The SWiFT hydraulic system is equipped with several test fittings to connect temporary equipment to various places in the system for testing, maintenance, or troubleshooting purposes. The test fittings were included in the FMEA analysis, and the failure mode of a test fitting leak and subsequent effects on the system were evaluated. Because the test fittings connect to the main lines of different sections of the system, and because a leak in the line would have the same system effects as a leak from the test fittings, the lines, manifold blocks, and fittings were not included as components in the FMEA analysis.

4.2 Nodes

Because the Vestas hydraulic system has three distinct sections that perform different functions (supply fluid and pressure, operate the pitching ram, operate the brake calipers) and more than one function for the sections (the pitching section can pitch to “run”, pitch to “feather”, or align the accumulator pressure directly to “feather”, and the brakes can be aligned to pressure to apply the brake, or aligned to the drain to release the brake), the system was broken up into six nodes to examine all sections and operating functions. In order to thoroughly analyze the components and their effects on the system, each node shares at least one component with each adjacent node. Detailed schematics of the SWiFT hydraulic system, including highlighted flow paths for each node are included in Appendix C.

4.2.1 Node 1 – Pump Supply

Node 1 is the pump supply node, and includes all components from the system tank up to and including pressure sensor 12 and relief valve 13. Other major components include the system pump and high-pressure filter (HPF 10).

4.2.2 Nodes 2, 3 & 4 – Pitch Control

Nodes 2, 3, and 4 are pitch control modes, and include all components from and including pressure sensor 12 and relief valve 13, up to and including the pressure reduction valve (PRV 24). Major components in the pitch nodes include accumulator 16, solenoid valves 19.1 and 19.2, PPV 20, the safety block, and the pitching ram. Node 2 examines the system during pitch toward "run" (rotor speeding up, used during *Run* mode), node 3 examines the system in pitch to "feather" (rotor slowing down, used during *Run* and *Pause*), and node 4 examines the system in the most conservative mode of "feather" via direct accumulator pressure (used to quickly slow the rotor or hold it in a stationary position during *Stop* and *E-Stop*).

4.2.3 Nodes 5 & 6 – Brake

Nodes 5 and 6 are brake modes, and include all components from and including PRV 24 to the brake calipers. Major components in the brake nodes include accumulator 27 and solenoid valve 19.3. Node 5 examines the system while the brake is applied (aligned to pressure, used during *E-Stop*), and node 6 examines the system when the brake is not applied (aligned to the drain, used during all mode except *E-Stop*).

To examine and identify possible adverse effects of the separate nodes on the rest of the hydraulic system, the failure modes and effects of each node are compiled and included on the tables for adjacent nodes. For example, the first "component" on the pitching node FMEA tables is the pump supply node, allowing the failure modes of the pump supply node to be examined in the context of adverse effects on the pitching nodes.

The FMEA tables for each node are included in Appendix D, and include detailed descriptions and functions of each component.

4.3 Controls

For each failure mode and subsequent system effect, controls were identified that either prevented the failure mode or mitigated the subsequent system effect. Controls that are always in effect are only listed if the control would prevent against the failure mode or mitigate the effect of the failure mode. The controls identified in the FMEA analysis are listed and described in tabular form in Appendix E.

Failure mode scenarios that rely on rotor speed controls to put the turbine into a safe state are of particular concern, especially if the hydraulic system failure is such that the only mechanism for the rotor speed controls to put the turbine in the safe state is the hydraulic brake. The brake is expected to stop the turbine without assistance from the pitching system, but such a situation would subject the turbine to potentially damaging forces, and is not ideal.

5.0 Conclusions

The hazards of greatest concern to the hydraulic system are low-pressure hazards (leaks, pump malfunctions, faulty sensor readings that affect pressure controls, etc.) and contamination. Both low pressure and contamination could lead to the failure of both the pitch and brake nodes, but it is very unlikely that both nodes would fail at once, without operator detection or triggering of protective functions.

5.1 Leaks

Two types of leaking possibilities exist in the hydraulic system: internal leaks (a relief valve, check valve, or needle valve that holds pressure in the pitch or braking nodes leaks hydraulic fluid/pressure into the drain line, and back to the system tank), and external leaks (a component leaks hydraulic fluid/pressure outside the system).

5.1.1 Internal Leaks

If an internal leak occurs, the pressurized system will lose pressure and fluid, but the fluid will return to the tank, and will not be lost from the system. Pressure sensor 12 will trigger the pump motor to restore pressure in the system, and will continue to raise pressure as the component continues to leak. Leaks from a needle valve or check valve would likely be minimal, and well within the capacity of the pump. Such small leaks are unlikely to adversely affect the system. Larger internal leaks that approach the capacity of the supply node would trigger frequent responses from pressure sensor 12 and the pump. Such leaks may lead to pump wear and increased hydraulic fluid temperature, either of which could trigger an automatic protective safety functions. If the leak back to the tank were greater than the pump capacity, pressure in the associated node would continue to drop until the low pressure alarms and subsequent protective functions were initiated. Internal system leaks have the potential to disrupt continuous turbine operability, but are unlikely to cause catastrophic turbine failure or prevent a needed protective function.

5.1.2 External Leaks

If an external leak occurs, the pressurized system will lose pressure, and the hydraulic system will lose fluid. Pressure sensor 12 will cause the pump motor to raise pressure in the system, and will continue to raise pressure as the system continues to leak. If the leak is within the capacity of the pump, pressure in the associated node will be restored and maintained. The system will continue to lose fluid until the fluid level in the system tank drops below the tank level switch and the tank level switch turns off, initiating an *E-Stop*. If the leak is greater than the pump capacity, pressure in in the associated node will continue to drop until the low pressure alarms and subsequent protective functions are initiated. Large external leaks may lead to wear of the pump, automatic protective safety functions, and loss of hydraulic fluid into the nacelle, but are unlikely to cause catastrophic turbine failure or prevent a needed protective function.

Normal operating pressure in the pitch nodes (75 – 90 bar) is maintained by reserve pressure in accumulator 16 and the pump supply node. Normal operating pressure of the brake nodes (20.5 – 17.5 bar) is maintained by reserve pressure in accumulator 27 and reduced pressure flow from the pitch nodes via spring-activated PRV 24. A sudden loss of pressure in the brake nodes would cause PRV 24 to open, drawing pressure from the pitch nodes. An automatic *E-Stop* is triggered if pressure in the pitch nodes is < 50 bar (via pressure sensor 12), or if pressure in the brake nodes is < 14 bar (via pressure switch 26). These set points are designed to be high enough that residual pressure will be adequate to execute the protective functions of the pitch nodes (active pitching to "feather" via direct accumulator line-up), and the brake nodes (applying the brake), unless pressure is degrading rapidly.

The pitch node is protected from rapidly degrading pressure by the safety block (position 31). The safety block allows one-way pressure into the "feather" side of the pitching ram when *Stop* or *E-Stop* is initiated, and holds the pressure in. The brake node is protected from sudden loss of pressure in the pitch node by check valve 11.4. It is unlikely that both nodes will lose adequate operating pressure at the same time. However, assuming the *worst-case scenario* of a sudden, high-capacity leak that degrades pressure in both the pitch and brake nodes rapidly enough to render both protective functions impossible, the failure cannot disable the turbine's passive pitch design. In such a situation, the blades will passively pitch to feather via the aerodynamic forces on the blades, slowing and eventually stopping the rotor, even at high wind speeds.

The single failure of a leak will not prevent the turbine from slowing and stopping, even in a worst-case scenario.

5.2 Failure of Pressure Components

Pressure components of concern are the pump motor, pressure sensor 12, PRV 24, pressure switch 26, and the pitching and braking accumulators. As explained in more detail below, the failure of a pressure control component will have similar system effects as a leak. In the worst-case scenario of rapidly degrading pressure in either or both nodes, a failure of a pressure component cannot disable the passive pitch design. Pressure component failure may lead to disruption of operation, automatic safety functions, and reduced operability, but will not cause catastrophic turbine failure or prevent a needed protective action.

5.2.1 Pump Motor

Pitch node pressure is maintained via the pump motor, pressure sensor 12, and the nacelle controller. In automatic mode, the nacelle controller turns the pump motor on (to raise pressure) at 75 bar and off at 90 bar via readings from pressure sensor 12. If the pump motor fails to turn on, pressure in the pitch node will fall below the normal operating band. At <50 bar, pressure alarm 163 initiates an *E-Stop*. Pressure in the brake node will be unaffected, because brake node pressure is maintained by PRV 24, regardless of fluctuations in pitching node pressure.

If the pump motor fails "on", system pressure will rise. System pressure in the pitching nodes will increase until relief valve 13 lifts at >100+5 bar and relieves excess node pressure/fluid back to the system tank. Excess system pressure will not affect the brake node, because brake node pressure is maintained by PRV 24, regardless of increases in pitching node pressure. The capacity of relief valve 13 is 4.5 L/min, which is within the range of the pump capacity (4.3 – 5.0 L/min). Therefore, the relief valve provides adequate over-pressure protection for the pitching node, unless the pump were to run continuously at a rate greater than the capacity of the relief valve. High system pressure would likely reduce pump capacity. Further, a continuously running pump would raise system temperature and would likely initiate temperature alarm 167. (More analysis is needed to make this determination.)

Assuming the worst-case scenario, undetected, unmanageable pitching node over-pressurization and a subsequent rupture would not disable braking node capabilities or passive pitch design.

5.2.2 Pressure Sensor 12

Pressure sensor 12 monitors pressure in the pitching node and sends the reading to the nacelle controller. In automatic mode, the nacelle controller turns the pump on (to raise pressure) at 75 bar and off at 90 bar. If pressure sensor 12 sends a faulty reading to the nacelle controller, pressure may not be maintained in the normal operating band of the pitching node. This could result in undetected low system pressure. (High system pressure is both less likely and less of a safety concern, but is discussed under pump motor, above.) Below 30 bar, the pitching nodes affectively lose active pitching capability. Loss of pitching capability would likely initiate pitching alarms 191 and 192 and the associated automatic protective actions, or otherwise alert operators to a problem with the turbine. Assuming loss of pitching capability went undetected, pressure could conceivably drop lower than 30 bar.

Because pressure in the brake node is regulated via PRV 24, low pressure in the pitching node would not affect brake node pressure, unless pitch pressure dropped below the normal operating pressure of the brake node, < 19+-1.5 bar. In this event, pressure switch 26 (and associated pressure alarm 162) would protect the brake node from depressurization at <14 bar. The brake is expected to stop the turbine in the absence of active pitching capabilities. However, assuming the *worst-case scenario* of an undetected loss of both active pitching and braking capabilities, failure of pressure sensor 12 cannot disable the turbine's passive pitch design. In such a situation, the blades will passively pitch to feather via the aerodynamic forces on the blades, slowing and eventually stopping the rotor, even at high wind speeds.

5.2.3 PRV 24

PRV 24 maintains constant pressure in the brake node, regardless of fluctuations in the pitching node pressure. If PRV 24 failed to regulate pressure within the operating band of the brake node due to mechanical failure or contamination, the brake node is protected against high pressure by relief valve 29 (which relieves excess node pressure/fluid back to the system tank), and against depressurization by pressure switch 26 (and associated pressure alarm 162). The single failure of PRV 24 may lead to an automatic safety action, disruption of operation, and possible pump wear, but cannot disable active or passive pitching capabilities.

5.2.4 Pressure Switch 26

Pressure switch 26 monitors pressure in the brake node, and sends a signal to the nacelle controller. If the switch turns off (indicating pressure <14 bar) or otherwise fail to send the associated signal, the nacelle controller logic initiates an *E-Stop*. Unlike pressure sensor 12, pressure switch 26 does not regulate node pressure. In the event of a faulty pressure switch 26 reading, the brake nodes would be without a low pressure indication, but pressure would still be regulated by PRV 24. The single failure of pressure switch 26 is likely to initiate an unneeded automatic protective action, but could also fail to indicate low pressure in the brake node. In such a case, assuming a simultaneous failure of PRV 24 and the worst-case scenario of no braking capability, active and passive pitching capabilities would be unaffected by the failures.

5.2.5 Accumulators

Both the pitching and brake nodes store reserve pressure in the associated node accumulator via a compressible air bladder. A failure in the air bladders would interfere with associated node function and affect node operability. The failure of one accumulator air bladder is unlikely to affect the operability of the other, meaning either active pitching or braking capabilities would likely be intact after a single failure of either accumulator 16 or 27. However, neither accumulator can fail in such a way to disable passive pitch design.

5.3 Contamination

5.3.1 Pitching Node Contamination

Components with failure modes of concern in the pitch nodes are solenoid valve 19.2, nozzle 23, and the safety block. If these components fail in a way that does not allow fluid/pressure flow through the component (due to either contamination or mechanical failure), the blockage will obstruct a flow path necessary for passive pitch. With active and passive pitch disabled, the only method of stopping the turbine is the emergency brake. The emergency brake is expected to stop the turbine, even without the help of the pitching system, but such an action would subject the turbine to potentially damaging forces, and would not be ideal.

Such failures would have to block or severely hinder fluid/pressure flow through solenoid valve 19.2, nozzle 23, or the safety block in order to disable active and passive pitching and rely solely on the system brake. In other words, such failures do not include any normal operating modes of the components. For example, solenoid valve 19.2 aligns the “run” side of the ram to either PPV 20 (to allow pitching control via the nacelle controller during *Run* and *Pause*) or to the system drain line (to allow the pitching ram to move toward “feather” during *Stop* and *E-Stop*). In order to disable both active and passive pitch, solenoid valve 19.2 must fail in such a way that pressure/fluid flow is obstructed, not merely misdirected. This could happen if the valve got stuck between the two alignments in a way that did not allow fluid/pressure flow, or if the valve became highly contaminated.

Such a failure in the safety block is particularly unlikely. In order for a mechanical or contamination failure to obstruct the flow path through the safety block, the failure would have to obstruct both the path through the safety block solenoid valve and the path through the safety block check valve. Such a mechanical failure is unlikely, because there are no moving parts that could become stuck and obstruct both paths in the safety block simultaneously. Such a contamination failure is also unlikely, because check valve contamination tends to hinder seating of the valve (and allow the failure mode of backflow), rather than preventing a check valve from opening and obstructing pressurized flow.

5.3.2 Brake Node Contamination

Components with failure modes of concern in the brake nodes are PRV 24 and solenoid valve 19.3.

If PRV 24 were sufficiently contaminated, the pressure reduction set point could be affected, causing low brake node pressure. Pressure below 14 bar in the brake node could affect brake operability. The system is protected from a low-pressure failure by pressure switch 26.

Solenoid valve 19.3 controls alignment of the brake calipers, either aligning them to brake node pressure (to apply the brake during *E-Stop*) or to the system drain line (to release the brake in all modes except *E-Stop*). Failure of solenoid valve 19.3 could either fail to apply the brake when required, or apply the brake when not required. Failures that prevent the application of the brake are of particular concern because such a failure could hinder a necessary protective safety function. If solenoid valve 19.3 became stuck in a way that did not allow fluid/pressure flow to the brake calipers, or if the valve became highly contaminated to a point that fluid/pressure flow to the brake calipers was obstructed, braking capabilities would be reduced or disabled.

Reduced or disabled braking capability alone would only hinder, and not disable, protective safety functions because the brake is only applied in *E-Stop*; protective functions that initiate *Pause* or *Stop* do not require braking force and would not be directly affected by a failure of solenoid valve 19.3. *E-Stop* also relies on the pitching system as well as the brake to slow down and stop the rotor, and can only be disabled if both the pitch node and the brake node experience failures.

5.3.3 Hydraulic System Contamination

The purpose of the SWiFT Hydraulic System FMEA is to determine if a single failure in the hydraulic system could reasonably disable both the pitching and brake nodes. Although multiple components would have to fail to disable both turbine braking capabilities and active and passive pitching, the single failure of a highly contaminated system could initiate multiple failures in the downstream nodes.

Contamination severe enough to cause obstruction of the system components mentioned above is unlikely to occur in the Vestas hydraulic system. The system is closed, and vented to atmosphere through the air/filling filter. The system filling procedure directs the [the type of hydraulic fluid used] and that the system must be filled via the air/filling filter to minimize contamination. The hydraulic system is regularly inspected and tested via the SWiFT Preventive Maintenance schedule (PM).

Contamination severe enough to cause obstruction of the system components mentioned above is unlikely to go undetected by the SWiFT turbine operators. HPF 10 is equipped with a clog indicator that alerts operators to problems with the system filter, including clogging caused by contamination. Assuming a failure of the clog indicator and the associated alarms, operators would likely be alerted to a problem in the hydraulic system through unusual system response from highly contaminated fluid. Slowed response in the pitching system would likely activate pitch alarms 190 and 191, which initiate a *Stop* in the event of unexpected pitch position or velocity response.

Given the current SWiFT control set, hydraulic system contamination is highly unlikely to cause the simultaneous failure of both the pitching and brake nodes while the turbine is operating, without operator detection, and without causing other component failures to trigger protective actions. Therefore, the single failure of hydraulic system contamination is highly unlikely to cause catastrophic turbine failure or prevent a needed protective action.

6.0 Recommended Actions

Because the conclusions of the FMEA are dependent on dynamic information, the recommended actions generated from the FMEA workshops should be completed. The results and subsequent conclusions of the FMES may not be valid if the recommended actions are not completed. The recommended actions recorded during the FMEA workshop are compiled in Appendix F.

6.1 Increase Filter Controls

The SWiFT Hydraulic System FMEA emphasized the safety importance of hydraulic fluid filter controls to the hydraulic system and the turbine. If feasible, increasing filter support could improve the reliability of the system. For example, increasing the frequency of fluid contamination checks, increasing the frequency of filter change-outs, and stocking spare filters at the SWiFT facility may improve system reliability. The system filling procedure should be reviewed to ensure that filling and filter requirements are clear and easily understood. SWiFT operators should be trained and knowledgeable on expected system response, and possible indications of a contaminated system.

6.2 Increase Pressure Controls

The SWiFT Hydraulic System FMEA emphasized the safety importance of pressure sensor 12 to the hydraulic system and the turbine. Currently, pressure sensor 12 has no redundant backup. If feasible, adding a redundant or backup pressure sensor to the pitching node could improve the reliability of the system.

There is also no indication or mitigative control if pressure sensor 12 is reading pressure higher than accurate. A high-reading pressure sensor 12 would maintain system pressure low (possibly reducing pitching capability), and would result in more hydraulic fluid stored in the system tank. A high-level indication in the tank could aid in alerting the operators or nacelle controller to a problem with pressure sensor 12, and subsequent low pressure in the system. Alternatively, nacelle controller monitoring of pressure sensor 12 signal plausibility, and associated alerts or alarms, may improve system reliability.

A hydraulic system leak within the capacity of the system pump may not be clearly indicated to the turbine operators. The SWiFT Hydraulic System FMEA showed that such leaks will not jeopardize the turbine, but internal leaks can lead to turbine wear and external leaks lose hydraulic fluid to the nacelle and could result in an automatic protective action. If feasible, an alert or alarm for frequent pump activity could improve the reliability of the system and avoid consequences of some leaks. An alert or alarm for frequent pump activity would also decrease the risk of over-pressurization of the pitch nodes due to a continuously-running pump.

6.3 Increase Pitch Ram and Position Sensor Controls

The SWiFT Hydraulic System FMEA emphasized the safety importance of the pitch ram and the associated position sensor, and the relative lack of associated controls. PM intervals and methods for other components are better established than those for the pitch ram position sensor and the pitch ram itself. The associated procedures should be reviewed and updated, if necessary, to include inspection of the ram and calibration of the sensor.

7.0 References

CCPS 2008 Guidelines for Hazard Evaluation Procedures, 3rd Edition, CCPS, 2008

Sandia 2013 MN471017, Safety Basis Manual, 2013

Sandia 2015a SWiFT Facility Safety Analysis, Sandia 2015

Sandia 2015b SWiFT Emergency Stop Circuit FMEA, Sandia 2015

Vestas 1994a Vestas V-27 Electrical Operating and Maintenance Manual, 1994

Vestas 1994b Vestas V-27 Mechanical Operating and Maintenance Manual, 1994

Appendix A—FMEA Attendance Sheets

Part #1.

SWiFT Hydraulic System FMEA
April 1st, 2015

LIST OF ATTENDEES

Name	Organization	Responsibility	Phone	E-Mail
1. Jonathan Berg	06121	SME	284-0905	jcberg@sandia.gov
2. Holly Chamberlin	0426	SME		hchambe@sandia.gov
3. Tim Stirrup [illegible]	4126	IPSB	845-4155	tsstirr@sandia.gov
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11.				
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16. Kelsey Curran	04126	Facilitator	845-1074	klfcurr@sandia.gov
17. Courtney Pruitt	04126	Scribe	845-7751	cjpruit@sandia.gov

SWiFT Hydraulic System FMEA
April 2015

Appendix A—FMEA Attendance Sheets

SWiFT Hydraulics System FMEA

Hydraulics System FMEA Workshop, Part 2

April 9, 2015

List of Attendees

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Appendix A—FMEA Attendance Sheets

SWiFT HS FMEA Part 3

May 6, 2015

List of Attendees

Name	Org #	Email
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Appendix B—Component and Failure Modes Table

ID #s	Component	Notes	Failure Modes (Normal Modes in Bold)
2.5 3.5 4.5	Accumulator 16	The pump motor and pressure sensor 12 keep accumulator 16 charged to 75 – 90 bar. Below this pressure, the pitching nodes have reduced operability. The accumulator is pre-charged to 30 bar, so if the system falls <30 bar, the pitching nodes have no operability.	High Pressure (>90 bar) **System Pressure (75 – 90 bar)** Low Pressure (<75 bar) No Pressure (<30 bar)
5.4 6.4	Accumulator 27	PRV 24 keeps accumulator 27 charged to 19+-1.5 bar. Below this pressure, the brake nodes have reduced operability. The accumulator is pre-charged to 9 bar, so if the system falls <9 bar, the brake nodes have no operability.	High Pressure (>20.5 bar) **System Pressure (19+-1.5 bar)** Low Pressure (9 – 17.5 bar) No Pressure (<9 bar)
1.5	Air/Filling Filter	The air/filling filter is a tank component that serves a dual purpose: it vents the tank to atmospheric pressure via a filter to prevent contamination of the tank, and it filters the hydraulic fluid during the loading procedure. The filter is designed to catch contamination either in the hydraulic fluid or the air.	**Normal** Fluid Flow—Broken Filter Air Flow—Broken Filter
5.11 6.11	Brake	When the brake is aligned to pressure, it is applied. Aligned to the drain, the brake is not applied.	**Applied** **Not Applied**
1.8 2.7 2.13 2.19 3.13 3.19 4.7 4.13 5.3 6.3	Check Valves	Check valves allow one-way flow/pressure downstream. These valves are reliable mechanical components. Back flow/back pressure because of valve failure or contamination would be minimal. Node 1 is analyzed in terms of flow, while the remaining nodes are analyzed in terms of pressure. The "Pressure" and "Flow" failure modes mean the same thing (that hydraulic fluid is moving through the valve), but highlight different systemic effects.	**In Node 1:** **Flow** Back Flow No Flow **In Nodes 2 – 6:** **Pressure** Back Pressure **No Pressure**
1.7	High-Pressure Filter (HPF)	The HPF consists of a filter, a bypass valve, and a pressure sensor across the filter. During normal ops, flow is through the filter and the sensor reads correct pressure. Failure of the HPF means flow does not go through the filter, or the senor is faulty.	**Flow—Filter, Sensor Reads Pressure** Flow—Broken Filter Flow—Bypass Faulty Signal—On Faulty Signal—Off/No Signal
2.8 3.8 4.8 5.7 6.7	Needle Valves	The system is equipped with needle valves to slowly bleed accumulator pressure to the tank before maintenance. Inadvertent flow ("pressure") because of valve failure or contamination would be minimal.	Pressure **No Pressure**

Appendix B—Component and Failure Mode Table

ID #s	Component	Notes	Failure Modes (Normal Modes in Bold)
2.6 **3.6** **4.6** **4.19** **5.6** **6.6**	Nozzles	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components. The normal mode for nozzles is "Pressure" (flow), and the failure mode is no flow due to contamination.	**Pressure** No Pressure
2.12 **3.12** **4.12**	Pitch Proportional Valve (PPV)	If the PPV is energized, it directs pressure (flow) either to the "run" side of the pitching ram, or the "feather" side. If it is deenergized, no pressure flows through the valve. All three are normal modes for the PPV.	**Pressure—"run"** **Pressure— "feather"** **No Pressure**
2.15 **3.15** **4.15**	Pitch Ram	The pitch ram is designed to move in response to pressure. The failure mode of the ram is "No Movement."	**Movement** No Movement
2.16 **3.16** **4.16**	Pitch Ram Position Sensor	In *Run* or *Pause*, the sensor's normal mode is to read the position of the pitching ram. In *Stop* or *E-Stop*, the sensor does not have inputs into software logic, and the normal mode is "No Reading."	**Reads Position** Faulty Reading—High/Low Faulty Reading—No/Stuck Reading **No Reading**
2.9 **3.9** **4.9** **5.2** **6.2**	Pressure Reduction Valve 24 (PRV 24)	PRV 24 reduces and regulates pressure to the brake nodes at 19 bar. At 25 bar, relief valve 29 relieves pressure. At 14 bar, pressure switch 26 turns off and triggers pressure alarm 162. Accumulator 27 is pre-charged to 9 bar, so if the system falls <9 bar, the brake nodes have no operability.	High Pressure (>25 bar) **Maintains Pressure (14 – 25 bar)** Low Pressure (9 – 14 bar) No Pressure (<9 bar)
1.9 **2.2** **3.2** **4.2**	Pressure Sensor 12	Pressure sensor 12 initiates actions for high, low, and no readings. If a faulty sensor reads in-range, a needed action or protection may not be initiated.	Faulty Signal—High Faulty Signal—In Range Faulty Signal—Low No Signal (reads -25 bar) **Reads Pressure**
5.5 **6.5**	Pressure Switch 26	Pressure switch 26 initiates protective actions for a low reading or no reading. If a faulty sensor reads high or in-range, a needed protective action may not be initiated.	Faulty Signal—High/In Range Faulty Signal—Low/No Signal **Reads Pressure**
1.3	Pump Motor	In automatic mode, the pump motor is operated according to pressure. Pressure sensor 12 sends a signal to turn the pump on at 75 bar and off at 90 bar.	**Automatic** Off On
1.9 **2.3** **3.3** **4.3**	Relief Valve 13	Relief valve 13 releases pressure from the pitch nodes at 100+5 bar. Failure modes include at too high setting (low or no flow, high pressure) or a too low setting (high flow, low pressure).	High Flow/Low System Pressure (<100 bar) **Pressure at 100+5 bar** Low/No Flow/High System Pressure (>105 bar)

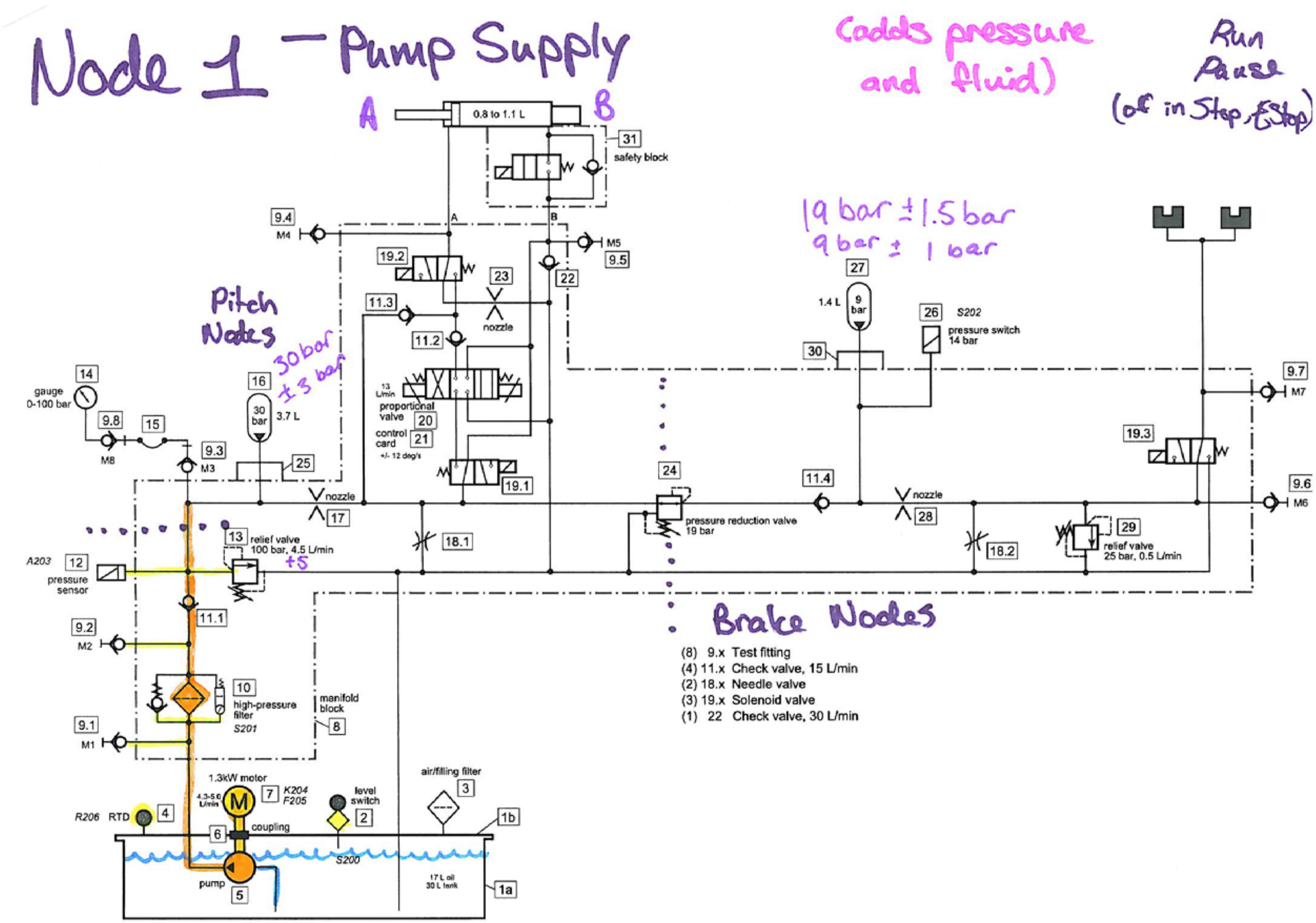
Appendix B—Component and Failure Mode Table

ID #s	Component	Notes	Failure Modes (Normal Modes in Bold)
5.8 **6.8**	Relief Valve 29	Relief valve 29 releases pressure from the brake nodes at 25 bar. Failure modes include at too high setting (low or no flow, high pressure) or a too low setting (high flow, low pressure).	High Flow/Low System Pressure (<25 bar) **Pressure at 25 bar** Low/No Flow/High System Pressure (>25 bar)
1.4	RTD	The system RTD initiates protective actions for both high and low temperatures. If a faulty RTD reads in-range, a needed protective action may not be initiated.	**Normal** Faulty Signal—High Faulty Signal—In Range Faulty Signal—Low/No Signal
2.17 **3.14** **4.14**	Safety Block	The purpose of the safety block is to hold pressure against the "feather" side of the ram in *Stop* or *E*-stop ("One-Way Pressure"). In *Run* or *Pause*, "Two-Way Pressure" is allowed.	**One-Way Pressure** **Two-Way Pressure** No Pressure
2.11 **3.11** **4.11**	Solenoid Valve 19.1	"Pressure—PPV" means the solenoid valve is energized and pressure/flow is directed to the PPV. "Pressure—Safety Block" means solenoid valve is deenergized and pressure/flow is directed to the Safety Block.	**Pressure—PPV** **Pressure—Safety Block** No Pressure
2.14 **3.18** **4.18**	Solenoid Valve 19.2	"Pressure—PPV" means the solenoid valve is energized and pressure/flow is directed from the PPV to the "run" side of the pitching ram. "Pressure—Drain" means solenoid valve is deenergized and the "run" side of the ram is aligned to the drain.	**Pressure—PPV** **Pressure—Drain** No Pressure
5.10 **6.10**	Solenoid Valve 19.3	"Pressure—Drain" means the solenoid valve is energized and the brake is aligned to the drain. "Pressure—Brake" means solenoid valve is deenergized and pressure/flow is directed to the brake.	**Pressure—Brake** **Pressure—Drain** No Pressure
1.1	Tank	30 L tank will hold all the hydraulic fluid in the system with the accumulators blown.	High Level **Normal Level (27 L)** Low Level
1.2	Tank Level Switch	The tank level switch initiates protective action at a low or no reading. If a faulty switch reads on when tank level is low, a needed protective action may not be initiated.	**On (High Level, Normal Level)** **Off (Low Level)** Faulty Signal—On Faulty Signal—Off/No Signal
1.6 **2.4** **2.18** **3.4** **3.17** **4.4** **4.17** **5.9** **6.9** **6.12**	Test Fittings	Test fittings allow temporary equipment such as gauges to be connected to the system. The normal mode for fittings is "No Flow/No Pressure." Node 1 is analyzed in terms of flow, while the remaining nodes are analyzed in terms of pressure. The "Pressure" and "Flow" failure modes mean the same thing (that hydraulic fluid is moving through the fitting), but highlight different systemic effects.	**In Node 1:** Flow **No Flow** **In Nodes 2 – 6:** Pressure **No Pressure**

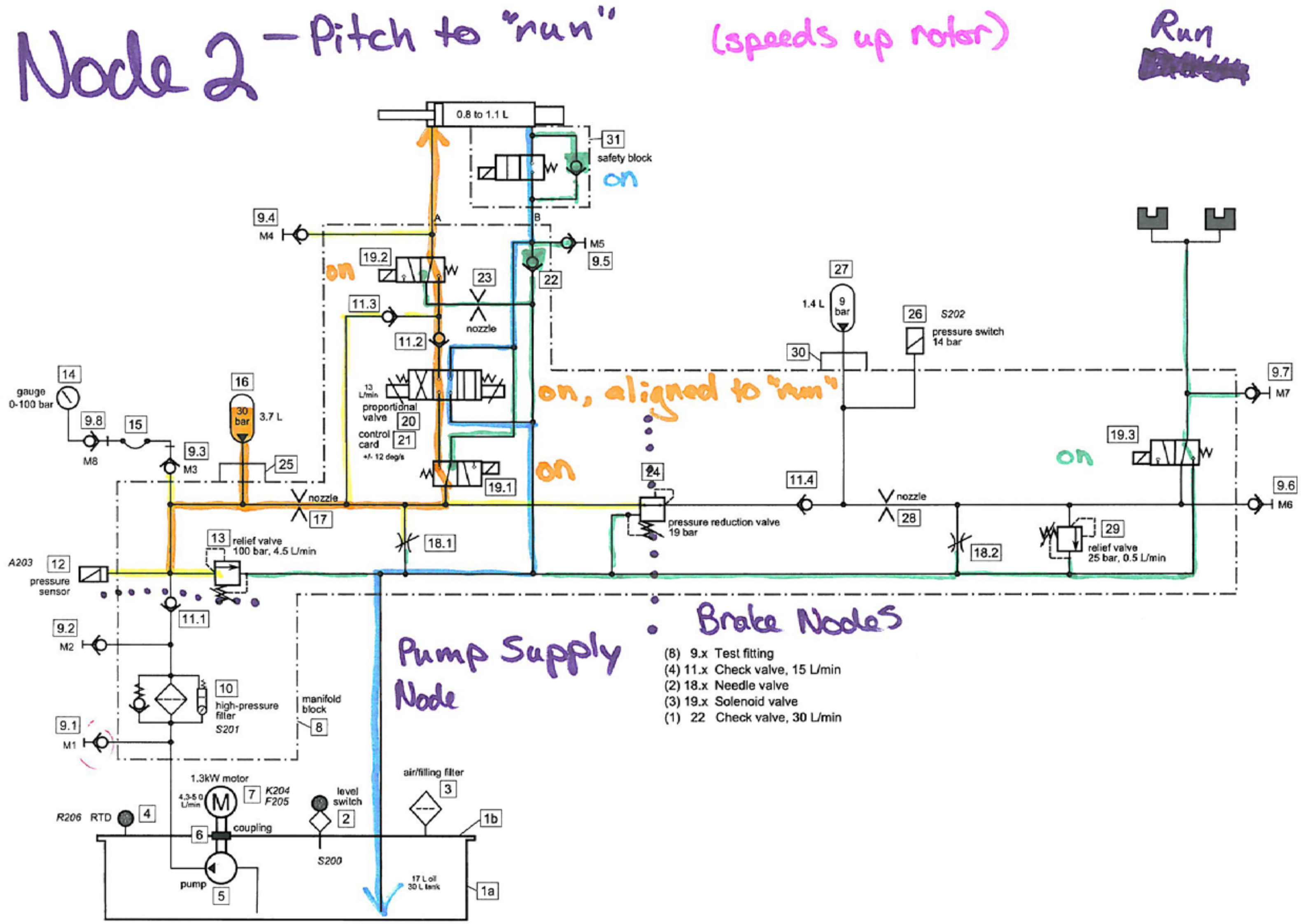
Appendix B—Component and Failure Mode Table

ID #s	Component	Notes	Failure Modes (Normal Modes in Bold)
2.1 **3.1** **4.1**	**Pump Supply Node (1)**	Node 1 can affect downstream nodes (pitch nodes and brake nodes) by delivering high, low, or no pressure, or by supplying contaminated fluid.	**On Downstream Nodes (2 – 4):** Contaminated Fluid High Pressure/Flow Low/No Pressure/Flow **Normal**
1.11 **5.1** **6.1**	**Pitch Nodes (Nodes 2, 3, 4)**	The pitch nodes can affect downstream nodes (brake nodes) by passing on any failure modes from node 1, loss of active pitching, or loss of passive pitching. A leak in the pitch nodes is captured in the "Low/No Pressure" failure mode. The pitch nodes can affect the upstream node (pump supply node) by a pressure/fluid loss caused by a pitch node leak.	**On Upstream Node (1):** Pressure/Fluid Loss (Leak) **Normal** **On Downstream Nodes (5, 6):** Contaminated Fluid High Pressure/Flow Low/No Pressure/Flow Pitch Malfunction—No Active Control Pitch Malfunction—No Passive Pitch **Normal**
2.10 **3.10** **4.10**	**Brake Nodes (5, 6)**	The brake nodes can affect upstream nodes (pitch nodes) by a pressure/fluid loss caused by a brake node leak, or by a misaligned brake.	**On Upstream Nodes (2 – 4):** Pressure/Fluid Loss (Leak) Brake Malfunction—Applied Brake Malfunction—Not Applied **Normal**

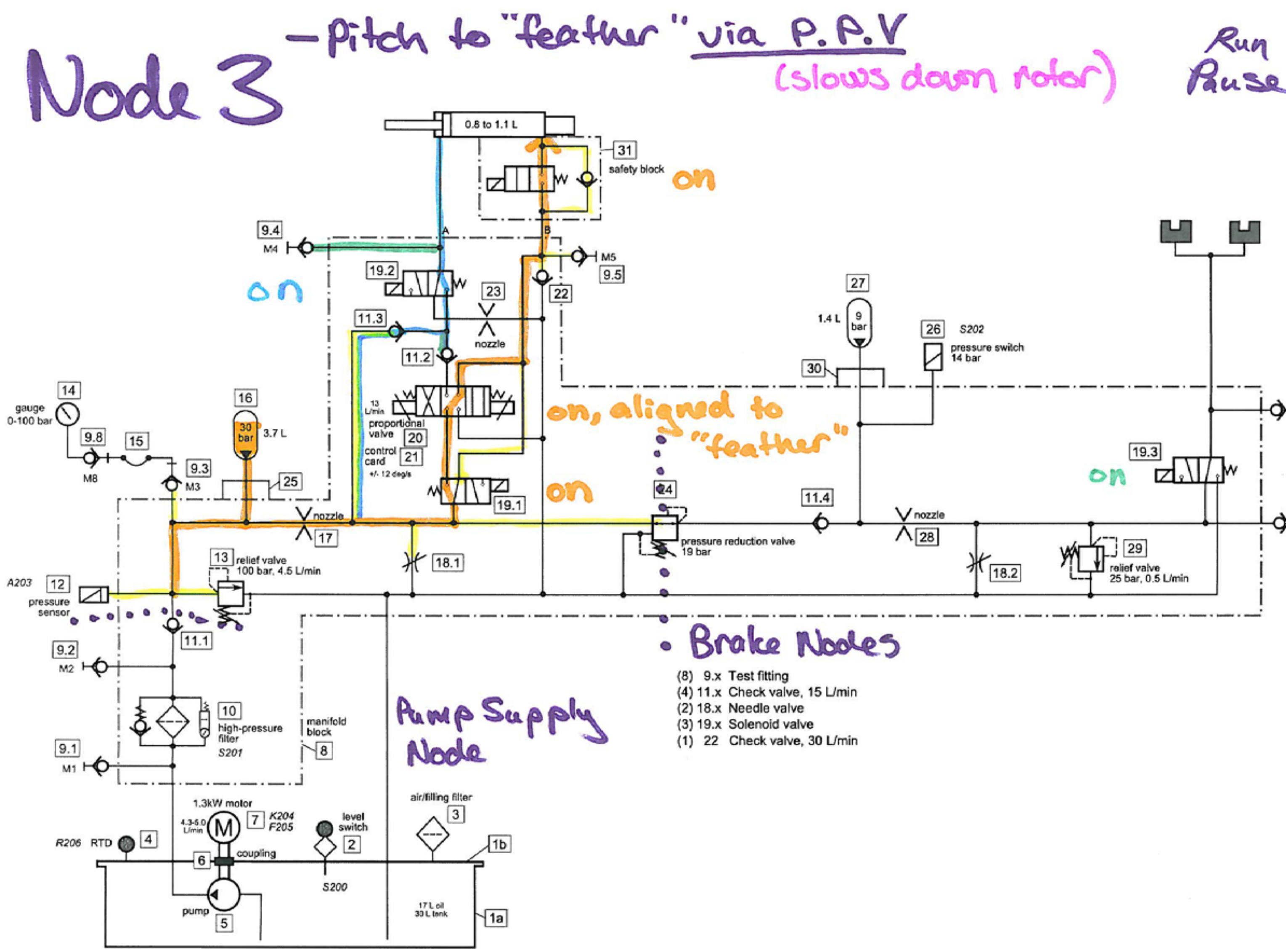
Appendix C—SWiFT Hydraulic System Nodes



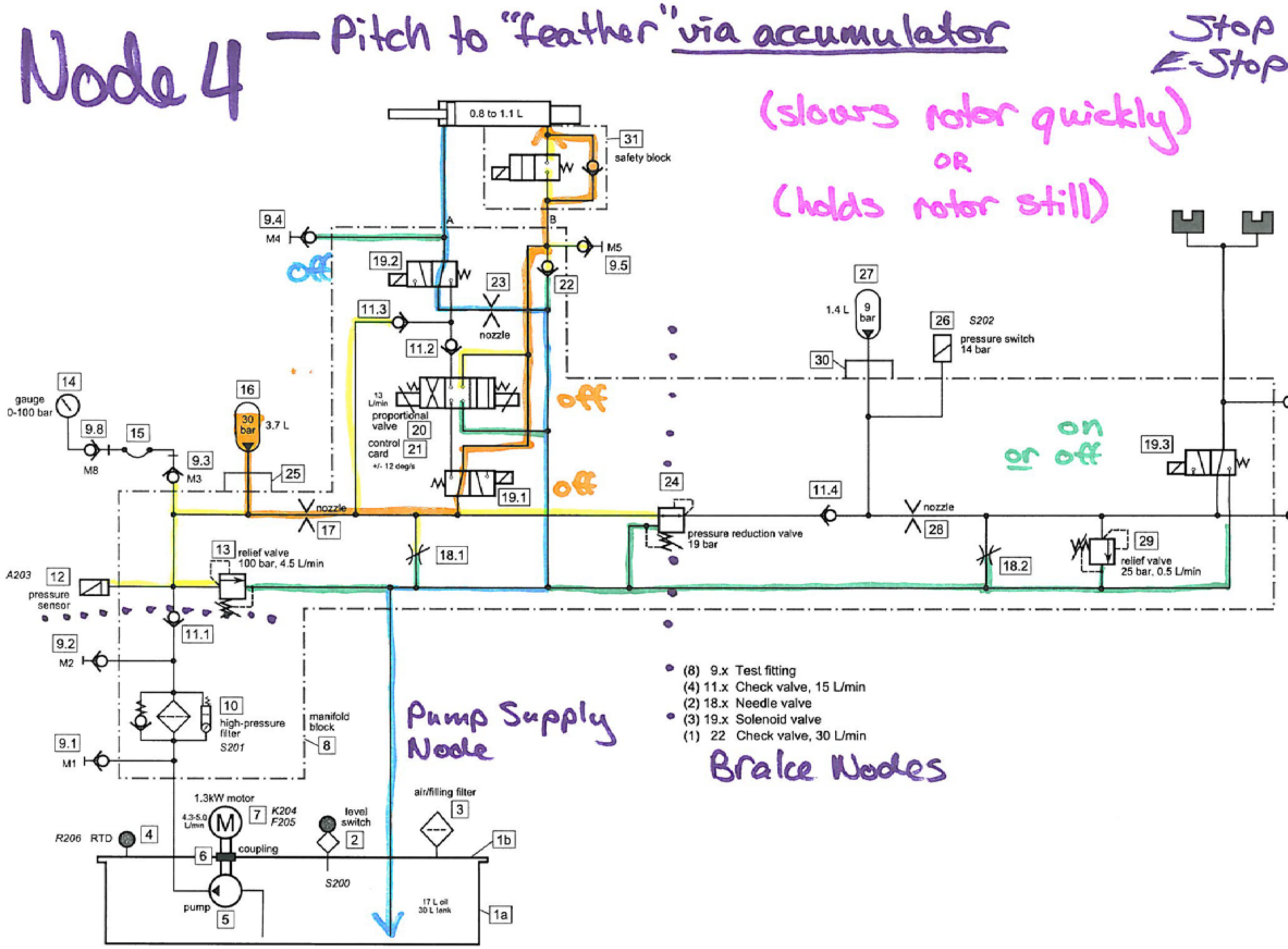
Appendix C—SWiFT Hydraulic System Nodes



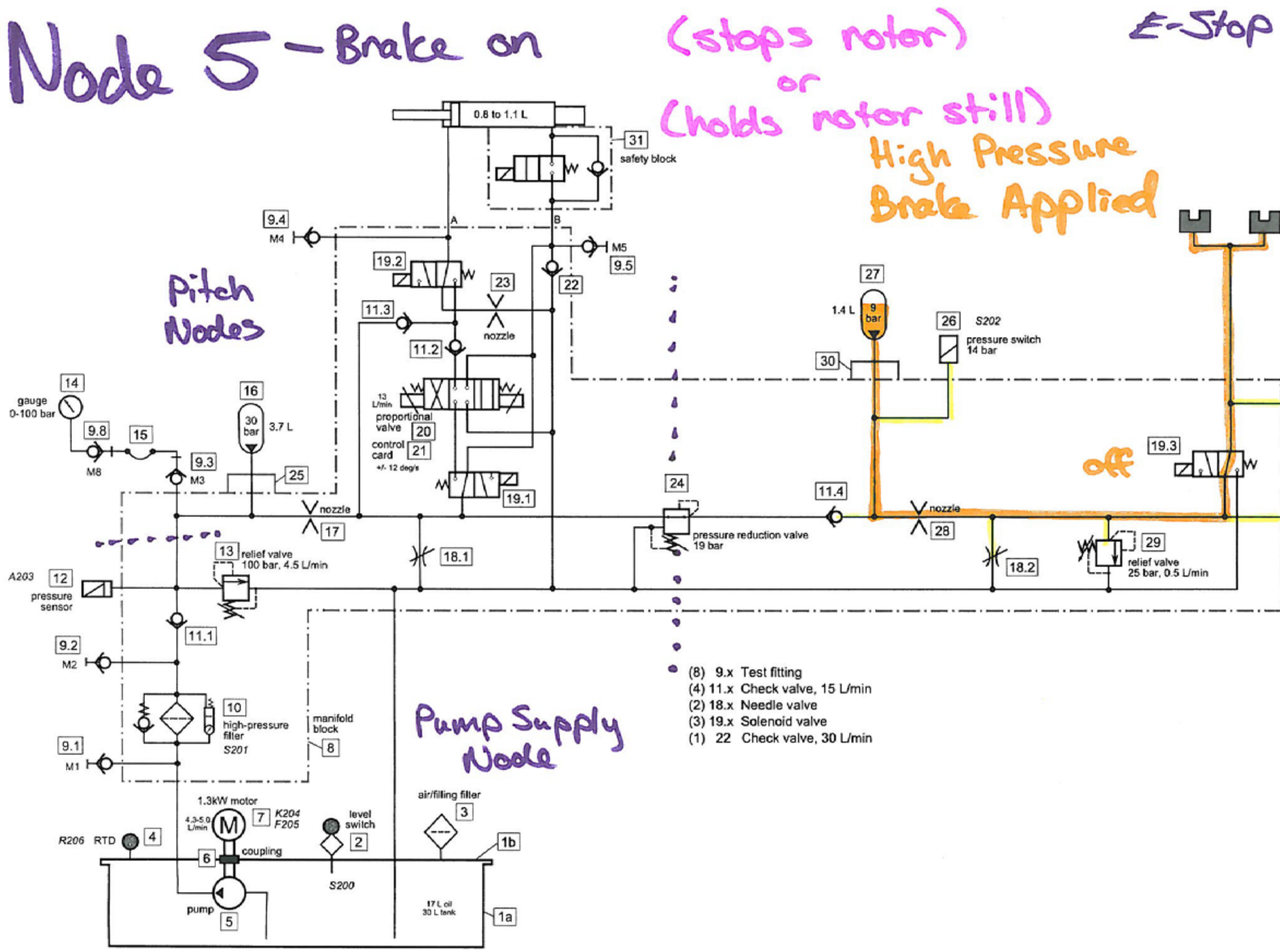
Appendix C—SWiFT Hydraulic System Nodes



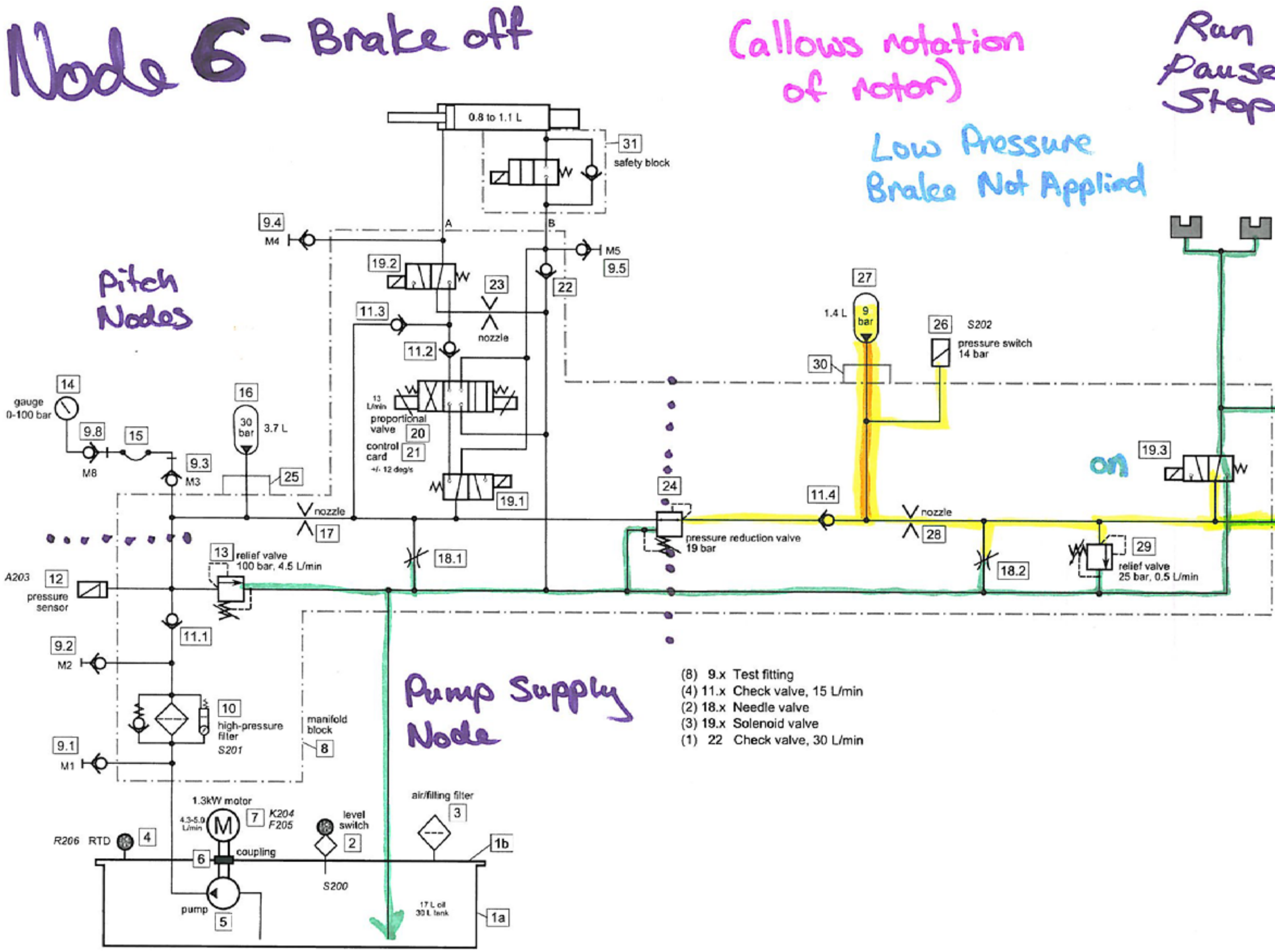
Appendix C—SWiFT Hydraulic System Nodes



Appendix C—SWiFT Hydraulic System Nodes



Appendix C—SWiFT Hydraulic System Nodes



Appendix D—FMEA Tables

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	**Node 1—Pump Supply Node**					
1.1.1	Tank	30 L tank will hold all the hydraulic fluid with system at atmospheric pressure (accumulators blown).	High Level	• Hydraulic fluid spill	• Human error	• Procedure—filling
1.1.2			**Normal Level (27 L)**	• **Normal ops**		
1.1.3			Low Level	• Pump wear • Pump cavitation (reduced system pressure) • Dry pump (no system pressure)	• System leak • Human error	• Level alarm 165 (initiates *E-Stop*) • Closed system • Procedure—filling • PM—hydraulic system
1.2.1	Tank Level Switch	On/off level switch with digital input to controller. Level alarm 165 sends turbine to *E-Stop* via controller if sensor is off (low level) for 2 seconds.	**On (High Level, Normal Level) Off (Low Level)**	• **Normal ops**		
1.2.2			Faulty Signal—On	• No indication of low tank level	• Sensor failure	• PM—tank level switch
1.2.3			Faulty Signal—Off/No Signal	• Level alarm 165 (initiates *E-Stop*)	• Sensor failure	• PM—tank level switch
1.3.1	Pump Motor	The pump supplies 4.3 – 5.0 L/min to the hydraulic system and is run by a 1.3 kW motor. In automatic mode, the nacelle controller turns the pump on at 75 bar (via pressure sensor 12) and off at 90 bar. Pump activity is indicated by the pump contactors	**Automatic**	• **Normal ops**		
1.3.2			Off	• Reduced system pressure • No system pressure	• Pump failure • Broken wire	• Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • PM—pump motor

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	**Node 1—Pump Supply Node**					
1.3.3		and Pressure Switch 12. The contactor is monitored by the controller. Pump alarm 161 sends turbine to *E-Stop* if the pump is on and pressure doesn't rise >75 bar within 60 seconds.	On	• Increased system pressure • System/component damage	• Pump contactor malfunction • Faulty controller signal	• Relief valve 13 • Temperature alarm 167 (initiates *E-Stop*)
1.4.1	RTD	The temperature sensor sends a signal to controller. High temperature could indicate the pump is cycling too often. Temperature alarm 167 sends turbine to *E-Stop* if sensor reads >65 C for 20 seconds, to prevent system damage. Very low temperature fluid could affect operability. Temperature alarm 88 sends turbine to *Pause* if the sensor reads <-20 C for 20 seconds, to prevent system damage. Controller alarm 212 sends the turbine to *Pause* when any RTDs sends an out-of-range reading (including no signal).	**Normal**	• **Normal ops**		
1.4.2			Faulty Signal—High	• Temperature alarm 167 (initiates *E-Stop*) • Controller alarm 212 (initiates *Pause*)	• Sensor failure	• PM—RTD • Running history (compare to ambient temperature)
1.4.3			Faulty Signal—In Range	• No indication of extreme temperatures • No indication of cycling pump/system leak	• Sensor failure	• PM—RTD • Procedure—Limited operations in extreme weather
1.4.4			Faulty Signal—Low/No Signal	• Temperature alarm 88 (initiates *Pause*) • Controller alarm 212 (initiates *Pause*)	• Sensor failure • Broken wire	• PM—RTD • Running history (compare to ambient temperature)
1.5.1	Air/Filling Filter	The air/filling filter is a tank component that serves a dual	**Normal**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	Node 1—Pump Supply Node					
1.5.2		purpose: it vents the tank to atmospheric pressure via a filter to prevent contamination of the tank, and it filters the hydraulic fluid during the loading procedure. The filter is designed to catch contamination either in the hydraulic fluid or the air.	Fluid Flow—Broken Filter	• System contamination • Degradation of valve and component function	• Human error • Mechanical failure	• Procedure—filling • HPF 10 • PM—air/filling filter
1.5.3			Air Flow—Broken Filter	• System contamination • Degradation of valve and component function	• Human error • Mechanical failure	• HPF 10 • PM—air/filling filter
1.6.1	Test Fittings 9.1 and 9.2	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	**No Flow**	• **Normal ops**		
1.6.2			Flow	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • Level alarm 165 (initiates *E-Stop*)
1.7.1	High-Pressure Filter 10	High-Pressure Filter with an on/off filter sensor and bypass valve. Sensor sends signal to	**Flow—Filter Sensor Reads Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	**Node 1—Pump Supply Node**					
1.7.2	(HPF 10)	controller. Sensor turns off at a pressure differential of 5 bar, indicating a clog in the filter. If the sensor turns off for 2 seconds, a message indicates that the filter/sensor needs maintenance. If sensor turns off/has no signal, filter alarm 164 sends the turbine to *Stop*. Bypass valve opens at a pressure differential of 7 bar, to avoid destroying the filter. (Both pressures are +-10%.) Hydraulic System filling procedure directs that the fluid be filtered before it is added to the system. The system tank is equipped with an air/filling filter to prevent contaminants in the system.	Flow—Broken Filter	• System contamination • Degradation of valve and component function	• Broken filter (pressure increase against clogged filter)	• Filter alarm 164 (initiates *Stop*) • Bypass valve • PM—HPF 10 • Procedure—filling • Air/filling filter
1.7.2			Flow—Bypass	• System contamination • Degradation of valve and component function	• Dirty filter • Mechanical failure of bypass valve	• Filter alarm 164 (initiates *Stop*) • PM—HPF 10 • Procedure—filling • Air/filling filter
1.7.3			Faulty Signal—On	• No indication of clogged filter	• Sensor failure	• PM—HPF 10
1.7.4			Faulty Signal—Off/No Signal	• Filter alarm 164 (initiates *Stop*)	• Sensor failure • Broken wire	• PM—HPF 10
1.8.1	Check Valve 11.1	Check valve 11.1 prevents the pressurized system from draining back to the tank, which is vented to atmospheric pressure. Because the check valve holds system pressure, the pump only has to cycle when pressure drops due to normal draining.	**Flow**	• **Normal ops**		
1.8.2			Back Flow	• Loss of system fluid/pressure • Pump cycling/wear	• Contamination • Mechanical failure	• HPF 10 • Air/filling filter • PM—hydraulic system • See endnote 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	Node 1—Pump Supply Node					
1.8.3			No Flow	• Pump turns on, pressure does not increase • No system pressure	• Contamination • Mechanical failure	• HPF 10 • PM—HPF 10, air/filling filter • Air/filling filter • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • Nacelle controller
1.9.1	Pressure Sensor 12	Pressure sensor 12 measures system pressure upstream of check valve 11.1 and downstream of Pressure Reduction Valve 24 (Nodes 2 – 4). The sensor sends a signal to the controller. At 75 bar, the controller turns on the pump to increase system pressure. At 90 bar, the controller turns the pump off. The controller prevents the turbine from moving to *Pause* until system pressure rises >(?) bar. Pressure alarm 163 sends turbine to *E-Stop* at <50 bar. Alarm (?) sends the turbine to *E-Stop* if pressure sensor 12 has no reading.	Faulty Signal—High	• Pump turns off • High level tank because less fluid in system	• Sensor failure	• PM—pressure sensor 12
1.9.2			Faulty Signal—In Range	• No indication of high/low pressure; no automatic pump activity	• Sensor failure	• PM—pressure sensor 12 • Relief valve 13 • Pump alarm 161 (initiates *E-Stop*)
1.9.3			Faulty Signal—Low	• Pump turns on • High pressure in system • System/component damage	• Sensor failure	• Relief valve 13 • Pump alarm 161 (initiates *E-Stop*) (see endnote 2) • Pressure alarm 163 (initiates *E-Stop*) • PM—pressure sensor 12
1.9.4			No Signal (reads -25 bar)	• Unknown system pressure	• Sensor failure • Broken wire	• Pressure alarm 163 (initiates *E-Stop)* • Pump alarm 161 (initiates *E-Stop*) • PM—pressure sensor 12

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	Node 1—Pump Supply Node					
1.9.5			**Reads Pressure**	• **Normal ops**		
1.10.1	Relief Valve 13	Relief Valve 13 relieves pressure from the Pitch Nodes to the tank if pressure rises >100+5 bar. The relief valve capacity is 4.5 L/min, which is in the range of the pump capacity (4.3 – 5.0 L/min)—i.e., unless the pump is running nearly continuously, the relief valve offers adequate protection for the system.	High Flow/Low System Pressure (<100 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced system pressure	• Mechanical failure • Contamination • Human error	• HPF 10 • Air/filling filter • Pressure sensor 12 (turns on pump) • PM—relief valve 13 • Procedure—maintenance
1.10.2			**Pressure at 100+5 bar**	• **Normal ops**		
1.10.3			Low/No Flow/High System Pressure (>105 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• HPF 10 • Air/filling filter • Pressure sensor 12 (turns off pump) • PM—relief valve 13 • Procedure—maintenance
1.11.1	Pitch Nodes (Nodes 2, 3, 4)	Nodes 2, 3, and 4 include all components from and including pressure sensor 12 and relief valve 13, up to and including PRV 24. These nodes operate the blade pitch system, pitching to “run” or “feather” to speed up or	Pressure/Fluid Loss (Leak)	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump	• Mechanical failure • Human error	• PM—hydraulic system • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • Level alarm 165 (initiates *E-Stop*)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
1	Node 1—Pump Supply Node					
1.11.2		maintain rotor speed via the PPV in *Run*, pitching to "feather" via the PPV in *Pause*, and applying pressure directly to the "feather" side of the ram in *Stop* and *E-Stop*. Pitch nodes include accumulator 16 to store reserve pressure and pressure sensor 12 to trigger protective actions.	**Normal**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.1.1	Pump Supply Node (1)	Node 1 includes all components from the system tank up to and including pressure sensor 12 and relief valve 13. Node 1 supplies filtered hydraulic fluid to downstream nodes. Node 1 adds fluid/pressure when the pitch nodes are 75 bar, and stops adding fluid/pressure with the pitch nodes are 90 bar. Node 1 includes filter controls and sensors that trigger protective actions.	High Pressure/Flow	• System/component damage	• Node 1 failure	• Relief valve 13 • Pressure sensor 12 (turns off pump) • PM—hydraulic system
2.1.2			Low/No Pressure/Flow	• Reduced active pitching • No active pitching	• Node 1 failure	• Pressure sensor 12 (turns on pump) • Check valve 11.1 • PM—hydraulic system
2.1.3			Contaminated Fluid	• System/component contamination • Reduced active pitching • No active pitching	• Node 1 failure	• HPF 10 • Air/filling filter • PM—HPF 10, air/filling filter • Procedure—filling
2.1.4			**Normal**	• **Normal ops**		
2.2.1	Pressure Sensor 12	Pressure sensor 12 measures system pressure upstream of check valve 11.1 and downstream of Pressure Reduction Valve 24 (Nodes 2 – 4). The sensor sends a signal to the controller. At 75 bar, the controller turns on the pump to increase system pressure. At 90 bar, the controller turns the pump off. The controller prevents	Faulty Signal—High	• Pump turns off • Reduced active pitching • No active pitching • High level tank because less fluid in system	• Sensor failure	• PM—pressure sensor 12
2.2.2			Faulty Signal—In Range	• No indication of high/low pressure; no automatic pump activity	• Sensor failure	• PM—pressure sensor 12 • Relief valve 13 • Pump alarm 161 (initiates *E-Stop*)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.2.3		the turbine from moving to *Pause* until system pressure rises >(?) bar. Pressure alarm 163 sends turbine to *E-Stop* at <50 bar. Alarm (?) sends the turbine to *E-Stop* if pressure sensor 12 has no reading.	Faulty Signal—Low	• Pump turns on • High pressure in system • System/component damage	• Sensor failure	• Relief valve 13 • Pump alarm 161 (initiates *E-Stop*) (see endnote 2) • Pressure alarm 163 (initiates *E-Stop*) • PM—pressure sensor 12
2.2.4			No Signal (reads -25 bar)	• Unknown system pressure	• Sensor failure • Broken wire	• Pressure alarm 163 (initiates *E-Stop)* • Pump alarm 161 (initiates *E-Stop*) • PM—pressure sensor 12
2.2.5			**Reads Pressure**	• **Normal ops**		
2.3.1	Relief Valve 13	Relief Valve 13 relieves pressure from the pitch nodes to the tank if pressure rises >100+5 bar. The relief valve capacity is 4.5 L/min, which is in the range of the pump capacity (4.3 – 5.0 L/min)—i.e., unless the pump is running nearly continuously, the relief valve offers adequate protection for the system.	High Flow/Low System Pressure (<100 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns on pump) • PM—relief valve 13 • Procedure—maintenance
2.3.2			**Pressure at 100+5 bar**	• **Normal ops**		
2.3.3			Low/No Flow/High System Pressure (>105 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns off pump) • PM—relief valve 13 • Procedure—maintenance

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.4.1	Test Fittings 9.3 and 9.4	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	**No Pressure**	• **Normal ops**		
2.4.2			Pressure	• Hydraulic fluid spill • Loss of system pressure • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (161, 163, 165)
2.5.1	Accumulator 16	Accumulator 16 stores reserve pressure for the pitching nodes via a compressible air bladder, pre-charged to 30+-3 bar. As hydraulic fluid presses against the bladder, the air compresses and pressure increases in the system. This component has been replaced with an equivalent part number.	High Pressure (>90 bar)	• System/component damage •	• Increased flow/pressure from node 1	• Relief valve 13 • Pressure sensor 12 (turns off pump)
2.5.2			**System Pressure (75 – 90 bar)**	• Normal ops		
2.5.3			Low Pressure (30 – 75 bar)	• Reduced active pitching	• Low flow/pressure from node 1 • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	**Node 2—Pitch toward "run" Node**					
2.5.4			No Pressure (<30 bar)	• No active pitching	• No flow/pressure from node 1 • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder
2.6.1	Nozzle 17	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components.	**Pressure**	• **Normal ops**		
2.6.2			No Pressure	• Reduced active pitching • No active pitching	• Contamination	• Filter controls from node 1
2.7.1	Check Valve 11.3	Check valve 11.3 allows hydraulic fluid to return to the pressurized system to reduce fluid returning to the tank and prevent cycling of the pump. It also provides a drain path for the "run" side of the pitch ram, allowing passive "feather".	Pressure	• NA—no pressure differential to allow passage		
2.7.2			Back Pressure	• No adverse effect		
2.7.3			**No Pressure**	• **Normal ops**		
2.8.1	Needle Valve 18.1	Needle valves 18.1 and 18.2 are designed to slowly relieve	**No Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.8.2		pressure from the accumulators for system maintenance. They are low-flow valves.	Pressure	• Cycling of hydraulic fluid • Cycling of pump • Reduced system pressure	• Mechanical failure • Human error	• Pressure sensor 12 (turns on pump) • Procedure—maintenance • PM—hydraulic system
2.9.1	Pressure Reduction Valve 24 (PRV 24)	Pressure Reduction Valve 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If Brake Node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.	High Pressure (>25 bar)	• System/component damage (increased braking force)	• Mechanical failure • Contamination	• PM—PRV 24 • Relief valve 29 • Filter controls from node 1
2.9.2			**Maintains Pressure (14 – 25 bar)**	• **Normal ops**		
2.9.3			Low Pressure (9 – 14 bar)	• Reduced active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
2.9.4			No Pressure (<9 bar)	• No active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
2.10.1	Brake Nodes (5, 6)	Nodes 5 and 6 include all components from and including	**Normal**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.10.2		PRV 24 to the brake calipers. These nodes operate the turbine brake, keeping the brake depressurized in *Run*, *Pause*, and *Stop*, and pressurizing the brake in *E-Stop*. Nodes 5 and 6 include accumulator 27 to store reserve pressure and pressure switch 26 to trigger protective action.	Pressure/Fluid Loss	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pitching • No active pitching	• Node 5, 6 failure	• PM—hydraulic system • Alarms from Node 1 (initiate *E-Stop*) (161, 163, 165)
2.10.3			Brake Malfunction—Applied	• System/component damage	• Node 6 failure (solenoid 19.3 misaligned)	• UPS • PM—hydraulic system • CM—controller software • Filter controls from node 1
2.10.4			Brake Malfunction—Not Applied	• No node effect • No overspeed protection	• Node 5 failure	• Filter controls from node 1 • Alarms from node 1 (see endnote 3) • PM—hydraulic system, accumulator 27, emergency brake, PRV 24, pressure switch 26 • Pressure alarm 162 (initiates *E-Stop*) • PRV 24 (supplies node pressure) • Active pitch • Procedure—maintenance • CM—controller software
2.11.1	Solenoid Valve 19.1	Solenoid valve 19.1 aligns accumulator 16 to the PPV when	**Pressure—PPV**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.11.2		energized (in *Run* and *Pause*) and to the "feather" side of the Pitch Ram when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the same power source.	Pressure—Safety Block	• Active "feather" • No "run"	• Power loss to 19.1 (wire break) • Power loss to system • Faulty controller command to solenoid valves • Contamination • Mechanical failure	• UPS • CM—controller software • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system
2.11.3			No Pressure	• No "run" • No active "feather"	• Contamination • Mechanical failure	• Check valve 11.3 • Check valve 22 • Passive "feather" • Filter controls from node 1 • PM—hydraulic system • See endnote 4
2.12.1	Pitch Proportional Valve (PPV)	The PPV is a 3-way proportional valve with three normal modes: Pressure to "run", Pressure to "feather", and no flow/pressure. The PPV is monitored and controlled by the Vickers Card (position 21), which moves the valve to achieve and maintain an optimum rotor speed.	**Pressure—"run"**	• **Normal ops**		
2.12.2			Pressure—"feather"	• Active "feather" • No "run"	• Vickers card failure • Contamination • Mechanical failure	• PM—Vickers card • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.12.3			No Pressure	• No "run"	• Vickers card failure • Contamination • Mechanical failure • Power loss to PPV (broken wire, source loss) • Power loss to system	• UPS • PM—Vickers card • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—Hydraulic system
2.13.1	Check Valve 11.2	Check valve 11.2 prevents hydraulic fluid from the "run" side of the Pitch Ram from draining to the tank, to reduce fluid loss and prevent cycling of the pump.	**Pressure**	• **Normal ops**		
2.13.2			Back Pressure	• NA—no pressure differential to allow passage		
2.13.3			No Pressure	• No "run"	• Contamination • Mechanical Failure	• Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system
2.14.1	Solenoid Valve 19.2	Solenoid valve 19.2 aligns the "run" side of the ram to the PPV	**Pressure—PPV**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.14.2		when energized (in *Run* and *Pause*) and to the drain when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the same power source.	Pressure—Drain	• No "run"	• Power loss to 19.2 (wire break) • Power loss to system • Faulty controller command • Contamination • Mechanical failure	• UPS • CM—controller software • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system
2.14.3			No Pressure	• No "run" • No drain for "run" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • PM—hydraulic system, emergency brake • See endnote 5
2.15.1	Pitch Ram	The pitch ram is designed to move in response to applied	**Movement**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.15.2		pressure. The movement of the ram translates to rotation of the turbine blades along their longitudinal axis, which controls the speed of the rotor.	No Movement	• No "run" • No active "feather" • No passive "feather"	• Leak in pitch ram • Loss of system pressure • Contamination • Bent ram/mechanica l failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • PM—hydraulic system, emergency brake • See endnote 6
2.16.1	Pitch Ram Position Sensor	This sensor tracks the pitch angle by measuring the linear position of the pitch ram. Pitch alarm 190 (Pitch Error) sends turbine to *Stop* if desired pitch position and measured pitch position are >10% different for >10 seconds. Pitch alarm 191 (pitch velocity alarm) sends turbine to *Stop* if desired rotor velocity and measured rotor velocity (via ?) do not match.	**Reads Position**	• **Normal ops**		
2.16.2			Faulty Reading—High/Low	• Sends pitch to wrong setting	• Calibration error • Sensor failure	• Pitch alarm 191 (initiates *Stop*) • Rotor speed controls (initiate *Stop*, *E-Stop*) • PM—sensor calibration • See endnote 7
2.16.3			Faulty Reading—No/Stuck Reading	• Sends pitch to wrong setting	• Sensor failure • Sensor coupling loose from shaft • Power loss to system	• Pitch alarm 191 (initiates *Stop*) • Pitch alarm 190 (initiates *Stop*) • Rotor speed controls (initiate *Stop*, *E-Stop*) • PM—sensor calibration • UPS

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.17.1	Safety Block	This component consists of a parallel solenoid valve and check valve. The purpose of the safety block is to allow 2-way pressure in and out of the "feather" side of the ram in *Run* and *Pause* (through the activated solenoid valve), but only allow and hold pressure in during *Stop* and *E-Stop* (through the check valve), to keep the turbine in "feather" even if upstream pressure degrades.	**Two-Way Pressure**	• **Normal ops**		
2.17.2			One-Way Pressure	• No drain for "feather" • No "run"	• Power loss to solenoid (wire break, source loss) • Contamination • Mechanical failure	• UPS • Pitch alarm 191 (initiates *Stop*) • Pitch alarm 190 (initiates *Stop*) • See endnote 8 • Filter controls from Node 1 • PM—hydraulic system
2.17.3			No Pressure	• No drain for "feather" • No supply for "feather" • No "run" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from Node 1 • PM—hydraulic system, emergency brake • See endnote 5
2.18.1	Test Fitting 9.5	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	**No Pressure**	• **Normal ops**		
2.18.2			Pressure	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from Node 1 (initiate *E-Stop*) (161, 163, 165)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
2	Node 2—Pitch toward "run" Node					
2.19.1	Check Valve 22	Check valve 22 allows fluid to enter the "feather" side of the Pitch Ram from the hydraulic system tank, allowing passive pitching.	Pressure	• NA—no pressure differential to allow passage		
2.19.2			Back Pressure	• No adverse effect		
2.19.3			**No Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.1.1	Pump Supply Node (1)	Node 1 includes all components from the system tank up to and including pressure sensor 12 and relief valve 13. Node 1 supplies filtered hydraulic fluid to downstream nodes. Node 1 adds fluid/pressure when the pitch nodes are 75 bar, and stops adding fluid/pressure with the pitch nodes are 90 bar. Node 1 includes filter controls and sensors that trigger protective actions.	High Pressure/Flow	• System/component damage	• Node 1 failure	• Relief valve 13 • Pressure sensor 12 (turns off pump) • PM—hydraulic system
3.1.2			Low/No Pressure/Flow	• Reduced active pitching • No active pitching	• Node 1 failure	• Pressure sensor 12 (turns on pump) • Check valve 11.1 • PM—hydraulic system
3.1.3			Contaminated Fluid	• System/component contamination • Reduced active pitching • No active pitching	• Node 1 failure	• HPF 10 • Air/filling filter • PM—HPF 10, air/filling filter • Procedure—filling
3.1.4			**Normal**	• **Normal ops**		
3.2.1	Pressure Sensor 12	Pressure sensor 12 measures system pressure upstream of check valve 11.1 and downstream of Pressure Reduction Valve 24 (nodes 2 – 4). The sensor sends a signal to the controller. At 75 bar, the controller turns on the pump to increase system pressure. At 90 bar, the controller turns the pump off. The controller	Reads Faulty Signal—High	• Pump turns off • Reduced active pitching • No active pitching • High level tank because less fluid in system	• Sensor failure	• PM—pressure sensor 12
3.2.2			Faulty Signal—In Range	• No indication of high/low pressure; no automatic pump activity	• Sensor failure	• PM—pressure sensor 12 • Relief valve 13 • Pump alarm 161 (initiates *E-Stop*)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.2.3		prevents the turbine from moving to *Pause* until system pressure rises >(?) bar. Pressure alarm 163 sends turbine to *E-Stop* at <50 bar. Alarm (?) sends the turbine to *E-Stop* if Pressure Sensor 12 has no reading.	Faulty Signal—Reads Low	• Pump turns on • High pressure in system • System/component damage	• Sensor failure	• Relief valve 13 • Pump alarm 161 (initiates *E-Stop*) (see endnote 2) • Pressure alarm 163 (initiates *E-Stop*) • PM—pressure sensor 12
3.2.4			No Signal (reads -25 bar)	• Unknown system pressure	• Sensor failure • Broken wire	• Pressure alarm 163 (initiates *E-Stop)* • Pump alarm 161 (initiates *E-Stop*) • PM—pressure sensor 12
3.2.5			**Reads Pressure**	• **Normal ops**		
3.3.1	Relief Valve 13	Relief Valve 13 relieves pressure from the pitch nodes to the tank if pressure rises >100+5 bar. The relief valve capacity is 4.5 L/min, which is in the range of the pump capacity (4.3 – 5.0 L/min)—i.e., unless the pump is running nearly continuously, the relief valve offers adequate protection for the system.	High Flow/Low System Pressure (<100 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns on pump) • PM—relief valve 13 • Procedure—maintenance
3.3.2			**Pressure at 100+5 bar**	• **Normal ops**		
3.3.3			Low/No Flow/High System Pressure (>105 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns off pump) • PM—relief valve 13 • Procedure—maintenance

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	**Node 3—Pitch toward "feather" Node**					
3.4.1	Test Fittings 9.3 and 9.4	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	**No Pressure**	• **Normal ops**		
3.4.2			Pressure	• Hydraulic fluid spill • Loss of system pressure • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (161, 163, 165)
3.5.1	Accumulator 16	Accumulator 16 stores reserve pressure for the pitching nodes via a compressible air bladder, pre-charged to 30+-3 bar. As hydraulic fluid presses against the bladder, the air compresses and pressure increases in the system. This component has been replaced with an equivalent part number.	High Pressure (>90 bar)	• System/component damage	• Increased flow/pressure from Node 1	• Relief valve 13 • Pressure sensor 12 (turns off pump)
3.5.2			**System Pressure (75 – 90 bar)**	• **Normal ops**		
3.5.3			Low Pressure (30 – 75 bar)	• Reduced active pitching	• Low flow/pressure from Node 1 • Contamination • Leak in node 3 • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E*-Stop) • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	**Node 3—Pitch toward "feather" Node**					
3.5.4			No Pressure (<30 bar)	• No active pitching	• No flow/pressure from Node 1 • Contamination • Leak in node 3 • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E*-Stop) • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder
3.6.1	Nozzle 17	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components.	**Pressure**	• **Normal ops**		
3.6.2			No Pressure	• Reduced active pitching • No active pitching	• Contamination	• Filter controls from node 1
3.7	Check Valve 11.3	Examined later in node				
3.8.1	Needle Valve 18.1	Needle valves 18.1 and 18.2 are designed to slowly relieve pressure from the accumulators for system maintenance. They are low-flow valves.	**No Pressure**	• **Normal ops**		
3.8.2			Pressure	• Cycling of hydraulic fluid • Cycling of pump • Reduced system pressure	• Mechanical failure • Human error	• Pressure sensor 12 (turns on pump) • Procedure—maintenance • PM—hydraulic system
3.9.1	Pressure Reduction Valve 24 (PRV 24)	Pressure Reduction Valve 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant	High Pressure (>25 bar)	• System/component damage (increased braking force)	• Mechanical failure • Contamination	• PM—PRV 24 • Relief valve 29 • Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.9.2		downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If Brake Node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.	**Maintains Pressure (14 – 25 bar)**	• **Normal ops**		
3.9.3			Low Pressure (9 – 14 bar)	• Reduced active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
3.9.4			No Pressure (<9 bar)	• No active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
3.10.1	Brake Nodes (5, 6)	Nodes 5 and 6 include all components from and including PRV 24 to the brake calipers. These nodes operate the turbine brake, keeping the brake depressurized in *Run*, *Pause*, and *Stop*, and pressurizing the brake in *E-Stop*. Nodes 5 and 6 include accumulator 27 to store reserve pressure and pressure switch 26	**Normal**	• **Normal ops**		
3.10.2			Pressure/Fluid Loss	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pitching • No active pitching	• Node 5, 6 failure	• PM—hydraulic system • Alarms from Node 1 (initiate *E-Stop*) (161, 163, 165)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.10.3		to trigger protective action.	Brake Malfunction—Applied	• System/component damage	• Node 6 failure (solenoid 19.3 misaligned)	• UPS • PM—hydraulic system • CM—controller software • Filter controls from node 1
3.10.4			Brake Malfunction—Not Applied	• No node effect • No overspeed protection	• Node 5 failure	• Filter controls from node 1 • Alarms from node 1 (see endnote 3) • PM—hydraulic system, accumulator 27, emergency brake, PRV 24, pressure switch 26 • Pressure alarm 162 (initiates *E-Stop*) • PRV 24 (supplies node pressure) • Active pitch • Procedure—maintenance • CM—controller software
3.11.1	Solenoid Valve 19.1	Solenoid valve 19.1 aligns accumulator 16 to the PPV when	**Pressure—PPV**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	**Node 3—Pitch toward "feather" Node**					
3.11.2		energized (in *Run* and *Pause*) and to the "feather" side of the Pitch Ram when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the same power source.	Pressure—Safety Block	• Faster active "feather"	• Power loss to 19.1 (wire break) • Power loss to system • Faulty controller command to solenoid valves • Contamination • Mechanical failure	• UPS • CM—controller software • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system • See endnote 9
3.11.3			No Pressure	• No active "feather" •	• Contamination • Mechanical failure	• Check valve 11.3 • Check valve 22 • Passive "feather" • Filter controls from node 1 • PM—hydraulic system • See endnote 10
3.12.1	Pitch Proportional Valve	The PPV is a 3-way proportional valve with three normal modes: Pressure to "run", Pressure to "feather", and no flow/pressure. The PPV is monitored and controlled by the Vickers Card (position 21), which moves the valve to achieve and maintain an optimum rotor speed.	Pressure—"run"	• Active "run"	• Vickers card failure • Contamination • Mechanical failure	• PM—Vickers card • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system • Rotor speed controls (initiate *Stop*, *E-Stop*)

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.12.2			**Pressure—"feather"**	• **Normal ops**		
3.12.3			No Pressure	• No active "feather" via PPV • See endnote 11	• Vickers card failure • Power loss to PPV (broken wire, source loss) • Power loss to system • Contamination • Mechanical failure	• UPS • PM—Vickers card • Filter controls from node 1 • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • PM—hydraulic system
3.13.1	Check Valve 22	Check valve 22 allows fluid to enter the "feather" side of the Pitch Ram from the hydraulic system tank under Passive Pitch Force.	Pressure	• NA—no pressure differential to allow passage		
3.13.2			Back Pressure	• Loss of system pressure	• Contamination • Mechanical failure	• Alarms from node 1 (initiate *E-Stop*) (161, 163) • Filter controls from node 1 • PM—hydraulic system
3.13.3			**No Pressure**	• **Normal ops**		
3.14.1	Safety Block	This component consists of a parallel solenoid valve and check	**Two-Way Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.14.2		valve. The purpose of the safety block is to allow 2-way pressure in and out of the "feather" side of the ram in *Run* and *Pause* (through the activated solenoid valve), but only allow and hold pressure in during *Stop* and *E-Stop* (through the check valve), to keep the turbine in "feather" even if upstream pressure degrades.	One-Way Pressure	• No drain for "feather" (see endnote 12)	• Power loss to solenoid (wire break, source loss) • Contamination • Mechanical failure	• UPS • Filter controls from node 1 • PM—hydraulic system
3.14.3			No Pressure	• No drain for "feather" • No supply for "feather" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • PM—hydraulic system, emergency brake • See endnote 5
3.15.1	Pitch Ram	The pitch ram is designed to move in response to applied pressure. The movement of the ram translates to rotation of the turbine blades along their longitudinal axis, which controls the speed of the rotor.	**Movement**	• **Normal ops**		
3.15.2			No Movement	• No active "feather" • No passive "feather"	• Leak in pitching ram • Loss of system pressure • Contamination • Bent ram/mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • PM—hydraulic system, emergency brake

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.16.1	Pitch Ram Position Sensor	This sensor tracks the pitch angle by measuring the linear position of the pitch ram. Pitch alarm 190 (Pitch Error) sends turbine to *Stop* if desired pitch position and measured pitch position are >10% different for >10 seconds. Pitch alarm 191 (pitch velocity alarm) sends turbine to *Stop* if desired rotor velocity and measured rotor velocity (via ?) do not match.	**Reads Position**	• **Normal ops**		
3.16.2			Faulty reading—high/low	• Sends to wrong pitch setting	• Calibration error • Sensor failure	• Pitch alarm 191 (initiates *Stop*) • Rotor speed controls (initiate *Stop*, *E-Stop*) • PM—sensor calibration
3.16.3			Faulty reading—No/Stuck reading	• Sends to wrong pitch setting	• Sensor failure • Sensor coupling loose from shaft • Power loss to system	• UPS • Pitch alarm 191 (initiates *Stop*) • Pitch alarm 190 (initiates *Stop*) • Rotor speed controls (initiate *Stop*, *E-Stop*) • PM—sensor calibration
3.17.1	Test Fitting 9.4	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pithing • No active pitching	• Mechanical failure • Aged equipment • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (161, 163, 165)
3.17.2			**No Pressure**	• **Normal ops**		
3.18.1	Solenoid Valve 19.2	Solenoid valve 19.2 aligns the "run" side of the ram to the PPV	**Pressure—PPV**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	**Node 3—Pitch toward "feather" Node**					
3.18.2		when energized (in *Run* and *Pause*) and to the drain when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the same power source.	Pressure—Drain	• No fluid recycle to high pressure node • Faster active "feather" (see endnote 12)	• Power loss to 19.2 (wire break) • Power loss to system • Faulty controller command • Contamination • Mechanical failure	• UPS • CM—controller software • Filter controls from node 1 • PM—hydraulic system
3.18.3			No Pressure	• No drain for "run" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • PM—hydraulic system, emergency brake • See endnote 5
3.19.1	Check Valve 11.2	Check valve 11.2 prevents hydraulic fluid from the "run" side of the Pitch Ram from draining to the tank, to reduce fluid loss and prevent cycling of the pump.	Pressure	• NA—no pressure differential to allow passage		
3.19.2			Back Pressure	• No fluid recycle to high pressure node	• Contamination • Mechanical failure	• Filter controls from node 1 • PM—hydraulic system
3.19.3			**No Pressure**	• **Normal ops**		
3.20.1	Check Valve 11.3	Check valve 11.3 allows hydraulic fluid to return to the pressurized	**Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
3	Node 3—Pitch toward "feather" Node					
3.20.2		system to reduce fluid returning to the tank and prevent cycling of the pump. It also provides a drain path for the "run" side of the pitch ram, allowing passive "feather".	Back Pressure	• Reduced active "feather"	• Contamination • Mechanical failure	• Filter controls from node 1 • Passive "feather"
3.20.3			No Pressure	• No drain for "run" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • PM—hydraulic system, emergency brake

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.1.1	Pump Supply Node (1)	Node 1 includes all components from the system tank up to and including pressure sensor 12 and relief valve 13. Node 1 supplies filtered hydraulic fluid to downstream nodes. Node 1 adds fluid/pressure when the pitch nodes are 75 bar, and stops adding fluid/pressure with the pitch nodes are 90 bar. Node 1 includes filter controls and sensors that trigger protective actions.	High Pressure/Flow	• System/component damage	• Node 1 failure	• Relief valve 13 • Pressure sensor 12 (turns off pump) • PM—hydraulic system
4.1.2			Low/No Pressure/Flow	• Reduced active pitching • No active pitching	• Node 1 failure	• Pressure sensor 12 (turns on pump) • Check valve 11.1 • PM—hydraulic system • Safety block
4.1.3			Contaminated Fluid	• System/component contamination • Reduced active pitching • No active pitching	• Node 1 failure	• HPF 10 • Air/filling filter • PM—HPF 10. Air/filling filter • Procedure—filling
4.1.4			**Normal**	• **Normal ops**		
4.2.1	Pressure Sensor 12	Pressure sensor 12 measures system pressure upstream of check valve 11.1 and downstream of Pressure Reduction Valve 24 (Nodes 2 – 4). The sensor sends a signal to the controller. At 75 bar, the	Reads Faulty Signal—High	• Pump turns off • Reduced active pitching • No active pitching • High level tank because less fluid in system	• Sensor failure	• PM—pressure sensor 12

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—“Feather” via Accumulator					
4.2.2		controller turns on the pump to increase system pressure. At 90 bar, the controller turns the pump off. The controller prevents the turbine from moving to *Pause* until system pressure rises >(?) bar. Pressure alarm 163 sends turbine to *E-Stop* at <50 bar. Alarm (?) sends the turbine to *E-Stop* if pressure sensor 12 has no reading.	Faulty Signal—In Range	• No indication of high/low pressure; no automatic pump activity	• Sensor failure	• PM—pressure sensor 12 • Relief valve 13 • Pump alarm 161 (initiates *E-Stop*)
4.2.3			Faulty Signal—Reads Low	• Pump turns on • High pressure in system • System/component damage	• Sensor failure	• Relief valve 13 • Pump alarm 161 (initiates *E-Stop*) (see endnote 2) • Pressure alarm 163 (initiates *E-Stop*) • PM—pressure sensor 12
4.2.4			No Signal (reads -25 bar)	• Unknown system pressure	• Sensor failure • Broken wire	• Pressure alarm 163 (initiates *E-Stop)* • Pump alarm 161 (initiates *E-Stop*) • PM—pressure sensor 12
4.2.5			**Reads Pressure**	• **Normal ops**		
4.3.1	Relief Valve 13	Relief Valve 13 relieves pressure from the pitch nodes to the tank if pressure rises >100+5 bar. The relief valve capacity is 4.5 L/min, which is in the range of the pump capacity (4.3 – 5.0 L/min)—i.e., unless the pump is running nearly	High Flow/Low System Pressure (<100 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns on pump) • PM—relief valve 13 • Procedure—maintenance

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—“Feather” via Accumulator					
4.3.2		continuously, the relief valve offers adequate protection for the system.	**Pressure at 100+5 bar**	• **Normal ops**		
4.3.3			Low/No Flow/High System Pressure (>105 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • Pressure sensor 12 (turns off pump) • PM—relief valve 13 • Procedure—maintenance
4.4.1	Test Fittings 9.3 and 9.5	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• Hydraulic fluid spill • Loss of system pressure • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (161, 163, 165)
4.4.2			**No Pressure**	• **Normal ops**		
4.5.1	Accumulator 16	Accumulator 16 stores reserve pressure for the pitching nodes via a compressible air bladder, pre-charged to 30+-3 bar. As hydraulic fluid presses against	High Pressure (>90 bar)	• System/component damage	• Increased flow/pressure from node 1	• Relief valve 13 • Pressure sensor 12 (turns off pump)
4.5.2			**System Pressure (75-90 bar)**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.5.3		the bladder, the air compresses and pressure increases in the system. This component has been replaced with an equivalent part number.	Low Pressure (30-75 bar)	• Reduced active pitching	• Low flow/pressure from node 1 • Contamination • Leak in node 4 • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E*-Stop) • Safety block • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder
4.5.4			No Pressure (<30 bar)	• No active pitching	• No flow/pressure from node 1 • Contamination • Leak in node 4 • Accumulator leak (air bladder or hydraulic fluid)	• Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E*-Stop) • Safety block • Filter controls from node 1 • PM—hydraulic system, accumulator, air bladder
4.6.1	Nozzle 17	Nozzles direct flow/pressure or make flow/pressure more	**Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.6.2		laminar for downstream components.	No Pressure	• Reduced active pitching • No active pitching	• Contamination	• Filter controls from node 1
4.7.1	Check Valve 11.3	Check valve 11.3 allows hydraulic fluid to return to the pressurized system to reduce fluid returning to the tank and prevent cycling of the pump. It also provides a drain path for the "run" side of the pitch ram, allowing passive "feather".	Pressure	• NA—no pressure differential to allow passage		
4.7.2			Back Pressure	• No adverse effect		
4.7.3			**No Pressure**	• **Normal ops**		
4.8.1	Needle Valve 18.1	Needle valves 18.1 and 18.2 are designed to slowly relieve pressure from the accumulators for system maintenance. They are low-flow valves.	**No Pressure**	• **Normal ops**		
4.8.2			Pressure	• Cycling of hydraulic fluid • Cycling of pump • Reduced system pressure	• Mechanical failure • Human error	• Pressure sensor 12 (turns on pump) • Procedure—maintenance • PM—hydraulic system
4.9.1	Pressure Reduction Valve 24	Pressure Reduction Valve 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant	High Pressure (>25 bar)	• System/component damage (increased braking force)	• Mechanical failure • Contamination	• PM—PRV 24 • Relief valve 29 • Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.9.2	(PRV 24)	downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If Brake Node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.	**Maintains Pressure (14 – 25 bar)**	• **Normal ops**		
4.9.3			Low Pressure (9 – 14 bar)	• Reduced active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
4.9.4			No Pressure (<9 bar)	• No active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Passive pitch
4.10.1	Brake Nodes	Nodes 5 and 6 include all components from and including	**Normal**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.10.2	(5, 6)	PRV 24 to the brake calipers. These nodes operate the turbine brake, keeping the brake depressurized in *Run*, *Pause*, and *Stop*, and pressurizing the brake in *E-Stop*. Nodes 5 and 6 include accumulator 27 to store reserve pressure and pressure switch 26 to trigger protective action.	Pressure/Fluid Loss	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pitching • No active pitching	• Node 5, 6 failure	• PM—hydraulic system • Alarms from Node 1 (initiate *E-Stop*) (161, 163, 165)
4.10.3			Brake Malfunction—Applied	• System/component damage	• Node 6 failure (solenoid 19.3 misaligned)	• UPS • PM—hydraulic system • CM—controller software • Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.10.4			Brake Malfunction—Not Applied	• No node effect • No overspeed protection	• Node 5 failure	• Filter controls from node 1 • Alarms from node 1 (see endnote 3) • PM—hydraulic system, accumulator 27, emergency brake, PRV 24, pressure switch 26 • Pressure alarm 162 (initiates *E-Stop*) • PRV 24 (supplies node pressure) • Active pitch • Procedure—maintenance • CM—controller software
4.11.1	Solenoid Valve 19.1	Solenoid valve 19.1 aligns accumulator 16 to the PPV when energized (in *Run* and *Pause*) and to the "feather" side of the Pitch Ram when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the	Pressure—PPV	• No active "feather"	• Contamination • Mechanical failure • Faulty controller command to solenoid valves	• Check valve 22 • Passive "feather" • Filter controls from node 1 • CM—controller software • PM—hydraulic system

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.11.2		same power source.	**Pressure—Safety Block**	• **Normal ops**		
4.11.3			No Pressure	• No active "feather"	• Contamination • Mechanical failure	• Check valve 22 • Passive "feather" • Filter controls from node 1 • PM—hydraulic system
4.12.1	Pitch Proportional Valve	The PPV is a 3-way proportional valve with three normal modes: Pressure to "run", Pressure to "feather", and no flow/pressure. The PPV is monitored and controlled by the Vickers Card (position 21), which moves the valve to achieve and maintain an optimum rotor speed.	Pressure—"run"	• Pressure loss to tank • Reduced active "feather" • No active "feather"	• Vickers failure in *Stop* or *E-Stop* • Contamination • Mechanical failure	• Filter from node 1 • Passive "feather" • Safety block • Alarms from node 1 (initiate *E-Stop*)
4.12.2			Pressure—"feather"	• No adverse effect		
4.12.3			**No Pressure**	• **Normal ops**		
4.13.1	Check Valve 22	Check valve 22 allows fluid to enter the "feather" side of the Pitch Ram from the hydraulic	Pressure	• NA—no pressure differential to allow passage		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	**Node 4—"Feather" via Accumulator**					
4.13.2		system tank under Passive Pitch Force.	Back Pressure	• Pressure loss to tank	• Contamination • Mechanical failure	• Alarms from node 1 (initiate *E-Stop*) (161, 163) • Filter controls from node 1 • PM—hydraulic system
4.13.3			**No Pressure**	• **Normal ops**		
4.14.1	Safety Block	This component consists of a parallel solenoid valve and check valve. The purpose of the safety block is to allow 2-way pressure in and out of the "feather" side of the ram in *Run* and *Pause* (through the activated solenoid valve), but only allow and hold pressure in during *Stop* and *E-Stop* (through the check valve), to keep the turbine in "feather" even if upstream pressure degrades.	Two-Way Pressure	• No node effect • No pressure loss protection		
4.14.2			**One-Way Pressure**	• Normal ops		
4.14.3			No Pressure	• No drain for "feather" • No supply for "feather" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiate *E-Stop* via brake) • PM—hydraulic system, emergency brake • Filter controls from node 1
4.15.1	Pitch Ram	The pitch ram is designed to move in response to applied	**Movement**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.15.2		pressure. The movement of the ram translates to rotation of the turbine blades along their longitudinal axis, which controls the speed of the rotor.	No Movement	• No active "feather" • No passive "feather"	• Leak in pitching ram • Loss of system pressure • Contamination • Bent ram/mechanical failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • Pressure sensor 12 (turns on pump) • Pump alarm 161 (initiates *E-Stop*) • Pressure alarm 163 (initiates *E-Stop*) • PM—hydraulic system, emergency brake
4.16.1	Pitch Ram Position Sensor	(The system is already in *Stop* or *E-Stop*, so the pitch ram position sensor has no input to alarms or controls. Relay K932a overrides the signal to the Vickers card and sets it to 0.)	**No reading**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.17.1	Test Fitting 9.4	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active pitching • No active pitching	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (161, 163, 165)
4.17.2			**No Pressure**	• **Normal ops**		
4.18.1	Solenoid Valve 19.2	Solenoid valve 19.2 aligns the "run" side of the ram to the PPV when energized (in *Run* and *Pause*) and to the drain when de-energized (in *Stop* and *E-Stop*). 19.1, 19.2, and the Safety Block solenoids are on the same power source.	Pressure—PPV	• Reduced active "feather"(see endnote 13)	• Contamination • Mechanical failure • Faulty controller command to solenoid valves	• Check valve 11.3 • Passive "feather" • Filter controls from node 1 • CM—controller software • PM—hydraulic system
4.18.2			**Pressure—Drain**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
4	Node 4—"Feather" via Accumulator					
4.18.3			No Pressure	• No drain for "run" • No active "feather" • No passive "feather"	• Contamination • Mechanical failure	• Rotor speed controls (initiate *E-Stop* via brake) • Filter controls from node 1 • PM—hydraulic system, emergency brake
4.19.1	Nozzle 23	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components.	**Pressure**	• **Normal ops**		
4.19.2			No Pressure	• No drain for "run" • No active "feather" • No passive "feather"	• Contamination	• Filter controls from node 1 • Rotor speed controls (initiate *E-Stop* via brake) • PM—hydraulic system, emergency brake
4.20.1	Check Valve 22	Examined earlier in node				
4.21.1	Pitch Proportional Valve	Examined earlier in node				

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.1.1	Pitching Nodes (2, 3, 4)	Nodes 2, 3, and 4 include all components from and including pressure sensor 12 and relief valve 13, up to and including PRV 24. These nodes operate the blade pitch system, pitching to “run” or “feather” to speed up or maintain rotor speed via the PPV in *Run*, pitching to “feather” via the PPV in *Pause*, and applying pressure directly to the “feather” side of the ram in *Stop* and *E-Stop*. Pitch nodes include accumulator 16 to store reserve pressure and pressure sensor 12 to trigger protective actions.	High Pressure/Flow	• System/component damage (increased braking force)	• Node 1 failure	• Relief valve 13 • Relief valve 29 • PRV 24 (supplies/relieves node pressure) • Pressure sensor 12 (turns off pump) • PM—hydraulic system
5.1.2			Low/No Pressure/Flow	• Reduced active braking • No active braking • See endnote 14	• Node 1 – 4 failure	• Pressure sensor 12 (turns on pump) • Check valve 11.4 • PM—hydraulic system • Passive pitch
5.1.3			Contaminated Fluid	• System/component contamination • Reduced active braking • No active braking • See endnote 15	• Node 1 failure	• HPF 10 • Air/filling filter • PM—HPF 10, air/filling filter • Procedure—filling

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.1.4			Pitch Malfunction—No Active Control	• No active pitching	• Node 2 – 4 failure	• Filter controls from node 1 • Alarms from node 1 (initiate *E-Stop*) • Pressure sensor 12 • PM—hydraulic system, accumulator 16, emergency brake • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • UPS • CM—controller software • Passive pitch
5.1.5			Pitch Malfunction—No Passive Pitch	• No passive pitching	• Node 2 – 4 failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • Alarms from node 1 (initiate *E-Stop*) • Pressure sensor 12 • PM—hydraulic system, emergency brake
5.1.6			**Normal**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.2.1	Pressure Reduction Valve 24 (PRV 24)	Pressure Reduction Valve 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If Brake Node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.	High Pressure (>25 bar)	• System/component damage (increased braking force)	• Mechanical failure • Contamination	• PM—PRV 24 • Relief valve 29 • Filter controls from node 1
5.2.2			**Maintains Pressure (14 – 25 bar)**	• **Normal ops**		
5.2.3			Low Pressure (9 – 14 bar)	• Reduced active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Active pitch
5.2.4			No Pressure (<9 bar)	• No active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Active pitch
5.3.1	Check Valve 11.4	Check valve 11.4 prevents degradation of brake node pressure by allowing pressure and fluid flow into the node from PRV 24, but not allowing backflow toward the pitch	**Pressure**	• **Normal ops**		
5.3.2			Back Pressure	• No node effect • No pressure loss protection	• Mechanical failure • Contamination	• Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.3.3		nodes.	No Pressure	• Reduced/no active braking	• Mechanical failure • Contamination	• Filter controls from node 1 • Pressure alarm 162 (initiates *E-Stop*) • Active pitch
5.4.1	Accumulator 27	Accumulator 27 stores reserve pressure for the brake nodes via a compressible air bladder, pre-charged to 9 bar. As hydraulic fluid presses against the bladder, the air compresses and pressure increases in the system. This component has been replaced with an equivalent part number.	High Pressure (>20.5 bar)	• System/component damage (increased braking force) •	• Increased flow/pressure from PRV 24	• PM—PRV 24 • Relief valve 29
5.4.2			**System Pressure (19+-1.5 bar)**	• **Normal ops**		
5.4.3			Low Pressure (9 – 17.5 bar)	• Reduced active braking	• Low flow/pressure from PRV 24 or pitch nodes • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • PM—hydraulic system, Accumulator, PRV 24 • Active pitch
5.4.4			No Pressure (<9 bar)	• No active braking	• No flow/pressure from PRV 24 or pitch nodes • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • PM—Hydraulic system, accumulator, air bladder, PRV 24 • Active pitch

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.5.1	Pressure Switch 26	On/off sensor that monitors pressure in the brake nodes. When pressure drops <14 bar, the sensor signal to the controller turns off, initiating an *E-Stop*.	Faulty Signal—High/In Range	• No indication of low pressure	• Switch failure	• PM—pressure switch 26
5.5.2			Faulty Signal—Low/No Signal	• Pressure alarm 162 (initiates *E-Stop*)	• Switch failure	• PM—pressure switch 26
5.5.3			**Reads Pressure**	• **Normal ops**		
5.6.1	Nozzle 28	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components.	**Pressure**	• **Normal ops**		
5.6.2			No Pressure	• Reduced active braking • No active braking	• Contamination	• Filter controls from node 1 • Active pitch
5.7.1	Needle Valve 18.2	Needle Valves 18.1 and 18.2 are designed to slowly relieve pressure from the accumulators for system maintenance. They are low-flow valves.	**No Pressure**	• **Normal ops**		
5.7.2			Pressure	• Cycling of hydraulic fluid • Cycling of pump • Loss of system pressure	• Mechanical failure • Human error	• PRV 24 (supplies node pressure) • Pressure alarm 162 (initiates *E-Stop*) • Procedure—maintenance • PM—hydraulic system

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.8.1	Relief Valve 29	Relief Valve 29 relieves pressure from the brake nodes to the tank if pressure rises >25 bar. The relief valve capacity is 0.5 L/min.	High Flow/Low System Pressure (<25 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced active braking • No active braking	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • PRV 24 (supplies node pressure) • PM—relief valve 29 • Procedure—maintenance • Active pitch
5.8.2			**Pressure at 25 bar**	• **Normal ops**		
5.8.3			Low/No Flow/High System Pressure (>25 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • PRV 24 (relieves node pressure) • PM—relief valve 29 • Procedure—maintenance
5.9.1	Test Fittings 9.6 and 9.7	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active braking • No active braking	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) (see endnote 3) • Pressure alarm 162 (initiates *E-Stop*) • Passive pitch
5.9.2			**No Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
5	Node 5—Active Brake					
5.10.1	Solenoid Valve 19.3	Solenoid valve 19.3 aligns the brake to the drain line when energized (in *Run*, *Pause*, and *Stop*) and to brake node pressure when de-energized (*E-Stop*).	**Pressure—Brake**	• **Normal ops**		
5.10.2			Pressure—Drain	• No active braking	• Contamination • Mechanical failure • Faulty controller command to solenoid valves	• Filter controls from node 1 • PM—hydraulic system • Active pitch • CM—controller software
5.10.3			No Pressure	• No active braking	• Contamination • Mechanical failure	• Filter controls from node 1 • PM—hydraulic system • Active pitch
5.11.1	Brake	The brake is applied with hydraulic pressure to the turbine's high-speed shaft. The brake is able to quickly slow and stop the turbine, or hold the turbine in a stationary position, regardless of blade pitch.	**Applied**	• **Normal ops**		
5.11.2			Not Applied	• No active braking	• Leak in brake calipers • Loss of node pressure • Contamination • Broken caliper/mechanical failure • Human error (caliper valve setting)	• Filter controls from node 1 • PM—hydraulic system, emergency brake, PRV 24, pressure switch 26 • Pressure alarm 162 (initiates E-Stop) • PRV 24 (supplies node pressure) • Procedure—maintenance • Active pitch • Passive pitch

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.1.1	Pitching Nodes (2, 3, 4)	Nodes 2, 3, and 4 include all components from and including pressure sensor 12 and relief valve 13, up to and including PRV 24. These nodes operate the blade pitch system, pitching to "run" or "feather" to speed up or maintain rotor speed via the PPV in *Run*, pitching to "feather" via the PPV in *Pause*, and applying pressure directly to the "feather" side of the ram in *Stop* and *E-Stop*. Pitch nodes include accumulator 16 to store reserve pressure and pressure sensor 12 to trigger protective actions.	High Pressure/Flow	• System/component damage (increased braking force)	• Node 1 failure	• Relief valve 13 • Relief valve 29 • PRV 24 (supplies/relieves node pressure) • Pressure sensor 12 (turns off pump) • PM—hydraulic system
6.1.2			Low/No Pressure/Flow	• Reduced active braking • No active braking • See endnote 14	• Node 1 – 4 failure	• Pressure sensor 12 (turns on pump) • Check valve 11.4 • PM—hydraulic system • Passive pitch
6.1.3			Contaminated Fluid	• System/component contamination • Reduced active braking • No active braking • See endnote 15	• Node 1 failure	• HPF 10 • Air/filling filter • PM—HPF 10, air/filling filter • Procedure—filling

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.1.4			Pitch Malfunction—No Active Control	• No active pitching	• Node 2 – 4 failure	• Filter controls from node 1 • Alarms from node 1 (initiate *E-Stop*) • Pressure sensor 12 • PM—hydraulic system, accumulator 16, emergency brake • Pitch alarm 190 (initiates *Stop*) • Pitch alarm 191 (initiates *Stop*) • UPS • CM—controller software • Passive pitch
6.1.5			Pitch Malfunction—No Passive Pitch	• No passive pitching	• Node 2 – 4 failure	• Rotor speed controls (initiates *E-Stop* via brake) • Filter controls from node 1 • Alarms from node 1 (initiate *E-Stop*) • Pressure sensor 12 • PM—hydraulic system, emergency brake
6.1.6			**Normal**	• **Normal ops**		
6.2.1	Pressure Reduction Valve 24 (PRV 24)	Pressure Reduction Valve 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant	High Pressure (>25 bar)	• System/component damage (increased braking force)	• Mechanical failure • Contamination	• PM—PRV 24 • Relief valve 29 • Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.2.2		downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If Brake Node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.	**Maintains Pressure (14 – 25 bar)**	• **Normal ops**		
6.2.3			Low Pressure (9 – 14 bar)	• Reduced active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Active pitch
6.2.4			No Pressure (<9 bar)	• No active braking	• Mechanical failure • Contamination	• PM—PRV 24 • Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • Check valve 11.4 • Active pitch
6.3.1	Check Valve 11.4	Check valve 11.4 prevents degradation of brake node pressure by allowing pressure and fluid flow into the node from pressure reduction valve 24, but not allowing backflow toward the pitch nodes.	**Pressure**	• **Normal ops**		
6.3.2			Back Pressure	• No node effect • No pressure loss protection	• Mechanical failure • Contamination	• Filter controls from node 1
6.3.3			No Pressure	• Reduced active braking • No active braking	• Mechanical failure • Contamination	• Filter controls from node 1 • Pressure alarm 162 (initiates *E-Stop*) • Active pitch
6.4.1	Accumulator 27	Accumulator 27 stores reserve pressure for the brake nodes via a compressible air bladder, pre-	High Pressure (>20.5 bar)	• System/component damage (increased braking force)	• Increased flow/pressure from PRV 24	• PM—PRV 24 • Relief valve 29

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.4.2		charged to 9 bar. As hydraulic fluid presses against the bladder, the air compresses and pressure increases in the system. This component has been replaced with an equivalent part number.	**System Pressure (19+-1.5 bar)**	• **Normal ops**		
6.4.3			Low Pressure (9 – 17.5 bar)	• Reduced active braking	• Low flow/pressure from PRV 24 or pitch nodes • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • PM—hydraulic system, Accumulator, PRV 24 • Active pitch
6.4.4			No Pressure (<9 bar)	• No active braking	• No flow/pressure from PRV 24 or pitch nodes • Contamination • Accumulator leak (air bladder or hydraulic fluid)	• Pressure alarm 162 (initiates *E-Stop*) • Filter controls from node 1 • PM—Hydraulic system, accumulator, air bladder, PRV 24 • Active pitch
6.5.1	Pressure Switch 26	On/off sensor that monitors pressure in the brake nodes. When pressure drops <14 bar, the sensor signal to the controller turns off, initiating an *E-Stop*.	Faulty Signal—High/In Range	• No indication of low pressure	• Switch failure	• PM—pressure switch
6.5.2			Faulty Signal—Low/No Signal	• Pressure alarm 162 (initiates *E-Stop*)	• Switch failure	• PM—pressure switch
6.5.3			**Reads Pressure**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.6.1	Nozzle 28	Nozzles direct flow/pressure or make flow/pressure more laminar for downstream components.	**Pressure**	• **Normal ops**		
6.6.2			No Pressure	• Reduced active braking • No active braking	• Contamination	• Filter controls from node 1 • Active pitch
6.7.1	Needle Valve 18.2	Needle Valves 18.1 and 18.2 are designed to slowly relieve pressure from the accumulators for system maintenance. They are low-flow valves.	**No Pressure**	• **Normal ops**		
6.7.2			Pressure	• Cycling of hydraulic fluid • Cycling of pump • Loss of system pressure	• Mechanical failure • Human error	• PRV 24 (supplies node pressure) • Pressure alarm 162 (initiates *E-Stop*) • Procedure—maintenance • PM—hydraulic system
6.8.1	Relief Valve 29	Relief Valve 29 relieves pressure from the brake nodes to the tank if pressure rises >25 bar. The relief valve capacity is 0.5 L/min.	High Flow/Low System Pressure (<25 bar)	• Cycling of hydraulic fluid • Cycling of pump • Reduced active braking • No active braking	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • PRV 24 (supplies node pressure) • PM—relief valve 29 • Procedure—maintenance • Active pitch
6.8.2			**Pressure at 25 bar**	• **Normal ops**		

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.8.3			Low/No Flow/High System Pressure (>25 bar)	• No node effect • No overpressure protection	• Mechanical failure • Contamination • Human error	• Filter controls from node 1 • PRV 24 (relieves node pressure) • PM—relief valve 29 • Procedure—maintenance
6.9.1	Test Fitting 9.6	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• Hydraulic fluid spill • Loss of system fluid/pressure • Cycling of pump • Reduced active braking • No active braking • See endnote 16	• Mechanical failure • Human error	• PM—hydraulic system • Procedure—maintenance • Drip pan (secondary containment) • Alarms from node 1 (initiate *E-Stop*) • Pressure alarm 162 (initiates *E-Stop*) • Passive pitch
6.9.2			**No Pressure**	• **Normal ops**		
6.10.1	Solenoid Valve 19.3	Solenoid valve 19.3 aligns the brake to the drain line when energized (in *Run*, *Pause*, and *Stop*) and to brake node pressure when de-energized (*E-Stop*).	Pressure—Brake	• Active braking	• Mechanical failure • Contamination • Power loss to 19.3 (wire break) • Power loss to system • Faulty controller command to solenoid valves	• UPS • PM—hydraulic system • CM—controller software • Filter controls from node 1

Appendix C—SWiFT Hydraulic System Nodes

ID #	Component	Component Description	Failure Mode	Effects	Failure Cause	Controls
6	Node 6—Brake Off					
6.10.2			**Pressure—Drain**	• **Normal ops**		
6.10.3			No Pressure	• No node effect • Loss of overspeed protection	• Mechanical failure • Contamination	• Filter controls from node 1 • PM—hydraulic system
6.11.1	Brake	The brake is applied with hydraulic pressure to the turbine's high-speed shaft. The brake is able to quickly slow and stop the turbine, or hold the turbine in a stationary position, regardless of blade pitch.	Applied	• Active braking	• Solenoid valve 19.3 misaligned	• UPS • PM—hydraulic system • CM—controller software • Filter controls from node 1
6.11.2			**Not Applied**	• **Normal ops**		
6.12.1	Test Fitting 9.7	The system is equipped with test fittings to connect a temporary pressure gauge at various places in the system for testing, maintenance, or troubleshooting purposes.	Pressure	• No node effect • Reduced overspeed protection	• Mechanical failure • Contamination • Human error	• PM—hydraulic system • Procedure—maintenance
6.12.2			**No Pressure**	• **Normal ops**		

Endnotes:

1. Back flow would be much less than pump capacity, so low pressure alarm is unlikely.
2. If the sensor is reading very low, pressure rise will not be sensed with pump activity, initiating alarm 161.
3. Node 1 alarms trigger if fluid is leaking from system.
4. Pitch alarms 190 and 191 will trigger, but cannot initiate a full *Stop* without flow through 19.1.
5. Pitch alarms 190 and 191 will trigger, but cannot initiate a full *Stop*, and passive "feather" cannot help, if pressure is trapped on "run" side.
6. Pitch alarms 190 and 191 will trigger, but cannot initiate *Stop* without ram movement.

Appendix C—SWiFT Hydraulic System Nodes

7. Pitch alarm 190 only triggers when the Pitch Ram Position Sensor reading does not match the controller setting.
8. In *Stop*, pressure can still get to “feather” side, putting the turbine in a safe state.
9. Check valve 11.3 allows flow from “run” side back to the system, allowing ram movement.
10. Check valve 22 allows flow into the “feather” side of the ram—passive “feather” supplies force. Pitch alarms 190 and 191 will trigger, but cannot initiate a full *Stop*.
11. This effect is unique in the FMEA—no pressure will cause an interruption in ops, but does not remove the possibility of active “feather” via another flowpath.
12. Because the node is already in active “feather”, this effect does not cause a change in the system.
13. This is a possible adverse effect, but no system effect is more likely.
14. No active pitch; pressure loss assumed.
15. No passive pitch; contamination assumed.
16. Assuming enough fluid loss, active pitch could be inoperable.

Appendix E—List of Controls

SWiFT Hydraulic System Controls

Control	Description
Active Pitch	The active pitch system controls blade pitch with hydraulic pressure, via either PPV 20 to adjust or maintain rotor speed, or direct alignment from system pressure to the "feather" side of the ram. Active pitch is listed as a control for the brake nodes, because pitch control is sufficient to slow and stop the turbine without assistance from the brake.
Alarms	When hydraulic system alarms trigger, a lower turbine state is initiated according to the severity of the indications. • Controller alarm 212—initiates *Pause* when any RTD reads an out-of-range signal, including no signal • Filter alarm 164—initiates *Stop* when the clog sensor on the high pressure filter indicates a differential pressure of 5 bar (+-10%) • Level alarm 165—initiates *E-Stop* when tank level switch indicates low level (turns off) • Pitch alarm 190—initiates *Stop* when programmed pitch position and measured pitch position (via pitch ram position sensor) differ by >10% for >10 sec • Pitch alarm 191—initiates *Stop* when programmed rotor velocity and measured velocity (via pitch ram position sensor) differ • Pressure alarm 162—initiates *E-Stop* when brake node pressure (via pressure switch 26) falls <14 bar • Pressure alarm 163—initiates *E-Stop* when system pressure (via pressure sensor 12) falls < 50 bar or has no reading • Pump alarm 161—initiates *E-Stop* when the pump is on (via pump contactors) and system pressure (via pressure sensor 12) doesn't rise > 75 bar within 60 seconds • Temperature alarm 167—initiates *E-Stop* when system temperature (via RTD) is >65 C for 20 seconds (prevents system damage and indicates an over-cycled pump) (pending further analysis, this alarm may be an applicable control for failure modes 1.5.2, 1.9.1, 1.10.1, 2.3.1, 2.4.2, 2.18.2, 3.3.1, 3.4.2, 3.13.2, 3.17.1, 4.3.1, 4.4.1, 5.8.1, 6.8.1) • Temperature alarm 88—initiates *Pause* when system temperature (via RTD) is <-20 C for 20 seconds (prevents system damage)
Bypass Valve (High Pressure Filter)	The bypass valve on the high pressure filter opens at a differential pressure of 7 bar (+-10%) to avoid destroying a clogged filter.

Appendix E—List of Controls

SWiFT Hydraulic System Controls	
Control	**Description**
Check Valves	Check valves allow one-way pressure or fluid flow and are reliable mechanical components. Back flow/back pressure because of valve failure or contamination would be minimal. • Check valve 11.1—prevents the pressurized system from draining back to the tank, which is vented to atmospheric pressure. Because the check valve holds system pressure, the pump only has to cycle when pressure drops due to normal draining. • Check valve 11.3—allows hydraulic fluid to return to the pressurized system to reduce fluid recycle to the tank and prevent cycling of the pump. It also provides a drain path for the "run" side of the pitch ram, allowing passive "feather". • Check valve 11.4— prevents degradation of brake node pressure by allowing pressure and fluid flow into the node from pressure reduction valve 24, but not allowing backflow toward the pitch nodes. • Check valve 22— Check valve 22 allows fluid to enter the "feather" side of the Pitch Ram from the hydraulic system tank, allowing passive pitching.
Closed System	The Vestas hydraulic system is designed as a closed system to reduce the introduction of contamination to the system. The system tank is covered and vented through the air/filling filter, and is not open to the nacelle environment. Relief valves, drain valves, and needle valves for maintenance use direct hydraulic fluid back into the system tank, reducing the need to add fluid to the system, further reducing opportunities for system contamination.
Configuration Management	Configuration Management (CM) identifies and documents the functional and physical characteristics of a system or component, controls any changes to those characteristics, records and reports each change and its implementation status, and supports audits of the systems, components, and documentation to verify conformance to requirements. CM includes a change management method to ensure that all changes are properly identified, reviewed, approved, implemented, tested, documented, and tracked to maintain consistency among the design requirements, physical configuration, and documentation. For the SWiFT Hydraulic System FMEA, CM for nacelle controller software is used as a control, to reduce the frequency of faulty signals to the hydraulic system as a result of controller logic errors.
Drip Pan	The drip tray contains and shows evidence of slow leaks from system test fittings. Fast or spraying leaks may not be contained by the drip pan, and ongoing leaks allowing enough hydraulic fluid loss could overflow the drip pan.
Filter Controls from Node 1	Filter controls from Node 1 include the high-pressure filter, the on/off clog sensor, the bypass valve, filter alarm 164 (initiates *Stop*), PM on the high-pressure filter and associated components, the closed system design, the tank air/filling filter, and the hydraulic system filling procedure, which directs that the fluid be filtered before it is added to the system.

Appendix E—List of Controls

SWiFT Hydraulic System Controls	
Control	**Description**
High Pressure Filter (HPF 10)	High-Pressure Filter with an on/off filter sensor and bypass valve. Sensor sends signal to controller. Sensor turns off at a pressure differential of 5 bar, indicating a clog in the filter. If the sensor turns off for 2 seconds, a message indicates that the filter/sensor needs maintenance. If sensor turns off/has no signal, filter alarm 164 sends the turbine to *Stop*. Bypass valve opens at a pressure differential of 7 bar, to avoid destroying the filter. (Both pressures are +-10%.)
Nacelle Controller	The nacelle controller monitors a variety of sensors and conditions within the nacelle and uses software logic to place or keep the turbine in a safe state. The nacelle controller software was developed using the Sandia Safety-Critical Quality Assurance Process (ref#) and includes built-in redundancies and multiple inputs to avoid a single point of failure. The nacelle controller is equipped with a dedicated switch in the E-Circuit that requires an active signal to stay closed. If the controller withdraws the signal or loses power, the turbine goes into *E-Stop*. The nacelle controller can also place the turbine in *Stop* (e.g., if the signal from the HSS Sensor is lost or goes too high) or *Pause* (e.g., if the yaw system indicates that the nacelle has rotated two turns and needs to be untwisted), depending on inputs and software logic. The nacelle controller is programmed to only allow the turbine to move from *Stop* to *Pause* if the hydraulic system has working system pressure via pressure sensor 12.
Operating Procedures	Approved procedures are used to direct all stages and phases of work. Procedures are used both to perform work properly and to offer a layer of protection to workers and equipment. Procedures that are specifically credited as controls in the SWiFT Hydraulic System FMEA include the following: • Hydraulic system filling procedure • Limited operations in extreme weather • Maintenance procedures
Passive Pitch Design (Passive "feather")	If the pitching system loses the hydraulic pressure that holds the ram extended and the blades in the "run" position, the blades passively pitch to feather via the aerodynamic pitching moments acting on the rotating blades. This slows down and stops the rotor, even at high wind speeds. The blades cannot move toward a "run" position without hydraulic pressure.
Pressure Reduction Valve 24 (PRV 24)	PRV 24 is a spring-activated pressure reducing/ relieving valve that maintains a constant downstream pressure regardless of upstream pressure variations. It allows pressure flow from the pitch nodes to the brake nodes. Once the brake node pressure setting is reached (19+-1.5 bar), the spring compresses, restricting downstream pressure flow. If brake node pressure climbs, the spring compresses further, allowing excess pressure to relieve to the tank.

Appendix E—List of Controls

SWiFT Hydraulic System Controls	
Control	**Description**
Pressure Sensor 12	Pressure sensor 12 measures system pressure upstream of check valve 11.1 and downstream of Pressure Reduction Valve 24 (Nodes 2 – 4). The sensor sends a signal to the nacelle controller. At 75 bar, the controller turns on the pump to increase system pressure. At 90 bar, the controller turns the pump off. The controller prevents the turbine from moving into *Pause* until the system is within the operational pressure band. Pressure alarm 163 sends turbine to *E-Stop* if pressure falls below <50 bar or if pressure sensor 12 has no reading.
Pressure Switch 26	When pressure in the braking node falls <14 bar, pressure switch 26 sends a signal to the controller that initiates *E-Stop* to put the turbine in a safe condition if brake node pressure is falling.
Preventive Maintenance (PM)	A PM procedure/process provides guidance for keeping all equipment, systems, and components in good operating order by means of preventive maintenance, inspections, repairs, and calibrations. For the SWiFT Hydraulic System FMEA, PM on the following system components is used as a control: • Hydraulic system • Tank level switch • Pump motor • RTD • Air/filling filter • HPF 10 • Pressure sensor 12 and pressure switch 26 • Relief valves 13 and 29 • Accumulators 16 and 27 and associated air bladders • PRV 24 • Emergency brake • Vickers card • Pitch ram position sensor calibration
Relief valve 13	Relief valve 13 relieves pressure from the pitch node to the tank if pressure rises >100+5 bar. The relief valve capacity is 4.5 L/min, which is in the range of the pump capacity (4.3 – 5.0 L/min). The relief valve provides adequate protection for the pitching node, unless the pump were to run continuously at a rate greater than the capacity of the relief valve.
Relief valve 29	Relief valve 29 relieves pressure from the brake node to the tank if pressure rises >25 bar. The capacity is 0.5 L/min. Pressure in the brake nodes is regulated at 19 bar by PRV 24. The purpose of relief valve 29 is to protect against a misalignment of PRV 24 that results in high node pressure.

Appendix E—List of Controls

SWiFT Hydraulic System Controls	
Control	**Description**
Rotor Speed Controls	Rotor speed controls include the automatic hard-wired E-Circuit sensors that monitor the speed of the low-speed shaft (VOG-1 and VOG-2, or equivalent design features). The rotor speed controls will open the associated, dedicated E-Circuit switch if rotor speed exceeds the sensors' pre-set limit. Once interrupted, the E-Circuit activates relays that 1) disconnect the generators from the grid, 2) align the hydraulic accumulators to apply the turbine brake and push the blades to feather, 3) notify the nacelle controller that the E-Circuit is open and override the controller's signal to the pitch proportional valve, and 4) disconnect the power to the hydraulic and yaw motors. For more information about the E-Circuit and associated sensors, see the SWiFT Facility SA and SWiFT Emergency Stop Circuit FMEA. Rotor speed controls have three associated turbine stopping mechanisms: the hydraulic active pitching system, the hydraulic brake, and the passive pitching design. The brake is expected to stop the turbine if active and passive pitch are disabled by a single failure (such as a line blockage to or from the pitching ram). Passive pitch will stop the turbine if the pitching and brake nodes are disabled by a single failure (such as simultaneous, rapid pressure loss in both the pitching and brake nodes). Therefore, rotor speed controls are expected to always have a mechanism to stop the turbine for any single failure mode within the hydraulic system.
Running History (Ambient Temperature)	Ambient temperature and running history are an indication of a faulty RTD signal or an over-cycled pump. If the RTD alarms at an unexpected time, operators shall investigate possible causes.
Safety Block	The safety block allows two-way pressure in and out of the "feather" side of the ram in *Run* and *Pause*, but only allows (and holds) pressure in during *Stop* and *E-Stop*, to keep the turbine in "feather" if upstream pressure degrades.
UPS	The uninterruptable power supply system provides approximately thirty minutes of backup power to the nacelle equipment when normal p ower is lost. The UPS provides nearly instantaneous protection from interruptions of the main power supply.

F—Recommended Actions from FMEA Workshops

Supply

- Investigate incorporating hydraulic tank level switch signal check during start-up checklist.
- Investigate hydraulic fluid properties—is it flammable/combustible?
- Verify RTD sensors open and shorted circuit loop and update software
- Investigate feasibility of high-level hydraulic tank alarm to indicate high faulty pressure sensor reading.
- Determine if system must operate on continuous pressure or can operate on pump-fluctuated pressure and what are consequences.
- Evaluate need for indication of pump turning on or alarm for turning on too frequently.

Filter

- Consider increasing filter change frequency.
- Consider stocking spare filters at facility.
- Consider including fluid contamination checks as part of PM.
- Check filter burst pressure against relief valve setting and PM test settings.

Pressure Sensor

- Evaluate and document signal plausibility (health monitoring) of pressure sensor 12 or continuous monitoring or duplication of pressure sensor 12.
- Create PM schedule for pressure sensor 12.
- Consider stocking back up sensor at facility.
- Evaluate alarm for stuck sensor.
- Determine if Pressure Sensor 12 is connected to backup power source.

Vickers Card

- Investigate PM/testing of Vickers card.
- Consider stocking a back-up Vickers card at facility.
- Evaluate potential alarms associated with Vickers card.

Pitch Ram and Position Sensor

- Investigate controls for a bent pitching ram or leak in ram—is there a PM or inspection?
- Consider adding an alarm if the pitch ram position sensor is out of calibration range.
- Consider stocking a replacement pitch ram position sensor at facility.
- Add calibration interval to for pitch ram position sensor to preventive maintenance procedures.

Appendix E—List of Controls

Miscellaneous

- Evaluate temperature alarm 167 as a control against hydraulic system failure modes.
- Create CM program for controller software.
- Pitching moment of rotor (JB can figure out with new one, will use current blades to determine)
- Research life cycle for components (global).
- Evaluate fluid loss rates' effects in different areas of the system.