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Description and Analysis of the Hardware Safety Systems for the DOE/SNL SWiFT Wind Turbines

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Abstract

This report covers the design and analysis of the hardware safety systems of the DOE/SNL Scaled Wind Farm Technology facility wind turbines. An analysis of the stopping capability of the turbines in multiple scenarios is presented. Included are calculations of braking torque, simulations of high wind speed emergency stops including multiple fault scenarios, and comparisons of predicted turbine performance to the relevant design standards.

ACKNOWLEDGMENTS

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NOMENCLATURE

DLC	Design Load Case
DOE	Department of Energy
EOG	Extreme Operating Gust
ETM	Extreme Turbulence Model
IEC	International Electrotechnical Commission
FAST	Fatigue Aerodynamics Structures and Turbulence (NREL code)
NREL	National Renewable Energy Laboratory
NTM	Normal Turbulence Model
OSPR	Over-Speed Protection Rotor
OSPS	Over-Speed Protection Shaft
SNL	Sandia National Laboratories
SWiFT	Scaled Wind Farm Technology
VFD	Variable Frequency Drive

1. INTRODUCTION

This document describes the philosophy and function of the hardware safety systems for protection of the wind turbine generators at the Department of Energy (DOE) / Sandia National Laboratories (SNL) Scaled Wind Farm Technology (SWiFT) facility. Analysis of critical situations and component behavior is included.

The system consists of two independent braking methods to bring the turbine to a full stop in the event of an emergency in all turbine operating conditions. The following document will present the philosophy behind the system design, the mechanisms for bringing the turbine to a stop, and the software independent safety systems. This includes definitions of turbine states of STOP and EMERGENCY, the triggers to activate each state, and the responses of the turbine to each state.

In the IEC61400-1 standard, the controller is referred to as a “protection system”. Should a critical operating parameter exceed its normal limit as a result of a fault or failure in the wind turbine or the control system, the machine is maintained in a safe condition.

Critical operating parameters are:

- Turbine rotational speed
- Power output
- Vibration level
- Twist of pendant cables running up into nacelle

This document describes the sensors and connections to the emergency circuit, including the upgrade of the system, compared to the legacy machine. It describes the reactions of the turbines due to emergency stop and stop circuit activation and analyzes the cases relating to the critical parameters during stopping events.

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2. TURBINE STATES

For clarity, the turbine states that are directly relevant to the hardware safety systems are briefly described here. This section does not qualify as a full description of the turbine states. The full description of turbine operating states can be found in Section 3 of the “Electrical Operating and Maintenance Manual” for the SWiFT facility. The directly relevant turbine states are STOP and EMERGENCY.

While the turbine is in a STOP state, the pitch control system is mechanically by-passed forcing the blades to a fully feathered state, the automatic yaw is inactive, the brake is not engaged, and the hydraulic pump maintains the working pressure within the system. The Variable Frequency Drive, VFD, that controls the generator is notified to monitor the speed of the rotor and will apply torque to slow the rotor if it does not slow to a stop within a specified time. This state is utilized by the controller for a multitude of alarms to bring the turbine to a safe state. This state is also accessed by the hardware safety system in the event of an excessive vibration, cable over-twist, or loss of grid quality, frequency or voltage.

When the turbine is in EMERGENCY, all outputs from the turbine controller are mechanically by-passed, deactivating the pitch control system and hydraulically forcing it to feather, engaging the brake, notifying the VFD to bring the rotor to a stop, and deactivating the yaw and hydraulic systems. This is the default state of the turbine software controller. In order to elevate into other states, a series of checks and verifications need to take place by the control software. The turbine can be reduced to the EMERGENCY state from any other state depending upon errors generated, or when activated by the hardware safety circuit. The Emergency Stop circuit opens upon detection of turbine overspeed, brake caliper overheating, loss of turbine controller signal, controller operation, or any of the manual Emergency Stop buttons located at the facility, from within the turbine or the control building.

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3. EMERGENCY CIRCUIT

The hardware emergency system is the last line of defense of the turbine to prevent a catastrophic overspeed of the wind turbine and other key protection points. The hardware based sensing are associated with limits which are generally higher than normal operations, but still within safe operations according to standards and norms. Never the less, it is desirable that the circuit is not engaged.

The circuit includes redundant overspeed protection systems, a controller watchdog to ensure the controller is actively producing a heartbeat, brake temperature, and manual emergency buttons. It consists of a 24VDC circuit which must remain closed in order for the turbine to operate.

The main 24VDC power supply is designed to have a power backup UPS to avoid automatically putting the turbine into EMERGENCY in the event of a power supply failure. This is to allow the controller to bring the turbine to a controlled stop and aid in the analysis of the power failure without triggering ancillary error codes. This backup is wired at the main voltage source as to not interfere with the opening of the circuit in the event of a separate emergency. Figure 1 shows the electrical wiring of this circuit. When the circuit is open, power is lost to a set of normally open relays. These relays by-pass all necessary controller communications and bring the turbine to a stop by pitching the turbine to feather, notifying the VFD controller and applying the brake.

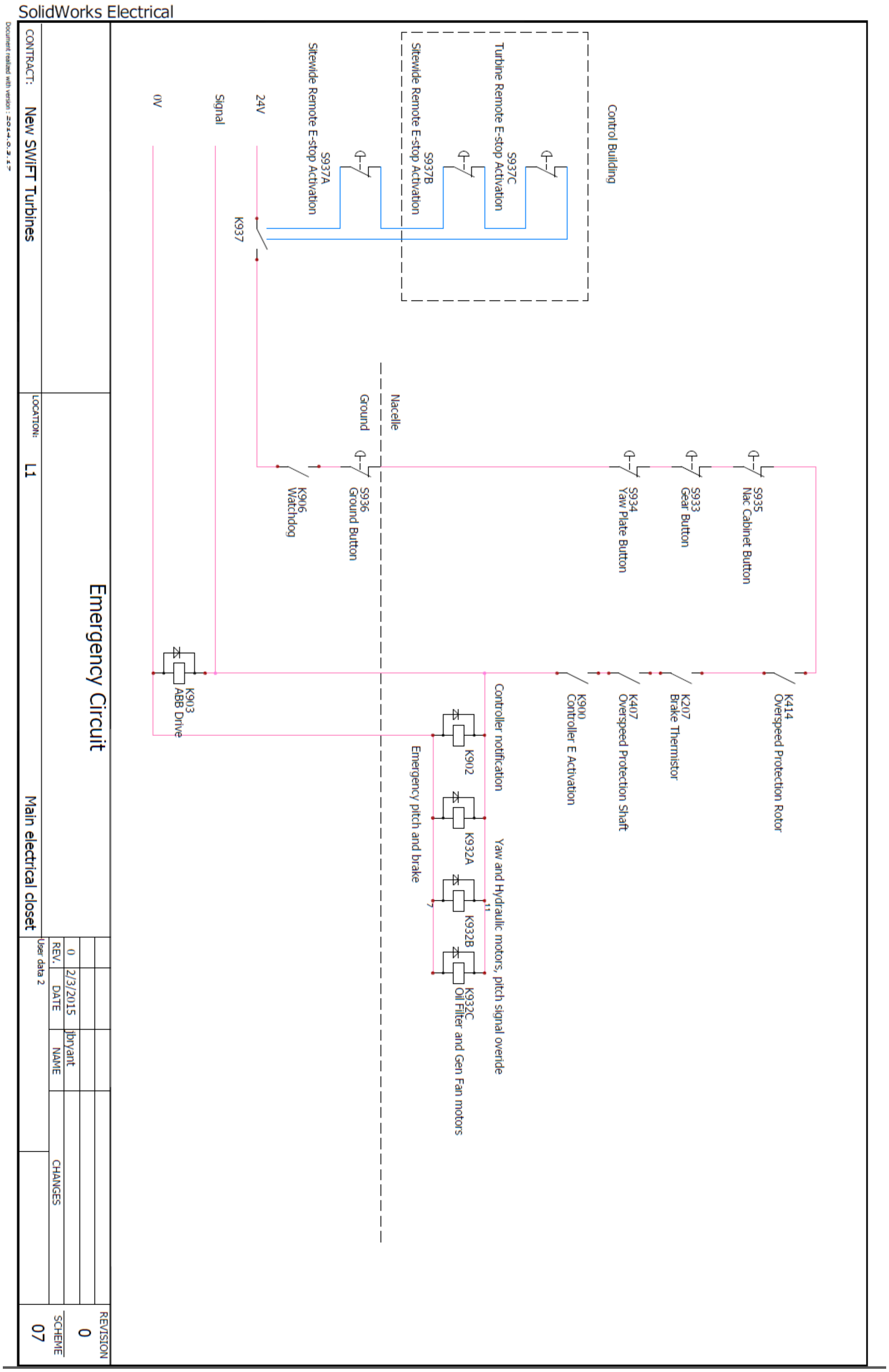

Figure 1. Emergency Circuit Diagram.

The circuit can be opened by any of the following:

- Emergency Stop Buttons
  - Turbine operator station
  - Main site button within the control room
  - Main site button on exterior of control building
  - Ground controller cabinet
  - Nacelle controller cabinet
  - Yaw deck
  - Gearbox
- Over Speed Protection System Rotor (OSPR)
- Over Speed Protection System Shaft (OSPS)
- Controller watchdog
- Controller direct activation
- Brake temperature thermistor

If the circuit is opened the following occurs:

- K902 opens
  - Notifies controller that the Emergency circuit has been opened
- K932A opens
  - Disconnects voltage to hydraulic system solenoids, pitches blades to feather, applies brake
- K932B opens
  - Disconnects voltage to pitch proportional valve controller
  - Disconnects controller activation to yaw motors and hydraulic pump
- K932C opens
  - Disconnects voltage to the oil filter and generator fan
- K903 opens
  - Communication to VFD (ABB Drive)

When the 24VDC emergency circuit opens, the power to the solenoids in the hydraulic system is removed causing them to open, and sending hydraulic fluid pressure to the brakes and the pitch ram. This applies the full force of the brakes, and forces the hydraulic pitch ram to the feather end stop. While in EMERGENCY the controller, still maintains the ability to collect data and monitor the state of the turbine. The sensor locations within the nacelle are shown in Figure 2.

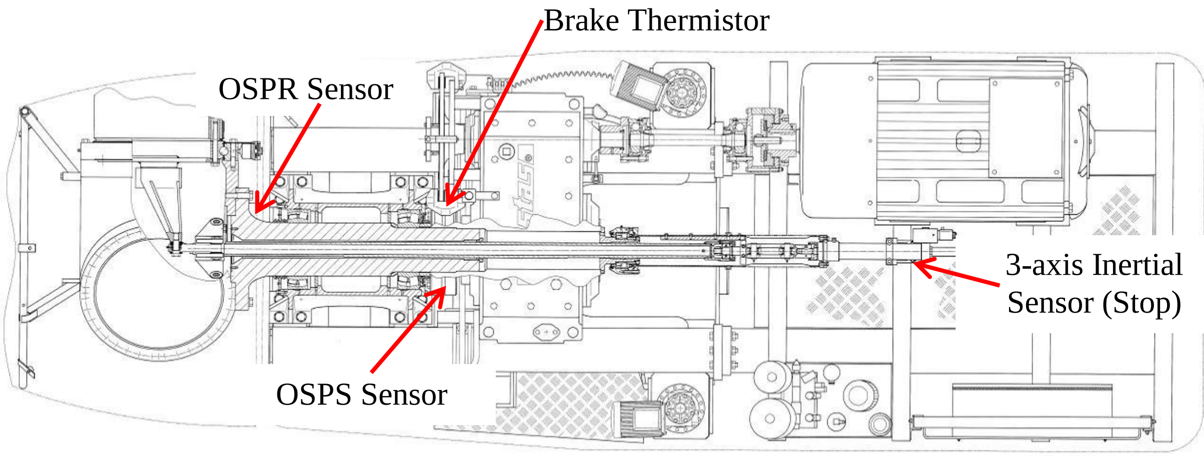

Figure 2. Nacelle Top View with Sensor Locations of the Hardware System.

3.1 Rotor Speed Sensors

Germanisher Loyds (GL), a wind certification body, elaborates beyond the IEC standard in their standard (often called the blue book) on the desired over speed protection characteristics required by wind turbines. There are four main levels of rotor rotational speed that are defined by the GL standard, as shown in Figure 3. The turbine normal operating range exists between n_1-n_3 with n_3 being the higher end of the normal deviation from expected rotational speed. When the turbine reaches n_4 the turbine controller should shut down the turbine due to high rotor speed. If the controller fails to react to the overspeed, the hardware safety systems will activate and open the Emergency Circuit at n_A. This corresponds to 52.7 RPM for the current SWiFT turbine setup.

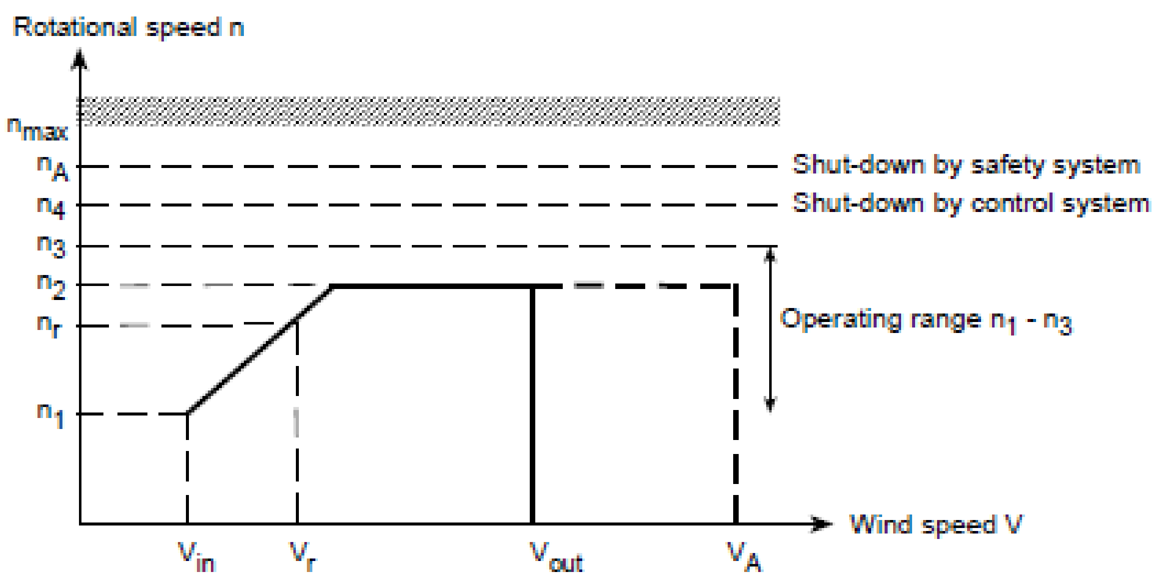

Figure 3. GL 2010 Definition of Rotational Speed Limits.

There are two redundant systems for monitoring the rotational speed of the rotor within the hardware safety system, and a third sensor which is solely monitored by the controller.

The first is an overspeed protection system designed by Phoenix Contact referred to as Over Speed Protection Rotor or OSPR. The OSPR is an electronic circuit designed to monitor an input signal frequency from a three wire inductive proximity sensor measuring steel flags mounted to the rotor bolts. When the frequency of targets exceeds the set limitation that corresponds with n_A, the OSPR latches open the Emergency Circuit, sending the turbine to EMERGENCY, requiring a reset button to be physically pressed within the nacelle in order to close the relay and reestablish the 24VDC Emergency circuit. A signal is sent to the turbine controller that the OSPR was triggered and a series of reviews must be completed by the SWiFT management staff to reestablish turbine function.

The second overspeed system, OSPS, monitors a low profile 3-wire inductive sensor mounted on the downwind side of the main bearing housing, shown in Figure 4. The sensor counts the flat face of the bolt heads on the slip disk which rotates with the low speed shaft. This overspeed system operates on the same principle as the OSPR. It is a speed and downtime monitor from Phoenix Contact specifically designed as a safety relay for machine overspeed protection. If the activation frequency is reached, the Emergency Circuit is opened and a signal is sent to the controller identifying which sensor caused the trip of the relay.

Both low speed shaft speed sensors are actively monitored by the turbine controller. The pulses received by each sensor, as well as a third inductive sensor on the high speed shaft are compared with logic to determine if a sensor has been damaged mechanically or electrically, or for some reason is not recording targets. The controller will signal an error and bring the turbine to Emergency Stop when any of the speed sensors (2 x low speed shaft, 1 x high speed shaft) is damaged. This functionality protects against faults in either of the systems, such as a wire being cut, or a target striking a sensor.

Each Phoenix Contact overspeed control box provides an error signal which is monitored by the controller if an internal error in the box occurs. The Emergency Circuit will be opened by the device and the controller will be notified of any internal errors within either of the Phoenix Contact overspeed modules. If any of the components are faulted by an electrical failure, they will open the emergency circuit relay and the controller will be notified by its status signal that a failure has occurred within the component.

The setup, testing, bracket design and sensor information for the OSPR and OSPS can be found in Appendix A: OSPR Information and Appendix B: OSPS Information.

Figure 4. left) Image of OSPR installed on mounting bracket, right) Second low speed shaft overspeed sensor (OSPS).

3.2 Controller Watchdog

The software controller operation is important for the first line of defense safety of the turbine, and should ideally prevent the hardware based circuits from being activated. However, as part of the research nature of the SWiFT turbines, the software controller may be changed from time to time to enable new testing campaigns. Like all software, there are potential scenarios where it may freeze or become unresponsive. In these scenarios it is preferred that the turbine shuts down to EMERGENCY as a direct response to the software being unresponsive, rather than the turbine reaching hardware sensed limits, which is only a second and final line of defense. Therefore an active watchdog has been included in the emergency circuit. The active watch is accomplished by having a watchdog relay monitor an active signal frequency output from the controller. If the controller is not active, or is frozen, the active signal will become constant, either at a known value or zero. This will cause the watchdog relay to trip opening the Emergency Circuit. Watchdog information and setup can be found in Appendix C: Watchdog.

3.3 Brake Thermistor

A brake thermistor mounted to one of the brake pads, shown in XXX, is directly connected to the 24 VDC Emergency circuit. When the brake pad bulk temperature rises above 150 Celsius the thermistor opens the circuit keeping the turbine in Emergency Stop until the temperature cools. This guarantees the turbine cannot start up directly after a braking event, and also ensures to catch things like brake rub, which may impair the braking ability of the turbine. Details about the brake thermistor sensor can be found in Appendix D: Brake Thermistor.

3.3 Controller Operated Relay

In addition to the watchdog, the controller software must actively hold closed the K900 contactor for the emergency circuit to maintain power. This relay is opened whenever the turbine controller software detects a situation that is deemed necessary to put the turbine into

EMERGENCY. As with the watch dog, this features secures that the turbine can quickly be shut down without needing to activate hardware based sensors and generally higher limits.

When the controller is not actively running on the turbine, this relay will remain open keeping the turbine in an EMERGENCY state. In order to ascend state level to STOP the controller must hold this contact closed, as well as put out an active signal to the controller watchdog, in order to complete the Emergency Stop circuit.

3.4 Emergency Stop Buttons

Emergency Stop buttons have been added to the control building for access by operators during turbine operation. The system is designed so that each turbine has an individual E-Stop button within the control building. Two additional E-Stop buttons are installed which shut down all turbines simultaneously, with one being located inside of the control building and one being located on the outside of the control building for use by on-site workers. Current layout of the control building is shown in Figure 5.

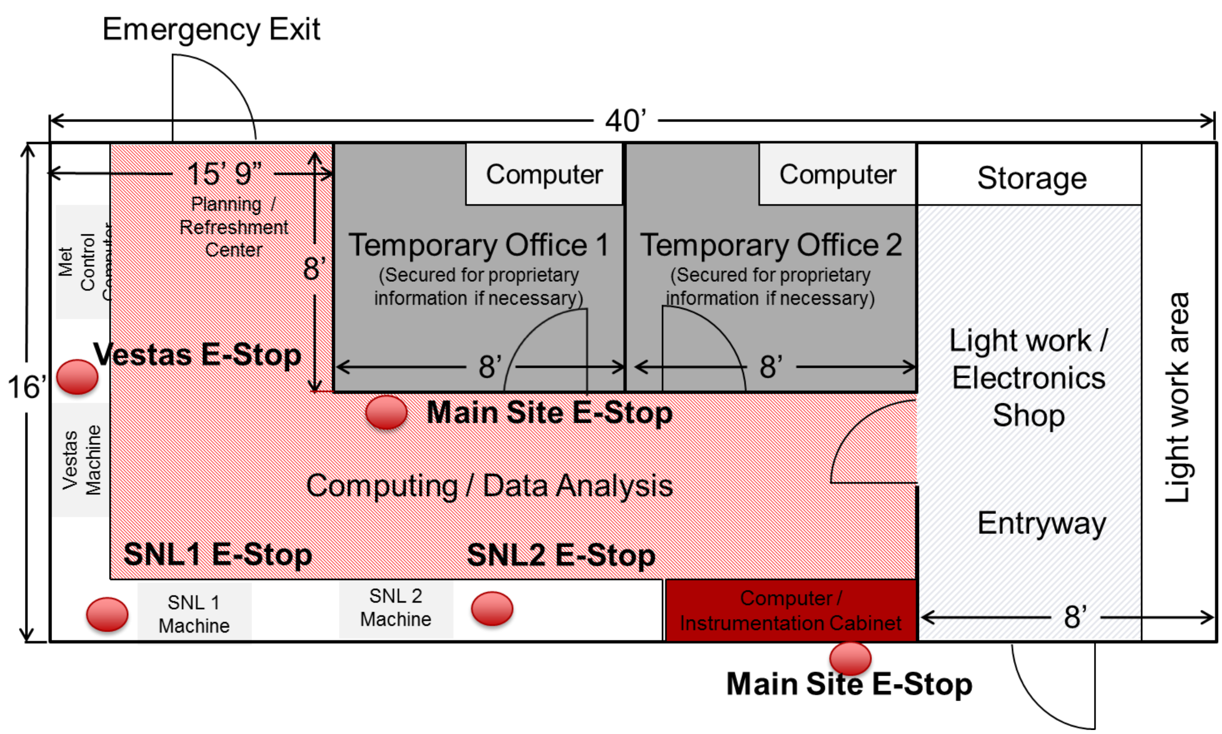

Figure 5. Mobile Control Building Layout with E-Stop Button Locations.

In order to extend the Emergency circuit within each turbine to the control building there must be a wired communication to the building. This is accomplished with a fiber-optic communication cable and contact closure. During the installation of the SWiFT facility multiple communication cables were installed between the turbines and the control building which allows for unused fiber optic lines to be used for the E-Stop buttons.

The devices used to transmit the hardwired circuits for Emergency Stop and Stop circuits are called Fiber Optic Contact Closures. These devices, shown in the conceptual drawing from the manufacturer in Figure 6, transmit an active signal across the fiber line to a receiver module in the turbine which energizes a relay to hold the safety circuit closed. The chosen devices are from Ultra Electronics (http://ultra-nspi.com/products/industrial-fiber-optic-networking/contact-closure/fotfor-cc-digital-data-link/). They were originally developed in the early 2000's for use in Emergency Stop circuits for Shell Oil, certified for use in nuclear power plants, and are designed to be fail safe in all known ways of communication failure.

Figure 6. Fiber Optic Contact Closures.

The receiver must read an active bit stream coming from the transmitting module within the control building in order to energize the relay, thereby closing the circuit and allowing operation of the turbine. If power is lost at either the control building transmitter or the receiver in the turbine, or if the communication is broken in any way, either from being disconnected, the cable broken, or simply the active signal freezing, the receiver will de-energize the relay causing the emergency circuit to open triggering an emergency stop of the turbine.

There are four Emergency Stop buttons directly tied into the Emergency Circuit within the turbine itself. These four buttons will open the circuit sending the turbine to an Emergency Stop and have remained unchanged from the original Vestas designs. They are located at the tower base, yaw deck, top controller cabinet, and mounted to the gearbox.

4. STOP CIRCUIT

In order to bring the turbine to a stop safely and to hold the turbine in a de-energized state, with minimal impact on the turbine, without relying on the turbine controller, a hardwired Stop circuit was designed. The Stop circuit includes a three axis inertial safety switch to monitor the vibration of the turbine at all times, a twist stop sensor preventing cable snap beyond the detection limits of the controller, grid monitoring devices for over voltage, under voltage and frequency content as well as a stop switch activated from within the control building.

Similar to the Emergency circuit, the Stop circuit consists of a 24 VDC circuit which must remain closed in order to keep a set of contactors closed, allowing the turbine to operate. If the circuit is opened, the controller will be notified, a contactor relay will open causing the pitch control to be bypassed, the pitch forced to feather, the automatic yaw is disabled and the VFD drive controller is notified. The circuit diagram is shown in Figure 7.

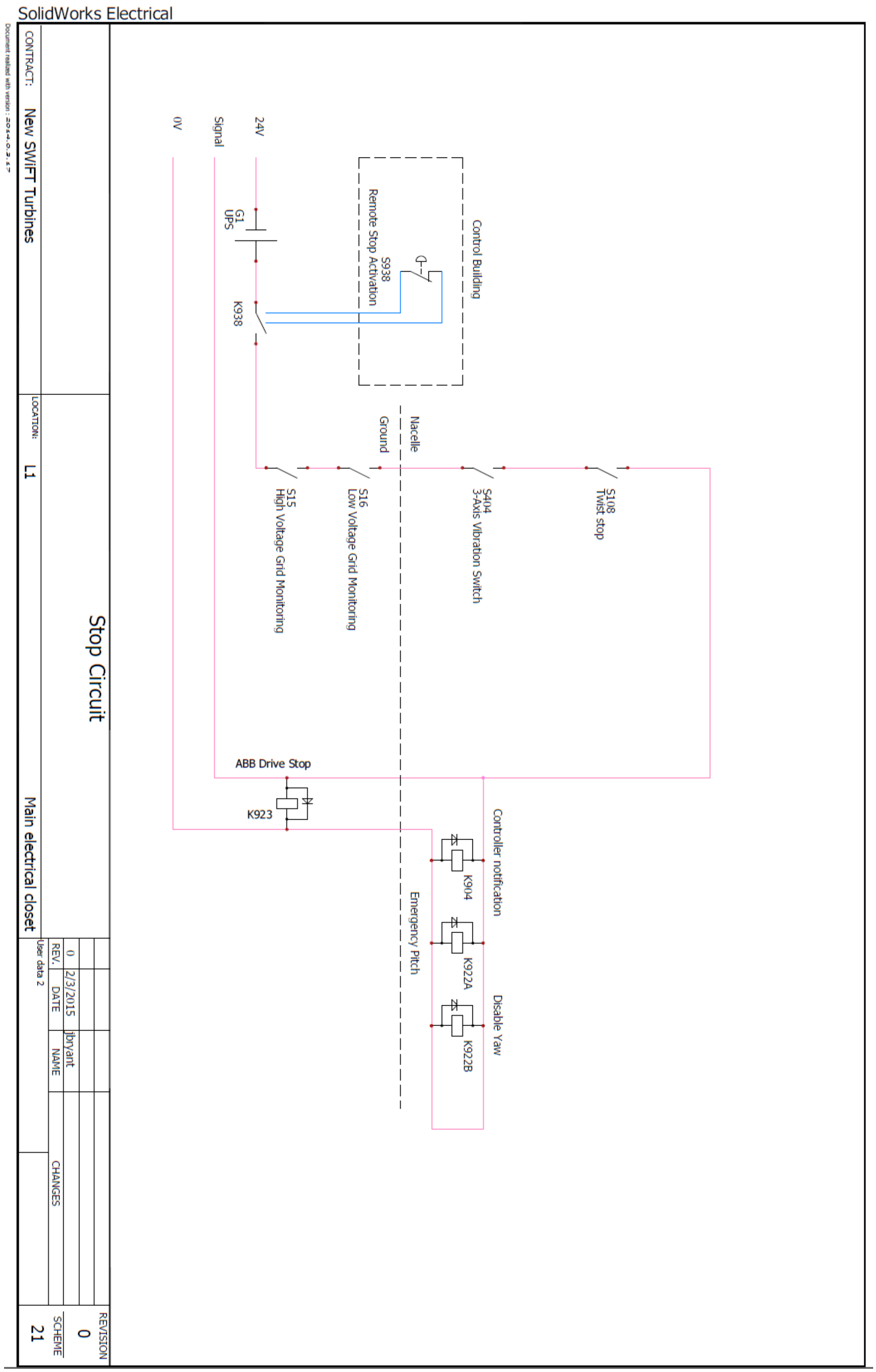

Figure 7. Stop System Diagram.

There is a fiber optic contact closure as described in the Emergency Stop circuit which is used to lock the turbine in the Stop position removing power to the Yaw and forcing the turbine to feather from the control building. These are switches for each turbine kept separately from the emergency stop buttons as to not confuse an operator during the case of an emergency.

To summarize, the circuit can be opened by any of the following:
- Grid loss detection
- Cable over-twist
- Vibration switch
- Control building stop switch

If the circuit is opened, the following occurs:
- K904 Opens
    - Notifies controller of open stop circuit
- K922A Opens
    - Disconnects voltage to solenoids for pitch system, forcing blades to feather
- K922B Opens
    - Disconnects communication from controller to yaw motors
- K923 Opens
    - Communication to VFD (ABB Drive)

4.1 Vibration Switch

When bringing the turbine to a safe stop during an event such as the vibration sensor being tripped during operation of the turbine, it is crucial that the actions of the wind turbine response do not cause more damage to the system. If a large impulse is imparted to the system while there is a large imbalance, like slamming on the brakes while pitching the blades from high speed, the turbine has the potential to vibrate even more by exciting critical modes of the structure. Therefore, when the mechanical vibration switch opens the Stop circuit during a high vibration, the pitch will feather reducing the rotor torque generated and slowing with aerodynamic drag, the VFD controller will monitor rotor speed and apply only the torque required to bring the turbine to a safe state in the specified time, and any yawing of the turbine will be stopped.

The three axis vibration sensor shown in Figure 8 consists of a normally open contact which is held closed with a magnet. If the sensor experiences a large vibration in any axis, the spring-mass system will move, causing the contactor to open, breaking the circuit. The circuit is held in this state with a separate spring, the sensor must be manually reset by pressing the external reset button to return the contactor to the closed position allowing the turbine to run normally. Details of the sensor and its set limits are discussed in Appendix E: Mechanical Vibration.

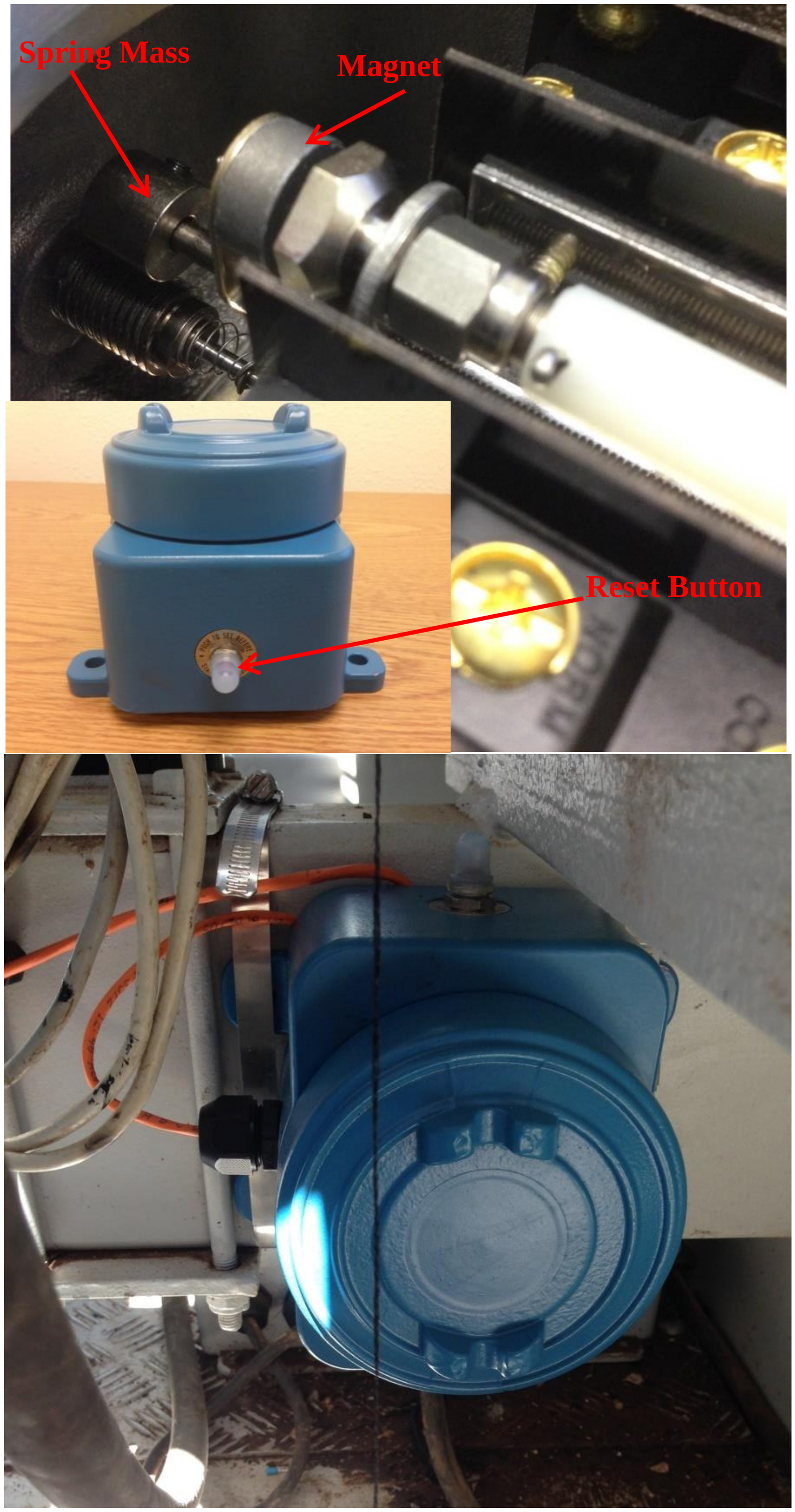

Figure 8. Mechanical Vibration Switch.

4.2 Yaw Over-twist Stop

The turbine controller monitors the amount of twists in the power cables in order to ensure the cable does not over twist and cause damage to the turbine components. However, it is required in international standards (GL 2010) to monitor this twist within the hardware safety systems. This is accomplished within the Stop circuit without interfering with the controller by monitoring the signals that are fed into the controller by the yaw sensor. The four outputs of the yaw sensor are shown in Figure 9.

The axis running along the top of the figure is a count of current yaw position in terms of amount of cable twist, from two turns counter clockwise (CCW) to two turns clockwise (CW). If the cable has no twists in it, the only signal that will have positive voltage is S104, twist stop. This informs the controller the turbine is in normal operation. When either S102 or S103 have positive voltage, the turbine controller will yaw the turbine to within one rotation whenever it is not actively producing power, i.e. the winds are below cut in speed. If S104 ever goes to zero voltage, the turbine controller will stop the turbine no matter the wind speed, and yaw in the opposite direction of the still positive signal (S102 or S103) until the cable is untwisted. S105 signals to the controller that the turbine is actively yawing by a pulse.

At all times during normal operation at least one of the three monitoring signals (S102, S103 or S104) will be positive. If the yaw rotation extends beyond where the twist stop signal S104 goes to zero, the active direction signal (S102 or S103) will also go to zero. When this happens, the Stop circuit will open removing power from the yaw motors and pitch the blades to feather. This is performed with a normally open relay on the Stop circuit (S108) that is powered through a parallel set of relays connected to S102, S103, and S104. If any one of the signals has a positive voltage the relay on the Stop circuit will remain powered. When all of the signals are zero, the power to the Stop circuit relay is completely cut, causing the relay to open and sending the turbine to Stop. A diagram of this is shown in Figure 10.

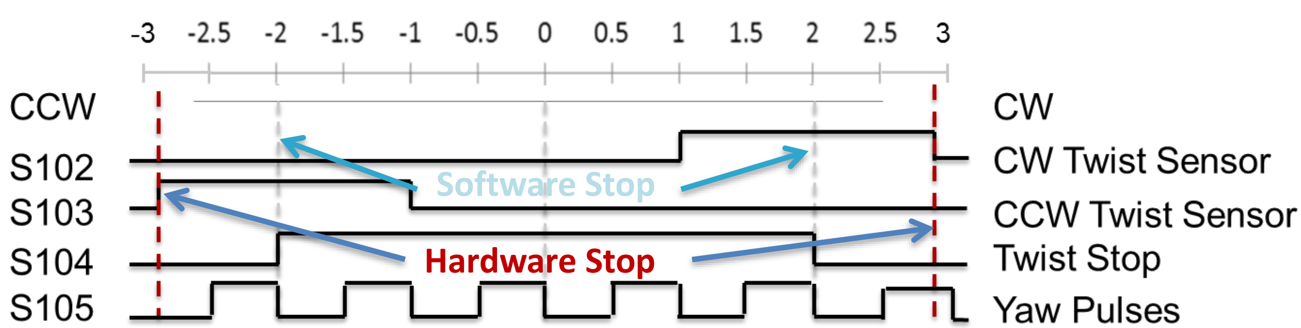

Figure 9. Yaw Sensor Output Vs. Yaw Position.

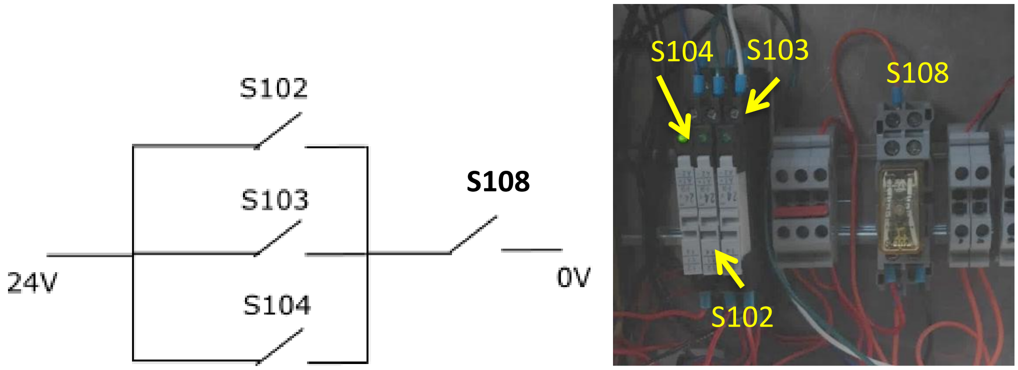

Figure 10. Yaw Relay for Stop Circuit.

4.3 Grid Loss Protection

There are two voltage monitoring relays measuring the voltage and frequency of the incoming grid. When the frequency or amplitude of the electrical grid varies beyond a set of predefined limits, as specified in IEEE 1547 / UL 1741 Islanding Protection Requirements, the relays are opened, engaging the Stop circuit. The controller is also notified of the grid disruption by the power electronics. Details of the systems, settings and parameters are discussed in **Error! Reference source not found.**.

5. STOPPING MECHANISMS

There are two independent stopping mechanisms aboard the SWiFT V27s that are designed to bring the turbine to a stop safely in all operating conditions of the turbine. In order to meet GL design standards, at least one of these systems must act directly on the rotor. The stopping system consists of a collective pitch to feather stop and a mechanical brake applied to the high speed shaft. Each of these systems is hydraulically activated. This section describes each stopping mechanism and the hydraulic system operation.

5.1 Hydraulic System

The hydraulic manifold on the SWiFT research turbines has remained unchanged from the commercial V-27. It has two functions, to control the pitching and apply the brakes on the machine. Figure 11 is a diagram of the hydraulic manifold. It is split into three distinct sections. The bottom left side of the drawing contains the pump and fluid reservoir, the upper left contains the pitch control mechanisms, and the upper right contains the high speed shaft braking system. The single pump provides pressure to the pitching system through a check valve (11.1); the fluid then goes through a pressure reduction valve and enters the braking system through check valve 11.4. The check valves prevent any fluid flow back to the previous level. There is a needle valve which will allow drainage of fluid back to the reservoir directly from the pitch side and the brake side for alleviation of pressure during maintenance of the system. Each side also has an accumulator with a volume of pressurized fluid within the system.

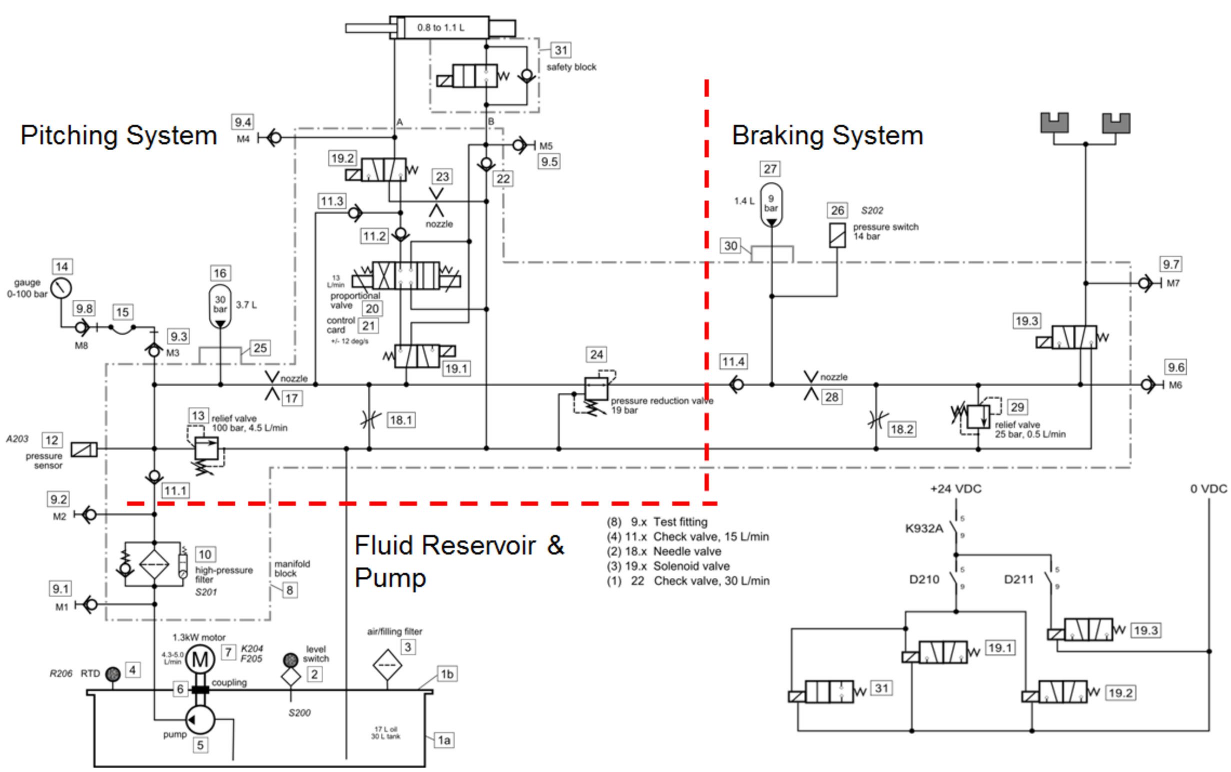

Figure 11. Hydraulic System Diagram of SWiFT Turbines.

There are two pressure sensors monitored by the controller within the hydraulic unit. The first is located within the pitching mechanism. This sensor, labeled as 12 in Figure 11, is used to control the operation of the hydraulic pump in order to keep the overall system within the desired operational pressure range. The second sensor is a limit switch on the brake accumulator. During operation of the turbine, if the hydraulic pressure in the braking system drops below the switch level, the controller triggers an "emergency stop" (E-Stop) event.

During normal operation, the turbine controller utilizes the proportional valve (20) to control hydraulic fluid flow to the pitch ram which is translated to blade pitch rotation by a spider linkage system located within the hub of the turbine. Brake application is controlled by solenoid valve 19.3. Whenever the turbine is in EMERGENCY no voltage will be applied to the solenoid valve, causing the brakes to be applied. When the turbine enters "Pause" or "Run" modes a 24 VDC excitation activates the solenoid, causing the brake calipers to drain to the fluid reservoir, releasing the brakes.

If a failure occurs in the pitch system, such as a broken hydraulic line, or a stuck solenoid valve, rendering pitch inoperable, the check valve 11.4 will prevent any reverse flow from the braking system. The controller will monitor the position of the pitching shaft, as well as the pressure of the system; a discrepancy from expected values will put the turbine in EMERGENCY. The brakes will apply and stop the turbine.

If a failure occurs within the brake system, such as the actuation solenoid valve becoming stuck, the pitch mechanism will be able to stop the turbine on its own. If a brake line is broken while the turbine is operating (brakes released), it will continue to operate normally until the brakes are applied. Once applied, the solenoid valve will open releasing brake fluid to the calipers, which will cause an immediate pressure drop sending the turbine into EMERGENCY, if not already there, activating the pitching mechanism to stop the turbine.

5.2 Pitch Mechanism

The collective pitch mechanism of the turbine is operated by a single traverse tube which extends through the LSS into the hub. There it connects to a spider linkage system consisting of a yoke, connecting link and crank arm which translates the linear motion of the yoke to blade rotation. This system is highlighted in Figure 12.

The pitch system requires two spring safe solenoid valves regulating the routing of the hydraulic fluid for pitching. When powered, the solenoid valves direct the fluid through the computer controlled proportional valve and allows the turbine to contract the traverse tube causing the turbine to pitch to run at the desired rate. When power is lost to either of these spring safe solenoid valves, the turbine will bypass the control system and pitch the turbine to feather, bringing the rotor to a safe state.

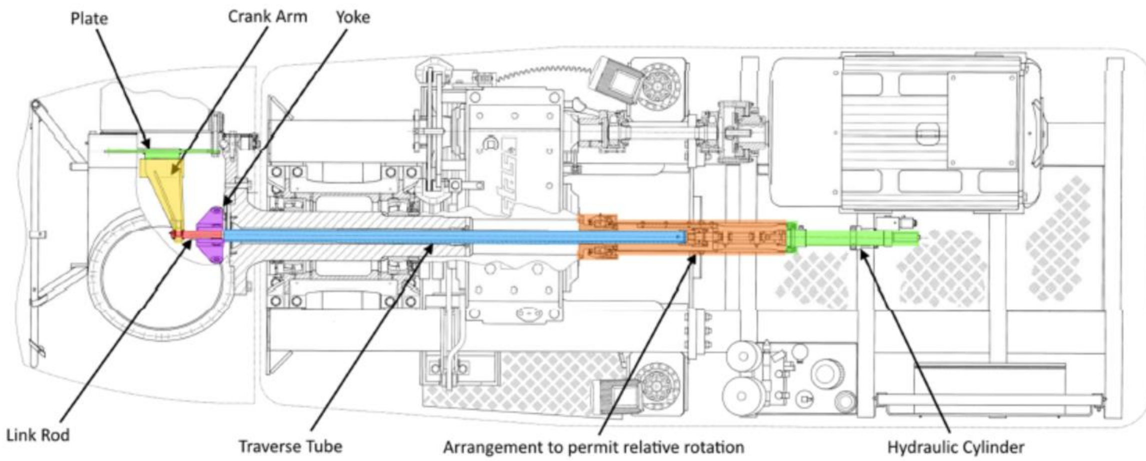

Figure 12. Pitch System of SWiFT Turbine.

The blades of the turbine are designed to passively pitch to feather caused by an intentionally designed aerodynamic pitching moment in case of complete hydraulic system failure. Therefore the blades must be actively held to pitch by the pitching system.

5.3 Generator Assisted Stopping (Variable Frequency Drive)

The Variable Frequency Drive (VFD), referred to as the "ABB Drive," or "ACS 800," controls the torque produced by the generator. Due to the turbine's ability to produce power at variable rotational speeds, variable frequency AC electricity is produced by the generator when power is being generated. The VFD converts this variable frequency power to DC voltage and then back to clean 60 Hz AC to be sent to the grid. The drive is located in a small building directly adjacent to the turbine tower. The drive itself is shown on the left side of Figure 13. A brake chopper, on the right in Figure 13, monitors the voltage (~680 VDC) on the DC bus of the drive. When more power is being produced by the generator than can be pushed to the grid, or when the grid is down, the DC Bus will rise in voltage. If the voltage rises above 775 VDC the brake chopper will engage dumping excess power to the resistor bank shown in Figure 13.

Figure 13. Variable Frequency Drive and Brake Chopper

The addition of the brake chopper to the VFD ensures that torque can be provided by the generator at any time, including when the grid is not available. Due to heating concerns it will only be used for one time stopping situations and allowed to cool prior to resuming turbine operations.

The VFD is notified by both the Stop and Emergency Stop hardware circuits to shut down the turbine. When either hardware stopping system is engaged, the stop interlock is interrupted to the drive, causing it to go into a user defined stopping procedure. There is a user defined stopping curve which determines a period of time in which the rotor must be ramped smoothly to zero RPM. The drive monitors the rotational speed of the generator with reference to the pre-defined stopping curve. If the rotor maintains a speed above the predefined stopping curve, the generator will provide braking torque to slow the rotor, with a maximum of 2,300 Nm of torque for a short duration during stopping.

5.4 Mechanical Brake

The wind turbines installed at the SWiFT facility employ a disc brake with two hydraulic calipers (red-colored) on the high speed shaft (HSS), shown in Figure 14 below.

Figure 14. SWiFT Nacelle during construction showing high speed shaft brake mounted to gear box housing.

The brake calipers are actuated by the removal of power to a spring safe solenoid valve within the hydraulic system providing 19 bar ($19x10^5$ Pa) of brake pressure. This corresponds to a braking torque on the HSS of 2.7 kN-m. The braking torque is amplified through the gearbox by the gearbox ratio of 27.565 for an effective braking torque on the rotor of 74 kN-m. During normal operation of the SWiFT turbines the nominal rated speed of the rotor is 43.9 RPM at a torque of 44kN-m, making the nominal power output of the turbine 202 kW. This corresponds to a brake torque to rated torque ratio of **1.7**. The reduction in power from the original 225kW machine is due to the torque limit on the new variable speed generator.

Within the turbine controller software, there is an allowance for 10% maximum overspeed variation before signaling an error and putting the turbine into STOP. If for some reason the turbine continues to accelerate, the software will put the turbine into EMERGENCY state and also apply the turbine brake. The hardwired “Emergency Stop” safety system will engage to stop the turbine completely independent of the software controller at 20% overspeed, or 52.7 RPM.

In order to understand the stopping capability of the brakes in an emergency stop scenario, several initial bulk calculations were performed to understand: (1) the amount of kinetic energy available in the rotor at the time of brake application, (2) the rate of acceleration (slowing down) of the rotor with the brakes applied, (3) the "brake-on-time," which is the amount of time it will take to dissipate all of the energy within the rotor bringing it to a stop, and (4) potential temperature rise of the brake disc due to the dissipation of the rotational kinetic energy. Modeling was performed in the National Renewable Energy Laboratory FAST code in order to capture the behavior of the turbine in several emergency scenarios.

The heating of the brake disc is determined by calculating the average power the brakes remove from the system and the heating area of the brake pads on the brake disc. The average power removed from the rotor is calculated by the amount of energy in the rotor divided by the time it takes to stop the rotor.

While the brake is applied, the power removed from the brake disc is calculated by the HSS brake torque multiplied by the HSS rotational speed. The braking power during an Emergency Stop event on the V27 in 15 m/s winds is shown in Figure 15.

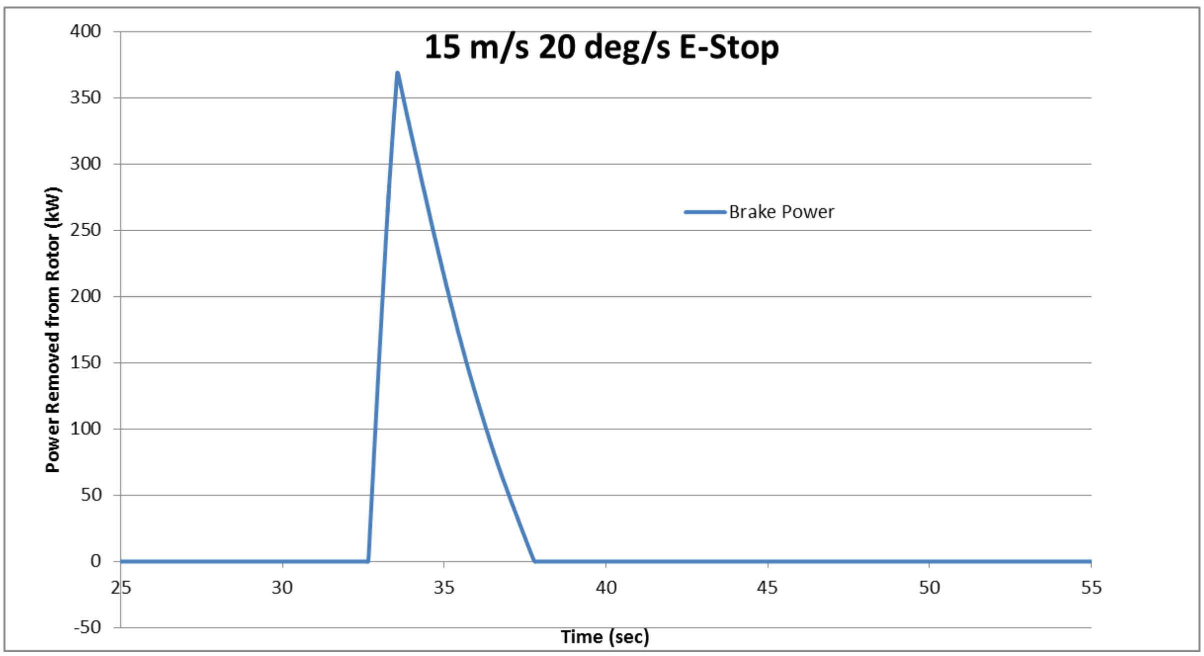

Figure 15. Brake power removed by the V27 brake during an E-stop at 15 m/s wind speed.

The heat flux into the brake disc is the amount of power into the disc divided by the overall active area of the brake disc. The temperature increase of the brakes is dependent upon the heat flux, the brake on time, and the material properties of the rotor disc, from "Equation 3-25 Brake Design and Safety, Rudolf Limpert".

$$T_{inc} = \frac{0.527q\sqrt{t}}{\sqrt{\rho C_p k}} \quad [1]$$

Where,
T_{inc}; Surface temperature increase
q; maximum heat flux into rotor (maximum brake power removed / usable area of brake disc)
ρ; density of brake disc
C_p; specific heat
k; conductivity

Several FAST simulations of emergency events in which the turbine operated normally at 43 RPM, when the generator was disconnected, and the rotor accelerated causing an emergency stop event were run. In wind speeds less than that of rated speed, or about 12 m/s, the rotor torque decreases as the rotor accelerates due to non-optimal tip speed ratio, see Figure 16. During operation, if winds exist greater than rated speed, the turbine will be controlling the pitch of the blades to maintain a rated torque of 44 kN-m.

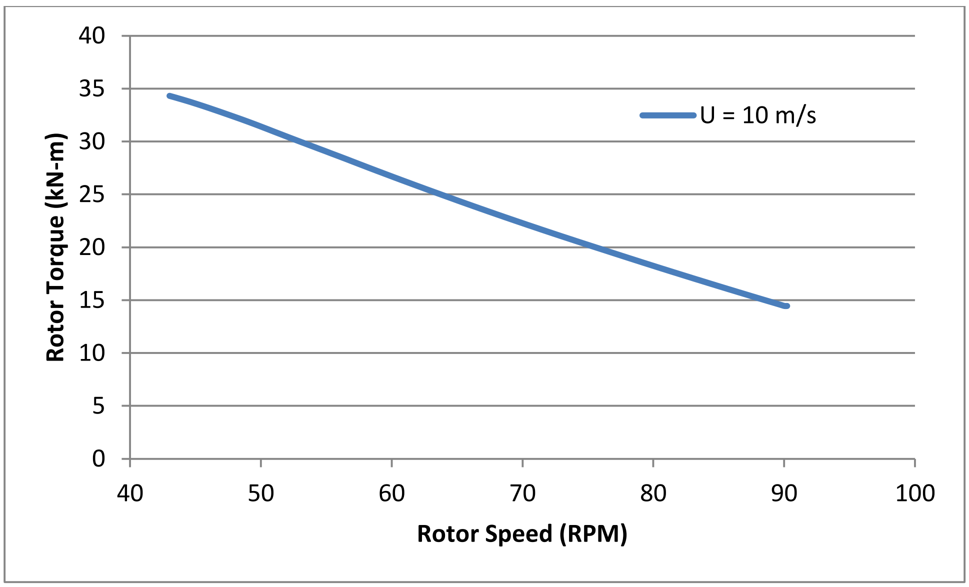

Figure 16. Rotor torque vs Rotor speed as the SWiFT rotor accelerates from rated speed without generator reactive torque

The V27 braking system was analyzed in FAST with the previously developed SWiFT V27 model. For this analysis, it was assumed that the turbine was in normal power production mode at a constant wind speed when a fault caused the turbine controller to fail and the generator to disconnect from the grid and thus supply no resistance torque. Based on accepted standards, wind speeds below, at, and above rated were studied, along with the cutout wind speed. Cases were modeled where the brake and pitch are active, and where the blades remain pitched and only the brake is active. For all analyses, the simple brake model was used where, upon deployment, the high speed shaft brake increases from zero to full torque over a specified time period. A brake application time of 0.9s and a maximum applied high speed shaft torque of 2.7

kN-m were used. Brake application time was based upon previous test reports generated during the original testing of the V27 by Riso, and brake torque was calculated based upon known values of brake pressure and caliper design. To use the simple inputs in FAST to model this problem, the times at which to deploy the brakes and/or pitch first were determined. This required an initial run where the blades remain at a fixed pitch and the generator was disconnected, allowing the rotor to freely accelerate. From these results, the time at which an E-Stop would be initiated by the emergency system based on rotor speed (currently set at 52.7 rpm) was observed. In subsequent runs, the generator was disconnected and the rotor accelerated until reaching this speed, where the high speed shaft brake was applied, and the blades either did not pitch or pitched towards feather at 18 °/s or 28 °/s. The different pitch values represent minimum and maximum pitch rates that have been measured on the machine and were used to envelope the effect of pitch rate on the machine. Graphical results from the simulations are shown in Figure 17.

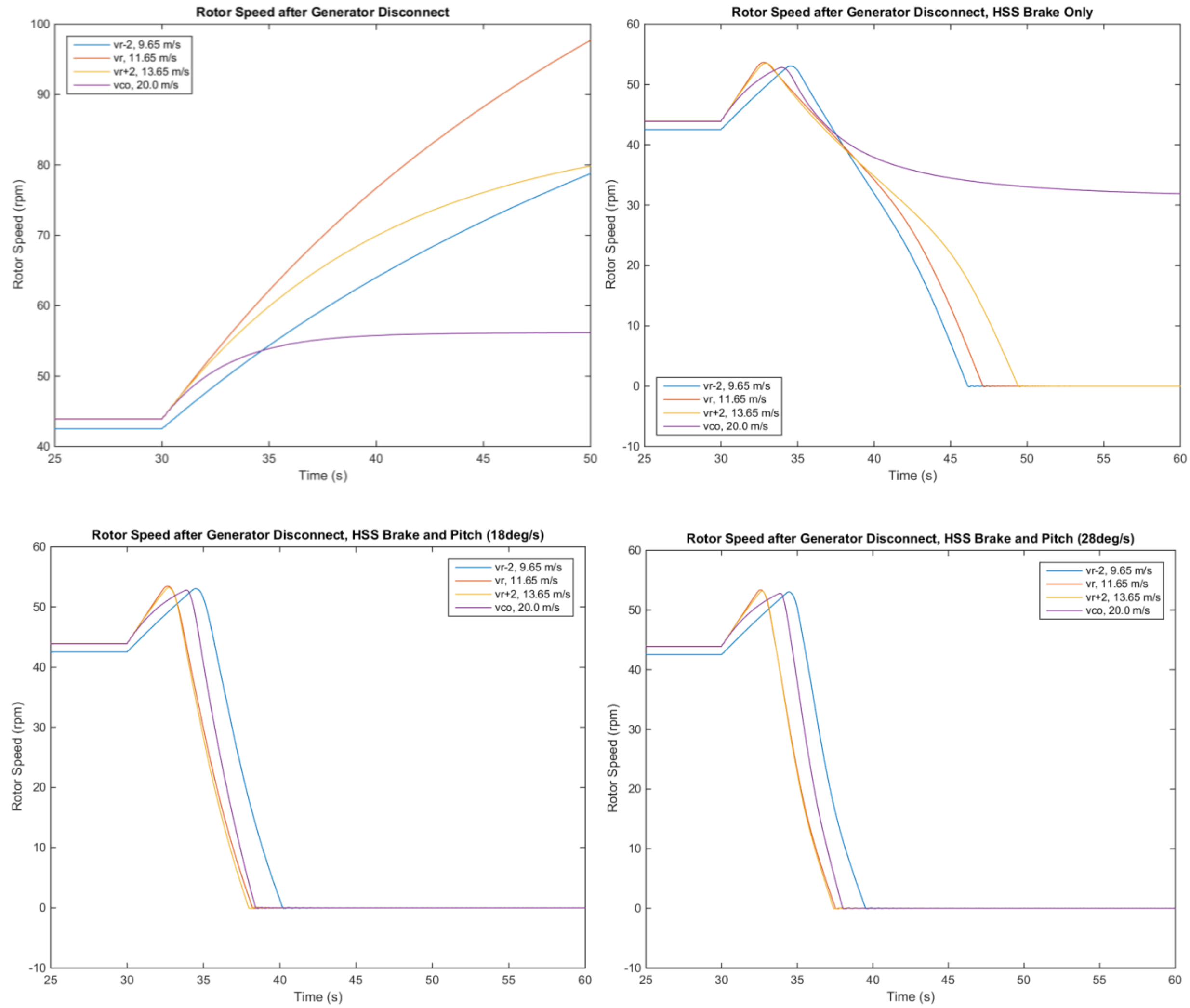

Figure 17: Rotor speed vs. time for V27 E-stop simulations.

The results of the simulations show the combined braking and pitching system is capable of bringing the rotor to a complete stop in all cases in 4.95-8.45 seconds. If only the brake is applied, the rotor will come to a stop in 12.25-16.95 seconds in the cases near rated wind speed. **However, in the 20 m/s cutout wind speed simulation case, the brake alone is not able to stop the machine.** This is because the rotor torque increases greatly as the machine slows down if the blades are not feathered due to more optimal tip speed ratios, eventually overcoming the torque from the brake.

Due to the large rotor torque generated at the previous cutout wind speed of 20 m/s causing the turbine brake to be overcome, and the turbine to overspeed. Further brake analyses were performed on the turbine system with the FAST model of the V27 for these conditions to better recommend an appropriate cut out speed. Maximum surface braking temperatures were calculated for the emergency stop scenarios in which the pitch mechanism becomes locked, and the brake is the only stopping mechanism. Figure 18 shows the simulated turbine performance in an emergency stop with a 20°/s pitch rate. The turbine comes to a full stop in approximately 5.2 seconds of brake application time. The resulting temperature increase is approximately 100 °C. Convective brake cooling is considered negligible because this is a single stop event, within a short period of time. This is a conservative assumption, and will predict a higher temperature increase than if cooling is considered.

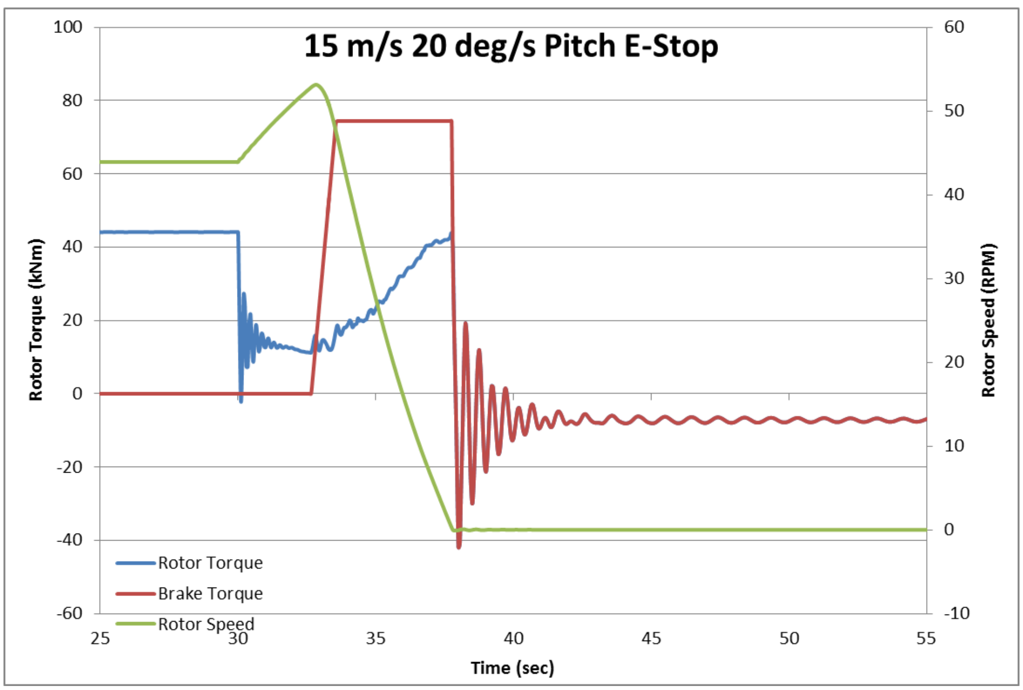

Figure 18. Simulated turbine performance in an Emergency Stop with 15 m/s wind speeds.

Figure 19 diagrams the same emergency stop situation as Figure 18 however the pitch mechanism is frozen in place and does not pitch the turbine to feather. The brake is able to overcome the torque created by the rotor, and bring the rotor to a stop in 18.6 seconds. This causes a maximum brake surface temperature of 435 °C. While this heating is significantly more than in the previous case, it is considered well within acceptable brake temperatures. It is recommended to stay below 800 °C for the cast iron brakes used on the turbine in repeated stops. 1100°C is the minimum melting temperature for the ductile cast iron that the turbine brake disc is made of. The calculation assumes negligible rotational inertia and friction of the gear box which while small compared to that of the rotor, will affect the energy required to be dissipated by the brakes.

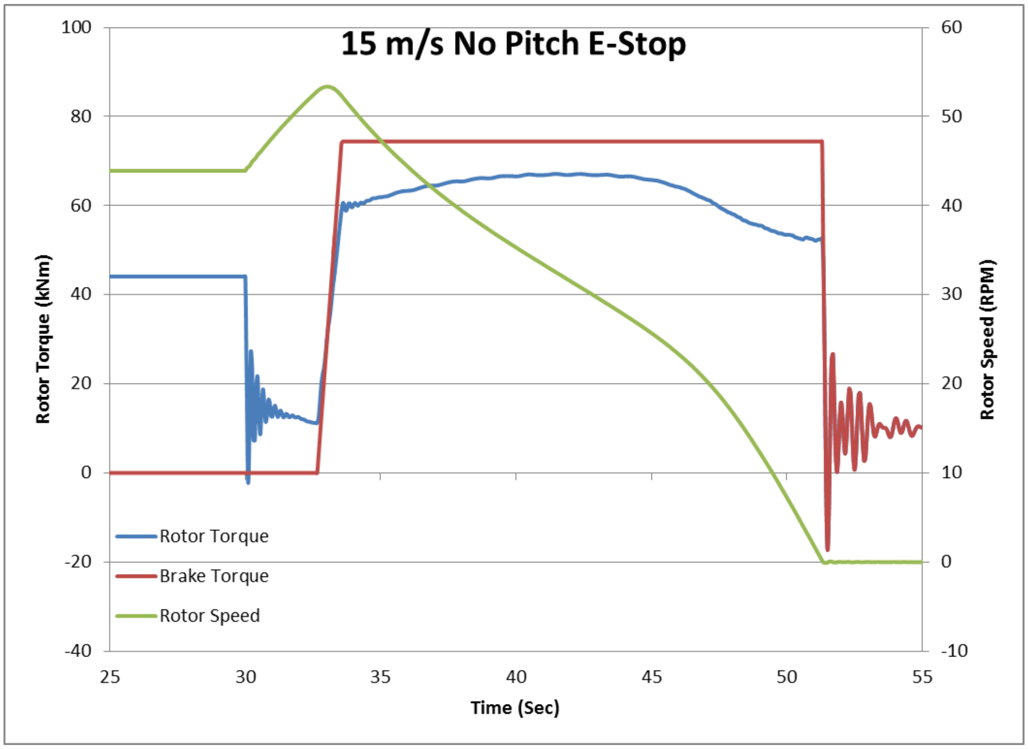

Figure 19. Simulated turbine performance in Emergency Stop when pitch mechanism is locked in 15 m/s wind speeds.

6. HIGH WIND EMERGENCY STOP MODELING

The original V27 turbines were configured to change state from "Run" to "Pause" when the wind speed exceeds 25 m/s for 1 second, and restart when the wind speed is less than 20 m/s for 10 seconds, this will be used to begin software simulations. Pause state consists of the blades being actively held in feather, with all other systems active, including yaw tracking. The turbine responds to exceedance of the high wind cutout by pitching to feather in Pause, and waiting for the restart conditions to be met. The generator is attached during this time, providing resistance torque. In accordance with IEC 61400-1 design load cases (DLC) 2.2 and 2.3, the SWiFT V27 machines were analyzed to determine the effect of a shutdown scenario with the occurrence of a fault. Specifically, the fault that was considered was the worst case scenario of the pitch system failing by locking in the position it was when the shutdown was initiated. As the turbine is a linked, collective pitch design, the mechanical brake alone would then have to stop the machine. In this case, the controller would sense the failure of the pitch system and initiate an Emergency Stop, which would disconnect the generator and apply the mechanical brakes.

6.1 Method

Several analyses were performed to determine the adequacy of the mechanical braking system to stop the turbine in the event of a pitch system failure. All analyses were performed using the FAST code (https://nwtc.nrel.gov/FAST) from NREL, along with the V27 model developed at Sandia National Laboratories.

In the first analysis the turbine was operated at a constant wind speed. This was done to determine the steady state wind speed at which the turbine would overcome the worst case available braking torque of 2,700 Nm. Additionally, increased braking torques of 3,500 Nm (130%) and 4,500 Nm (167%) were also examined, as the braking torque is dependent upon the friction coefficient of the pads and rotor.

The second analysis that was run assumed the turbine experienced an extreme operating gust (EOG) at cutout wind speed (V_{co}) as defined by IEC 61400-1. Again, additional braking capacities of 3,500 Nm and 4,500 Nm were also examined.

The third analysis used both the Normal Turbulence Model (NTM) and the Extreme Turbulence Model (ETM) to generate turbulent wind input files throughout the operating range which in some cases would generate a high wind cutout. Several combinations of cutout wind speeds and restart wind speeds were analyzed. Ten random seeds at wind speeds of 7 m/s to 18 m/s in 1 m/s intervals were used to generate 10-minute wind files in TurbSim (https://nwtc.nrel.gov/TurbSim) with both the NTM and ETM. The IEC 61400-1 standard only requires NTM to be used with the occurrence of a fault. Output files from FAST simulations were used to identify points at which the turbine would have been expected to experience a high wind shutdown for cutout wind speeds of 12, 14, and 15 m/s and restart wind speeds of 10 and 12 m/s. Each of these events was then re-analyzed assuming that the turbine controller would have attempted to initiate a high-wind shutdown, but then measured that the pitch system was not responding after 5 seconds, and initiates an Emergency Stop. During the stop, the generator is disconnected and the mechanical brake is actuated. The brake actuation time for the existing system is estimated to be 0.9 s to full torque. The results were then analyzed to determine stop times and braking temperatures. The brake temperature model conservatively assumes no cooling of the brake disk during the stop event.

The fourth analysis that was performed was of turbine response to a severe wind case measured at the site provided by the Texas Tech National Wind Institute. The entire record of the event is shown in Figure 20, and is shown to be accompanied by a large change in wind direction. For this analysis, the change in direction was ignored. In reality, this large of a direction change would have caused the turbine to shutdown long before any high winds were experienced. However, this case was chosen as an additional worst-case to test the redundancy of the system. From the record in Figure 20, two time periods are of particular interest, 285-585 s and 660-960 s (Figure 21).

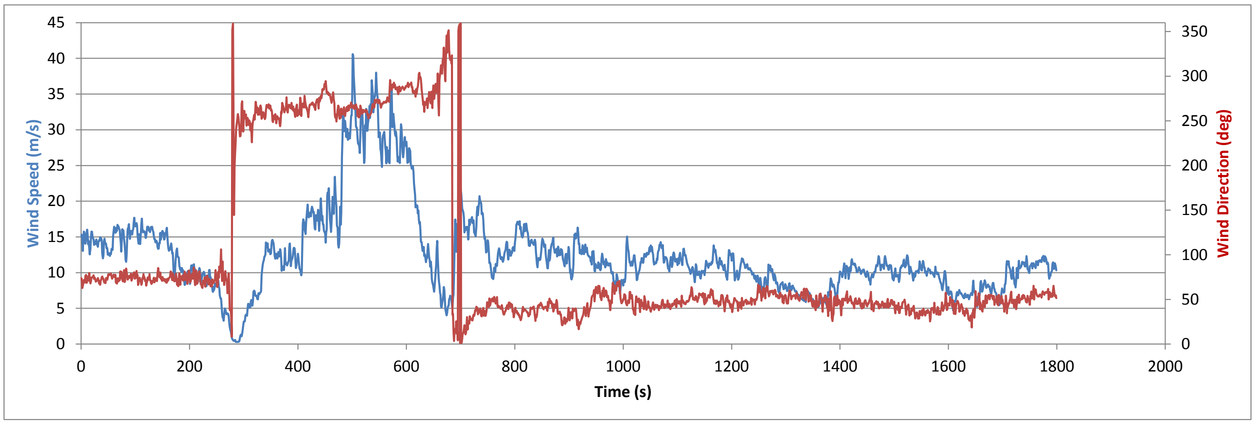

Figure 20: Extreme wind event measured near SWiFT site.

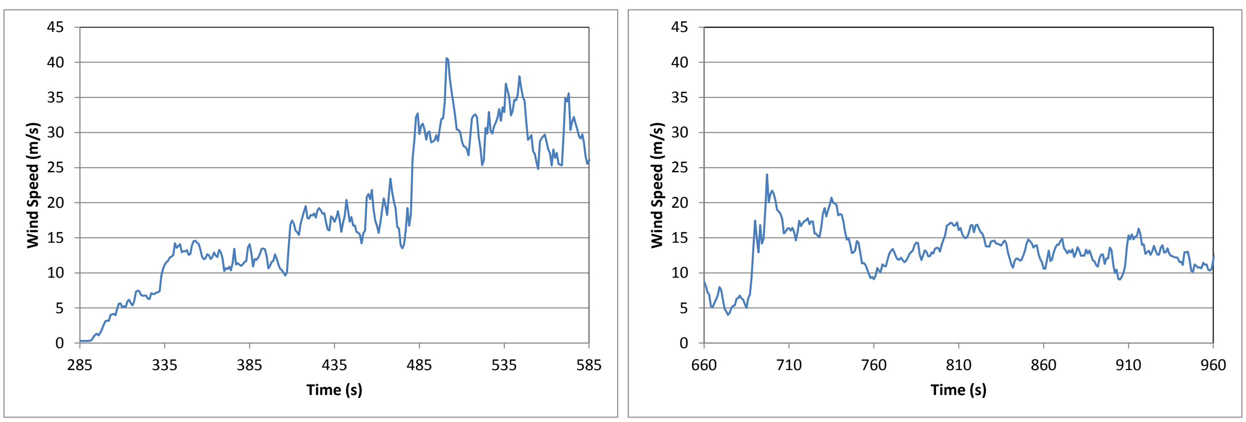

Figure 21: Periods of interest during measured extreme wind event.

6.2 Results and Analysis

Figure 22 shows the results of brake-only shutdowns with a constant wind speed for varying high wind speeds and varying brake torque. It is evident that the current brakes on the SWiFT turbines are incapable of stopping the turbine at wind speeds over 19 m/s due to torque limitation, and likely not realistically able to stop the turbine at speeds over 17 m/s due to excessive stopping time and heat generation. Increasing the stopping torque to 3500 Nm or 4500 Nm dramatically improves the stopping capability of the brakes.

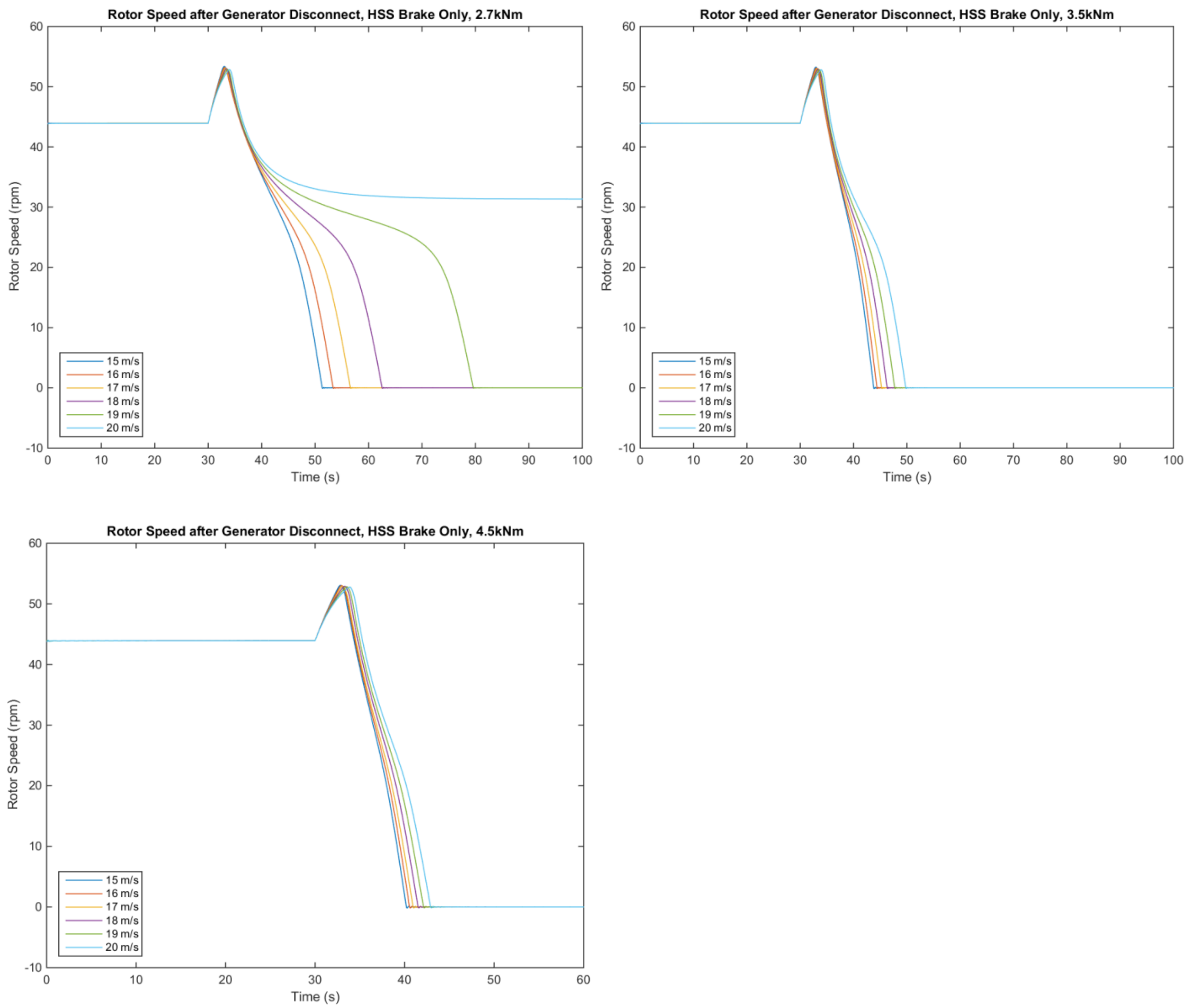

Figure 22: Brake-only stops from high winds for 2700 Nm (top left), 3500 Nm (top right), and 4500 Nm (bottom left) brake torque.

Figure 23 shows the results of brake-only shutdowns caused by an extreme operating gust. As the gust only occurs for a short period of time, it has little effect on stopping times or brake temperatures.

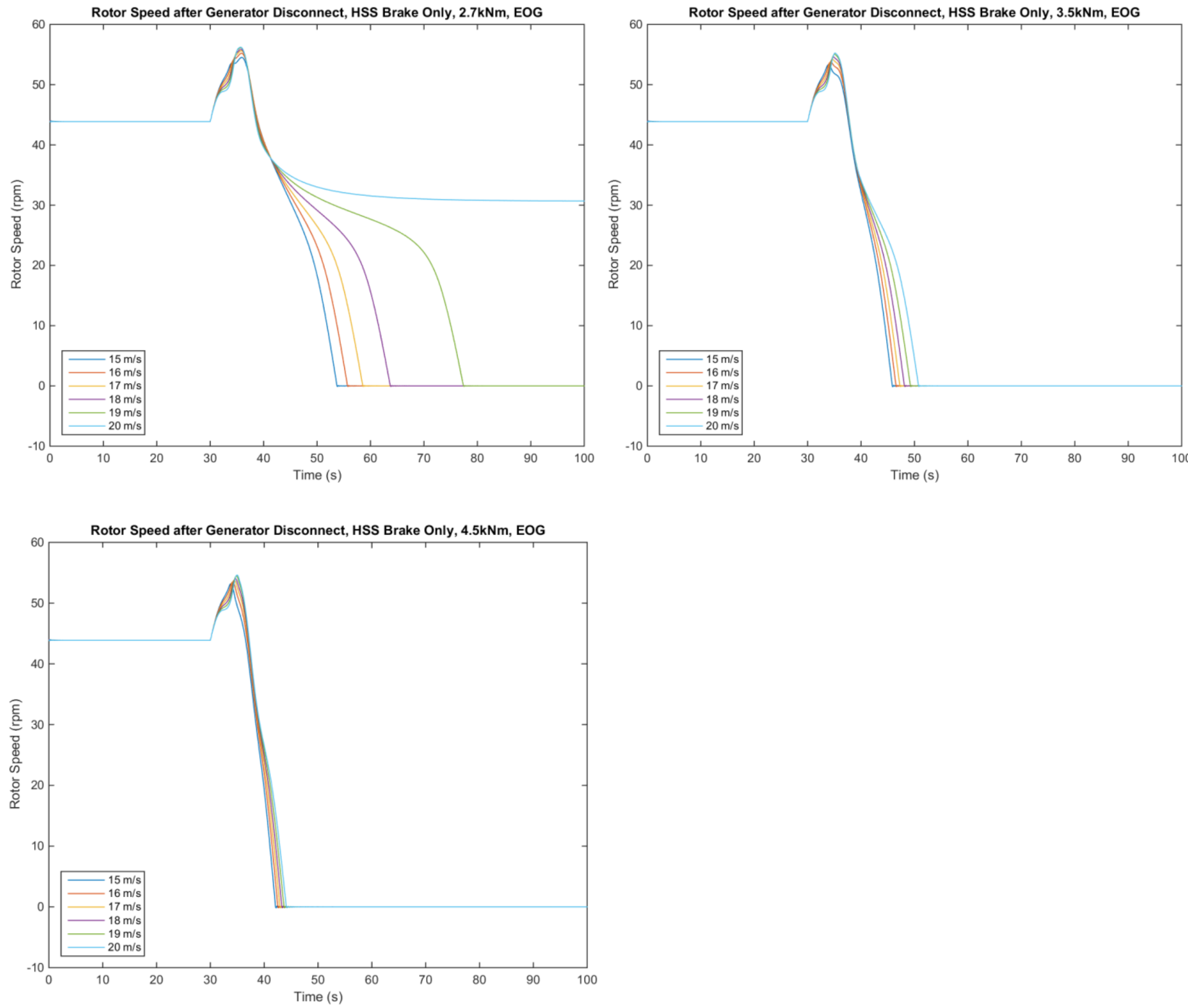

Figure 23: Brake-only stops from high winds with extreme operating gusts for 2700 Nm (top left), 3500 Nm (top right), and 4500 Nm (bottom left) brake torque.

Figure 24 and Figure 25 show binned results of stopping times and brake temperatures for brake-only high wind shutdowns using the NTM and ETM turbulence models. The majority of the results are seen to be below 20s and less than 800 °C, which is acceptable for repeated use of the brakes.

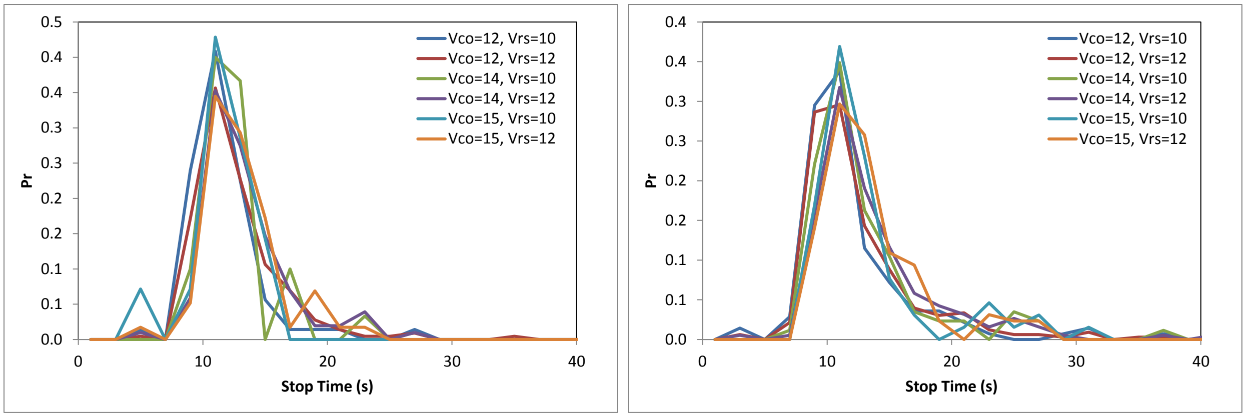

Figure 24: Probability distribution of stopping time for NTM (left) and ETM (right) stops with varying cut-out and restart wind speeds.

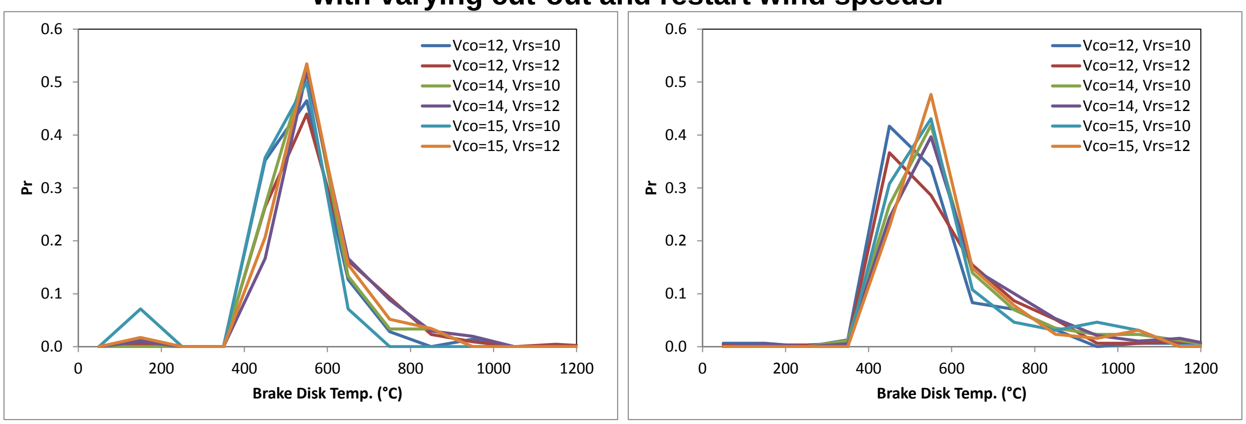

Figure 25: Probability distribution of brake temperature for NTM (left) and ETM (right) stops with varying cut-out and restart wind speeds.

Table 1 shows the compiled results of the turbulent wind brake-only shutdowns. The 3-sigma stop time and brake temperature is calculated, and shows that a 15 m/s cutout and 10 m/s restart speed result in the lowest brake temperature, although not largely different and possibly due to statistical variation. However, it could also be due to the angle of pitch during a cut-out event. Region three for the SWiFT turbines begins at a 12 m/s wind speed. Operating in region three requires the turbine to vary the pitch angle of the blades ensuring the rotor torque remains constant. If a pitch failure occurs while the turbine is controlling the pitch in region three, the angle will be less than at rated speed, and therefore the rotor is not at an optimal angle of attack for producing rotor torque.

Table 1: Results of NTM and ETM brake-only stops.

V_{co}	V_{rs}	NTM Events Analyzed	ETM Events Analyzed	NTM		ETM		NTM		ETM	
				3σ Brake Temp (°C)	Max Brake Temp (°C)	3σ Brake Temp (°C)	Max Brake Temp (°C)	3σ Stop Time (s)	Max Stop Time (s)	3σ Stop Time (s)	Max Stop Time (s)
12	10	71	156	832	940	1087	1505	20.4	26.1	20.5	28.3
12	12	216	328	900	1110	1096	1505	23.4	34.8	31.1	53.9
14	10	30	86	827	859	1035	1112	20.7	22.4	28.0	36.2
14	12	102	189	920	932	1052	1166	23.8	23.8	28.8	40.7
15	10	14	65	799	606	1012	1036	17.9	14.3	28.1	31.0
15	12	58	128	873	832	978	1053	22.6	23.5	25.8	27.0

The results of using the wind speed only, absent of direction, for the extreme event that was measured at the site are shown in Figure 26. In the first sub-event, the 12 and 14 m/s cutouts result in successful stopping of the machine while the 15 m/s limit does not. In the second sub-event, all cutouts fail to stop the machine in a reasonable period of time. However, the 15 m/s limit results in a much lower maximum rotor speed as the blades are more feathered.

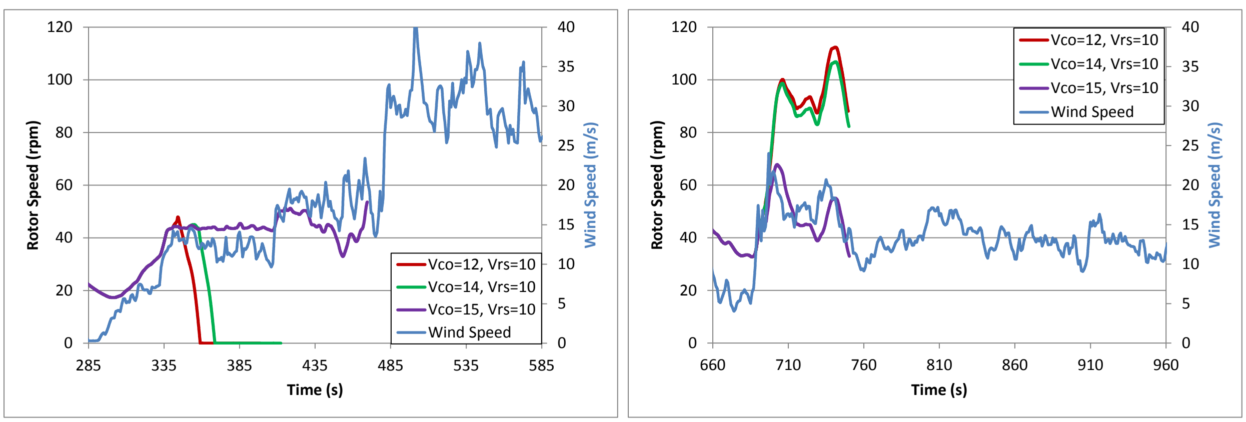

Figure 26: Rotor speed after brake initiation for brake only stops using TTU extreme wind events.

6.3 Stopping System Redesign

As the results of the initial analysis showed that the V-27 machines were vulnerable to overspeed in some extreme cases when wind speeds were high and the pitch system had locked in the run position, a design review committee comprised of wind technology experts recommended further analysis and possible improvement in the stopping system. The committee recommended an analysis of a case in which the pitch system became locked in the run position at a wind speed below when pitch control would activate. The machine then experiences a ramp to an increased, sustained wind speed. This case is particularly difficult as there would be no warning of the pitch failure. This case was simulated by operating the turbine at rated power wind speed of 11.65 m/s and then increasing the wind speed to 18 m/s over 3 seconds. The wind speed was then maintained at 18 m/s. The resultant wind speed file is shown in Figure 27.

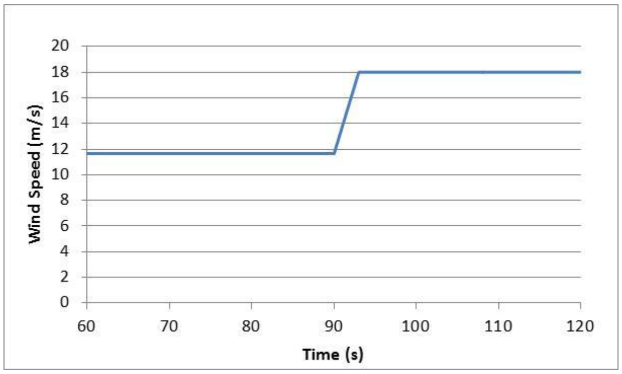

Figure 27: Wind gust from 12 m/s to 18 m/s over 3s.

Based on the design review and resulting simulation, a decision was made to improve the braking system if possible. Several options were considered including increasing the brake system pressure to increase the braking torque, modifying the pitch system to be independent blade pitch capable, and using the generator to slow the machine. It was decided that using the generator as an auxiliary brake was the best solution to add an independent braking mechanism without incurring the increased system risk that might result from the other two options. The ABB drive that controls the turbine generator contained an existing emergency stop feature, which could produce up to 2300 Nm of additional stopping torque. This alleviates problems shown in the first three analyses that were performed.

For this new analysis, a Matlab Simulink control system was developed to mimic the operation of the actual SWiFT turbine controller. Also, the functions of the Stop and E-Stop circuits were implemented. The effect of varying several parameters was examined as follows:

- Braking Torque: 2700 Nm, 3600 Nm, and 4500 Nm
- Maximum Generator Stopping Torque: 1600 Nm, 2000 Nm, and 2400 Nm
- Brake Application Delay Time: 0.25s and 0.50 s
- Generator Stopping Time: 10s and 20s
- Generator/Brake Overspeed Limit: 5% / 10%, 10% / 15%, 15% / 15%, 20% / 20%

The generator/brake overspeed limits simulated lower turbine controller limits, stock turbine controller limits, lower emergency system limits, and stock emergency system limits.

The maximum and minimum values for several important system outputs are shown in Table 2. The maximums for all parameters are within acceptable limits for the turbine.

Table 2: Outputs from gust analysis with locked pitch system and addition of generator stopping.

	Max	Min	Allowable
Stop Time (s)	19.56	7.94	N/A
Brake Temp (°C)	881	590	1000
Rotor Speed (rpm)	56.4	49.5	60
Blade Flap Moment (kN-m)	122.5	108.4	210
Blade Edge Moment (kN-m)	66.8	57.2	210
Tower Fore-Aft Moment (kN-m)	1531.7	1324.3	4510
Tower Side-Side Moment (kN-m)	206.2	123.3	4510

The rotor speed and applied generator torque for four important cases are show in Figure 28 through Figure 35. Figure 28 and Figure 32 show the case for when the turbine controller is functioning properly and with overspeed limits at 10% and 15% for applying the generator and brakes respectively, and the brake and generator stopping torques are at their nominal values. Figure 29 and Figure 33 show a case in which the emergency system overspeed limit is reduced from the original setting of 20% to 15% and the generator stopping torques are at their nominal values. Figure 30 and Figure 34 show a case in which the emergency system overspeed limit is at the original setting of 20% and the generator stopping torques are at their nominal values. Finally, Figure 31 and Figure 35 show the case in which the emergency system overspeed limit is at the original setting of 20% and the generator stopping torques are at their minimum expected values simultaneously. The last case is the worst and is reflected in the approximately 20s stopping time seen in Figure 31.

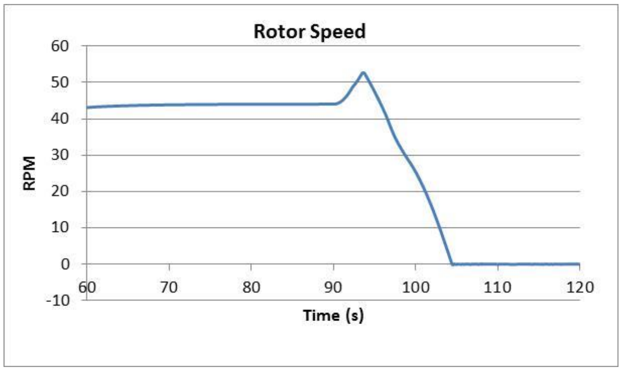

Figure 28: Rotor speed for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 48.3/50.5 rpm, brake delay time = 0.5s, and generator stop time = 20s.

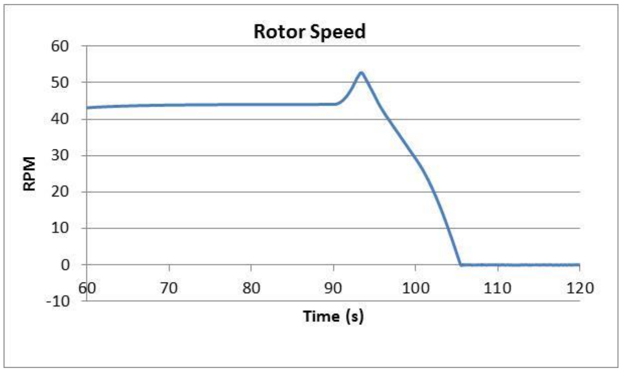

Figure 29: Rotor speed for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 50.5/50.5 rpm, brake delay time = 0.5s, and generator stop time = 20s.

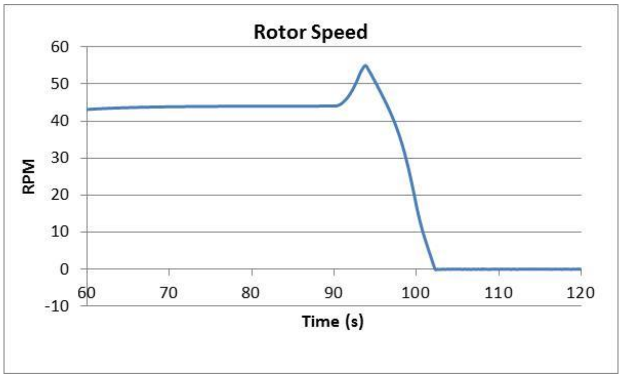

Figure 30: Rotor speed for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 52.7/52.7 rpm, brake delay time = 0.5s, and generator stop time = 20s.

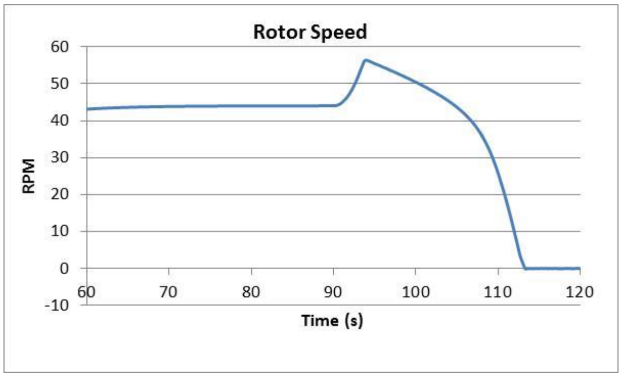

Figure 31: Rotor speed for E-Stop from 3s gust from 12-18 m/s with brake torque = 2.7kN-m, generator torque = 1.6 kN-m, overspeed limits 52.7/52.7 rpm, brake delay time = 0.5s, and generator stop time = 20s.

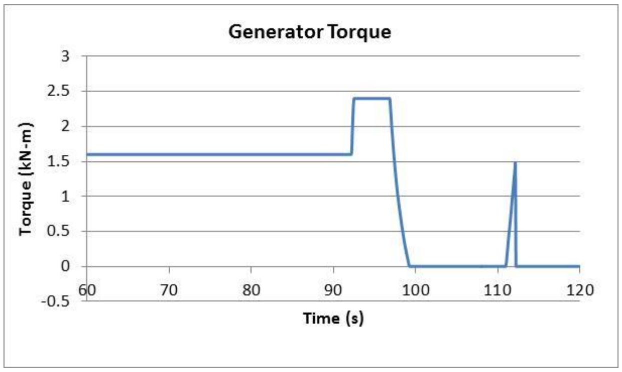

Figure 32: Generator torque for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 48.3/50.5 rpm, brake delay time = 0.5s, and generator stop time = 20s.

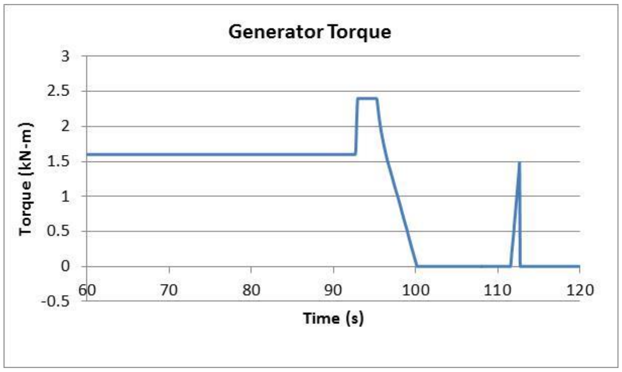

Figure 33: Generator torque for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 50.5/50.5 rpm, brake delay time = 0.5s, and generator stop time = 20s.

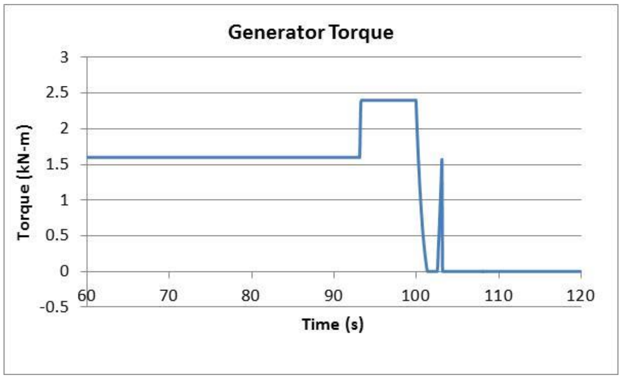

Figure 34: Generator torque for E-Stop from 3s gust from 12-18 m/s with brake torque = 3.2kN-m, generator torque = 2.4 kN-m, overspeed limits 52.7/52.7 rpm, brake delay time = 0.5s, and generator stop time = 20s.

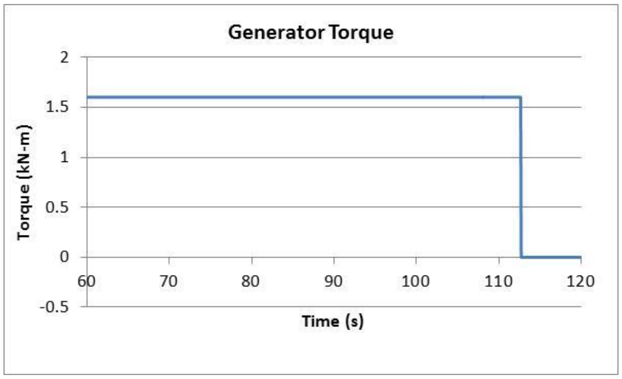

Figure 35: Generator torque for E-Stop from 3s gust from 12-18 m/s with brake torque = 2.7kN-m, generator torque = 1.6 kN-m, overspeed limits 52.7/52.7 rpm, brake delay time = 0.5s, and generator stop time = 20s.

The range of maximum values for stopping time, brake temperature, rotor speed, blade root flap moment, and tower base fore-aft moment are shown in Figure 36 through Figure 40. The worst and best stopping cases as determined by brake temperature are shown in Table 3 and Table 4 respectively.

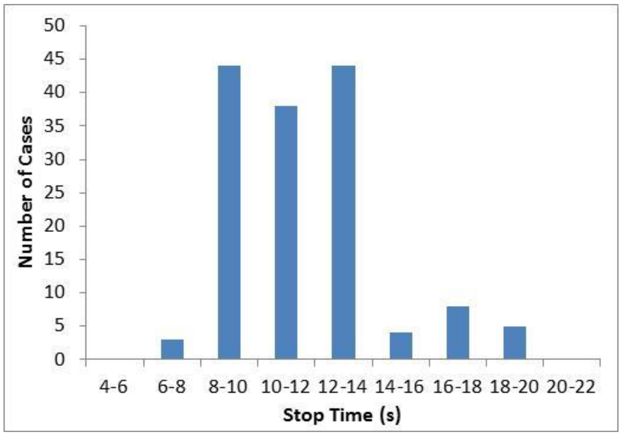

Figure 36: Number of cases by stop time.

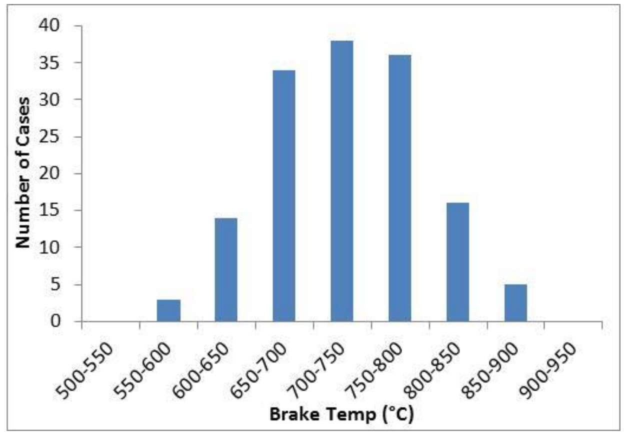

Figure 37: Number of cases by brake temperature.

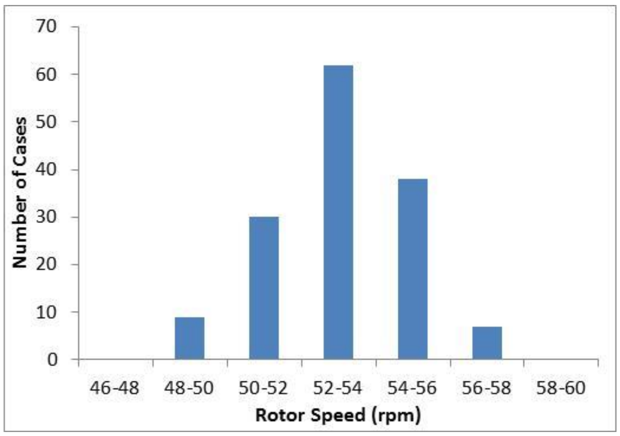

Figure 38: Number of cases by maximum rotor speed.

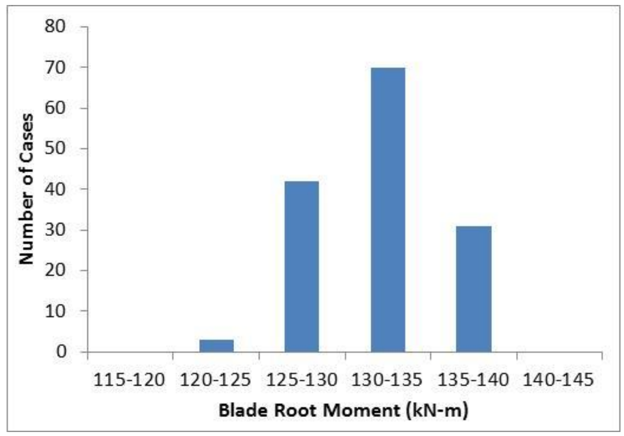

Figure 39: Number of cases by blade root flap moment.

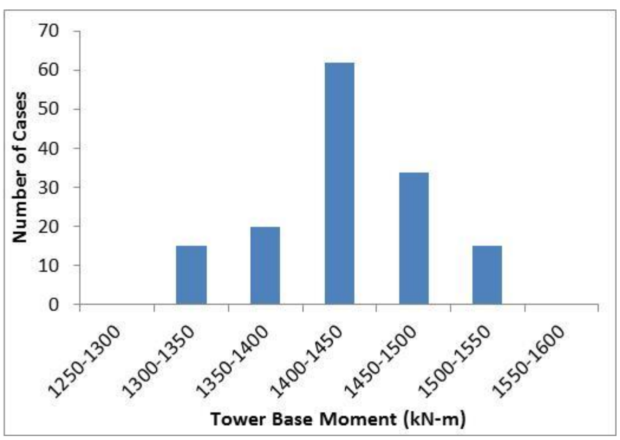

Figure 40: Number of cases by tower base fore-aft moment.

Table 3: Most severe stopping simulations for gust from 12 m/s to 18 m/s over 3-seconds with pitch lockup.

Stop Speed	E-Stop Speed	Gen Torque	Brake Torque	Brake Delay Time	Gen Decel Time	Stop Time	Brake Temp	Rotor Speed	Blade Root Flap Moment	Tower Base Fore-Aft Moment
(rpm)	(rpm)	(N-m)	(N-m)	(s)	(s)	(s)	(deg C)	(rpm)	(kN-m)	(kN-m)
52.7	52.7	1600	2700	0.50	10	19.6	881.3	56.4	122.5	1531.7
52.7	52.7	1600	2700	0.50	20	19.6	881.3	56.4	122.5	1531.7
52.7	52.7	1600	2700	0.25	10	18.8	851.0	55.6	121.3	1496.2
52.7	52.7	1600	2700	0.25	20	18.8	851.0	55.6	121.3	1496.2
50.5	50.5	1600	3600	0.50	10	11.0	837.8	53.9	117.4	1454.7
50.5	50.5	1600	3600	0.50	20	11.0	837.8	53.9	117.4	1454.7
50.5	50.5	1600	3600	0.25	10	11.0	823.9	53.0	115.3	1435.9
50.5	50.5	1600	3600	0.25	20	11.0	823.9	53.0	115.3	1435.9
50.5	50.5	2000	3600	0.50	10	10.7	816.8	53.3	115.7	1429.1
50.5	50.5	2000	3600	0.50	20	10.7	816.8	53.3	115.7	1429.1
48.3	50.5	1600	3600	0.50	10	10.4	815.6	53.9	117.4	1454.7
48.3	50.5	1600	3600	0.50	20	10.4	815.6	53.9	117.4	1454.7
52.7	52.7	1600	3150	0.50	10	12.4	814.6	56.3	122.5	1527.5
52.7	52.7	1600	3150	0.50	20	12.4	814.6	56.3	122.5	1527.5
52.7	52.7	1600	3600	0.50	10	9.4	808.6	56.2	122.5	1523.3
52.7	52.7	1600	3600	0.50	20	9.4	808.6	56.2	122.5	1523.3
50.5	50.5	2000	3600	0.25	10	11.0	808.3	52.4	113.5	1417.4
50.5	50.5	2000	3600	0.25	20	11.0	808.3	52.4	113.5	1417.4
50.5	50.5	2400	3600	0.50	10	10.7	805.5	52.8	114.2	1414.9
50.5	50.5	2400	3600	0.50	20	10.7	805.5	52.8	114.2	1414.9

Table 4: Least severe stopping simulations for gust from 12 m/s to 18 m/s over 3-seconds with pitch lockup.

Stop Speed	E-Stop Speed	Gen Torque	Brake Torque	Brake Delay Time	Gen Decel Time	Stop Time	Brake Temp	Rotor Speed	Blade Root Flap Moment	Tower Base Fore-Aft Moment
(rpm)	(rpm)	(N-m)	(N-m)	(s)	(s)	(s)	(deg C)	(rpm)	(kN-m)	(kN-m)
52.7	52.7	2400	2700	0.25	10	9.4	590.4	54.4	119.4	1452.1
52.7	52.7	2400	2700	0.25	20	9.4	590.4	54.4	119.4	1452.1
46.1	48.3	2400	2700	0.25	10	11.8	600.8	49.6	108.4	1327.8
46.1	48.3	2400	2700	0.25	20	11.8	600.8	49.6	108.4	1327.8
52.7	52.7	2400	2700	0.50	10	9.5	601.4	55.1	120.5	1479.4
52.7	52.7	2400	2700	0.50	20	9.5	601.4	55.1	120.5	1479.4
46.1	48.3	2400	2700	0.50	10	11.5	605.1	50.3	109.3	1339.1
46.1	48.3	2400	2700	0.50	20	11.5	605.1	50.3	109.3	1339.1

46.1	48.3	2000	2700	0.25	10	12.4	626.0	50.2	110.1	1346.2
46.1	48.3	2000	2700	0.25	20	12.4	626.0	50.2	110.1	1346.2
46.1	48.3	2000	2700	0.50	10	12.3	634.2	50.9	110.9	1373.7
46.1	48.3	2000	2700	0.50	20	12.3	634.2	50.9	110.9	1373.7
46.1	48.3	2400	3150	0.25	10	10.1	644.1	49.5	108.4	1326.0
46.1	48.3	2400	3150	0.25	20	10.1	644.1	49.5	108.4	1326.0
46.1	48.3	2400	3150	0.50	10	9.9	649.7	50.2	108.4	1338.4
46.1	48.3	2400	3150	0.50	20	9.9	649.7	50.2	108.4	1338.4
48.3	50.5	2400	2700	0.25	10	12.6	651.2	52.1	115.2	1395.7
48.3	50.5	2400	2700	0.25	20	12.6	651.2	52.1	115.2	1395.7
52.7	52.7	2400	3150	0.25	10	8.7	654.0	54.3	119.2	1452.1
52.7	52.7	2400	3150	0.25	20	8.7	654.0	54.3	119.2	1452.1

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7. CONCLUSION

The hardware safety system consists of two independent continuous 24 VDC power loops. The "Stop" circuit, which directly bypasses the pitch controller, opens the pitching mechanism to feather, and activates the generator stopping function; and the "Emergency" circuit, which directly bypasses the pitch controller, opens the pitching mechanism to feather, engages the brake and generator reaction torques to stop the turbine. The most important function of the hardware safety systems is to prevent overspeed and excessive vibration from catastrophically failing the turbine. These events and others are directly monitored by the hardware system which brings the turbine to a safe state in each emergency situation without aid of the turbine controller.

The legacy V27 system has been updated with additional sensors to bring it up to today's design standards and accommodating the experimental nature of the SWiFT turbines, in particular related to modifications with the ABB drive, overspeed detection and software functionality.
As required by current standards, it was shown through simulation that the brake is able to stop the turbine in wind conditions up to the recommended cut-out speed of 15 m/s including normal turbulence gusts (Reference IEC61400-1, section 6.3.1.3) including failure of the aerodynamic brake (pitching of the blades). The analysis included temperature rise in the disc brake according to normal practice for calculating brake temperature and torque.

In addition, extreme cases have been investigated with a normal functioning system. The cases included IEC standard DLC cases, cases recorded from near the SWiFT site over 10 years, and special cases suggested by the SWiFT oversight committee. These results show that normal operation is secure up to 15 m/s average wind speed, including considerations of the new variable speed drive, which is a different configuration than the legacy machine. The turbine cut-out speed of 15 m/s is determined as a combination of wind speed and blade pitch in region three of the power curve, for specific information of how it is implemented in the current controller, it is necessary to review the SWiFT Turbine Operating Manuals.

As part of the upgrade, the ABB variable frequency drive has been reconfigured, so use of the emergency stop function can be activated by the Emergency Stop and Stop circuits. This will apply braking torque to the shaft, even during grid loss. The is able to produce additional brake torque, and stop the rotor together with the mechanical brake and without the aerodynamic brake, up to 15 m/s wind.

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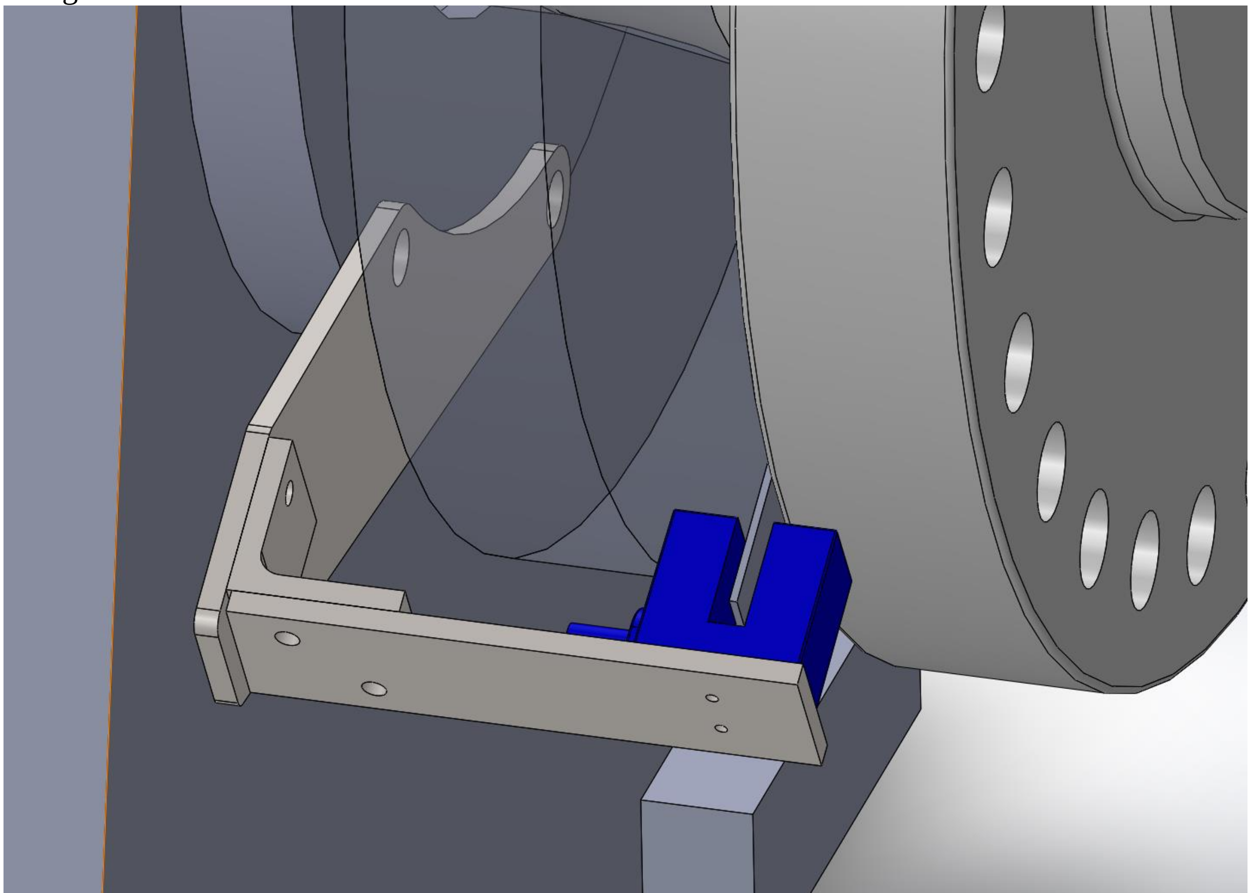
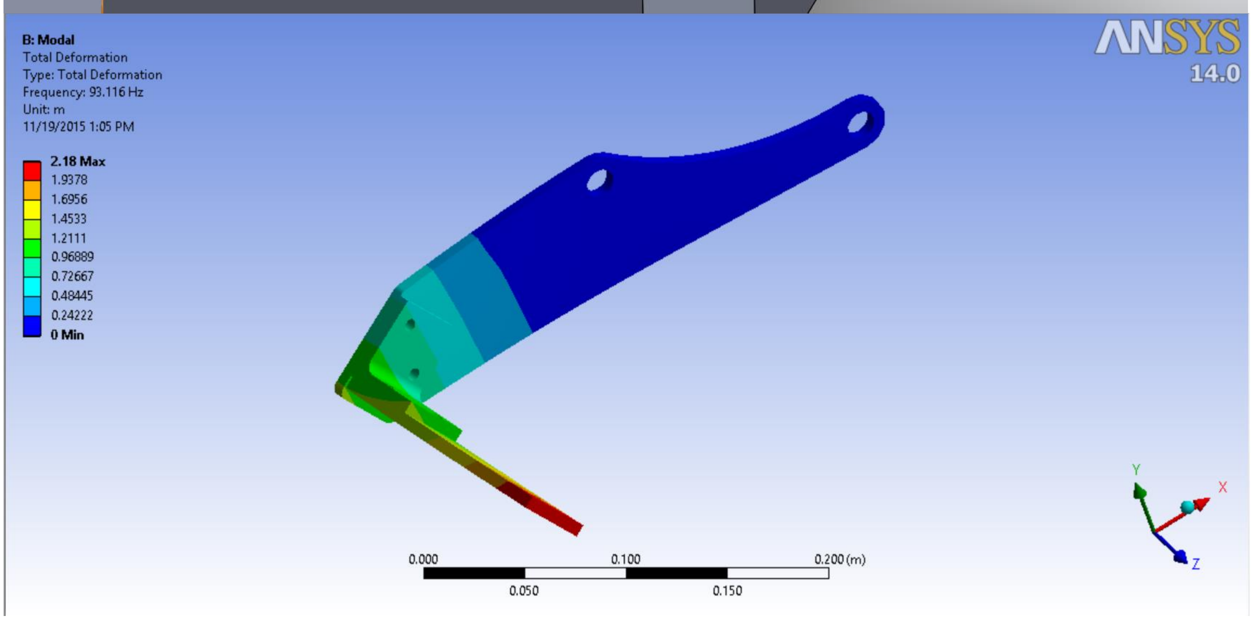
APPENDIX A: OSPR INFORMATION

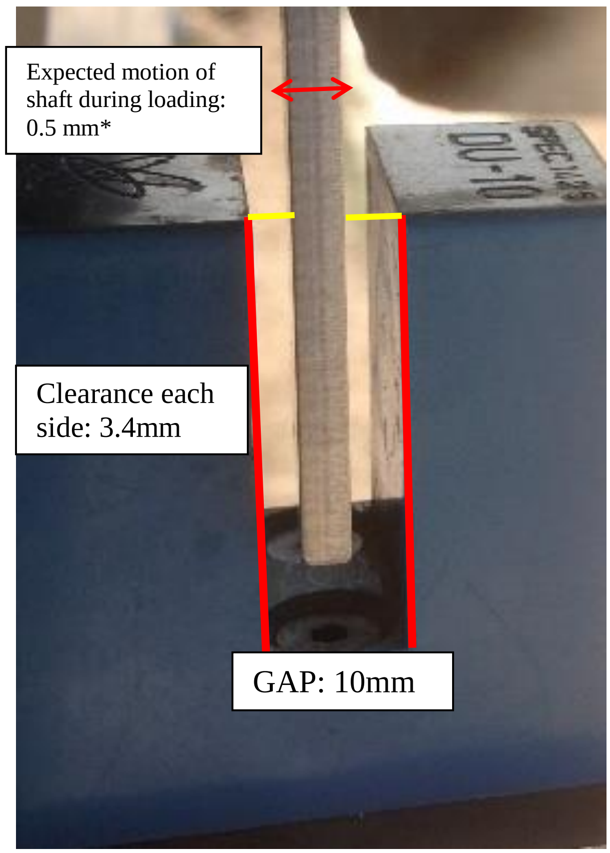
Design of OSPR Sensor Bracket





First mode of vibration of bracket at 93 Hz. Maximum expected Low Speed Shaft rotation is 0.72 Hz, the bracket is sufficiently stiff within all normal operating frequencies.

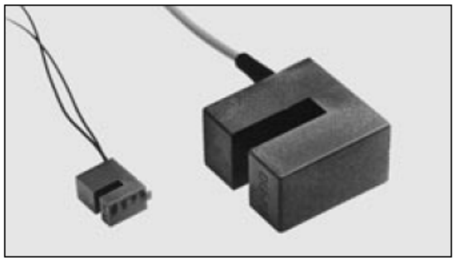
Bracket: 1/4 inch steel welded, bolted for initial alignment.



***Taken from SWiFT Mechanical Manual Section 8.3.2**

Proximity Sensors Inductive ABS Housing Type DU, Fork-shaped

CARLO GAVAZZI



- Fork-shaped ABS housing
- Slot sizes: 3.5, 5, 6, 10 mm
- Power supply: 8.2 VDC (NAMUR)
  24 VDC
- Output: NAMUR (DIN 19234)
  Transistor NPN, make switching
- Protection: Reverse polarity
- 2 m cable

Product Description

Special fork-shaped proximity switch. Slot sizes 3.5, 5.6 or 10 mm. With transistor NPN or made in accordance with NAMUR DIN 19234. Sturdy ABS housing.

Ordering Key

DU 10 E

Type
Slot size
Output type

Type Selection

Slot size mm	Ordering no. NAMUR	Ordering no. Transistor NPN Make swithcing
3.5	**DU 3.5**	
5	**DU 5**	
6	**DU 6**	**DU 6 E**
10	**DU 10**	**DU 10 E**

Specifications

	NAMUR	Transistor NPN
Rated operational volt. (U_e) (U_B)	8.2 VDC 7 to 9 VDC (6 to 35 VDC, all specifications not observed in extended supply range)	24 VDC 21.6 to 26.4 VDC (ripple incl.)
Self-inductance	≤ 500 µH	-
Self-capacitance	≤ 120 nF	-
Ripple	-	≤ 10%
Rated operational current (I_e)	-	≤ 200 mA
No-load supply current (I_o)	Activated: ≤ 1 mA Not activated: ≥ 3 mA Max.: 9.35 mA	≤ 15 mA
Voltage drop (U_d)	-	**DU 6 E** ≤ 2.0 V at max. load **DU 10 E** ≤ 1.0 V at max. load
Protection	None	Reverse polarity
Transient voltage	≤ 1 kV/0.5 J (prepared)	≤ 1 kV/0.5 J (prepared)
Power ON delay	None	None
Frequency of operating cycles (f)	**DU 3.5** 2000 Hz **DU 5** 1500 Hz **DU 6** 2000 Hz **DU 10** 1000 Hz	**DU 6 E** 2000 Hz **DU 10 E** 1000 Hz
Size of test object (height x length x width)	**DU 3.5** 10 x 10 x 0.5 mm **DU 5** 10 x 10 x 0.5 mm **DU 6** 16 x 16 x 1 mm **DU 10** 16 x 20 x 1 mm	**DU 6 E** 16 x 16 x 1 mm **DU 10 E** 16 x 20 x 1 mm

Specifications are subject to change without notice (20.08.01) 1

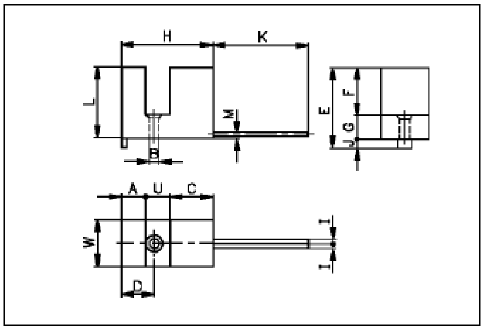
CARLO GAVAZZI

Specifications (cont.)

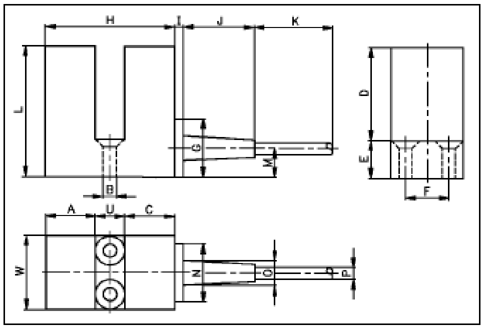
	NAMUR	Transistor NPN
Repeat accuracy (R)	≤ 10%	≤ 10%
Effective operating dist. (S_r)	$0.9 \times S_n \le S_r \le 1.1 \times S_n$	$0.9 \times S_n \le S_r \le 1.1 \times S_n$
Usable operating dist. (S_u)	$0.8 \times S_r \le S_u \le 1.2 \times S_r$	$0.8 \times S_r \le S_u \le 1.2 \times S_r$
Ambient temperature Operating Storage	 -20° to +60°C (-4° to +140°F) -25° to +70°C (-13° to +158°F)	 -20° to +60°C (-4° to +140°F) -25° to +70°C (-13° to +158°F)
Degree of protection	IP 67 (Nema 1, 3, 4, 6, 13)	IP 67 (Nema 1, 3, 4, 6, 13)
Housing material	Blue ABS	Blue ABS
Cable	**DU 3.5** 2 m, 2 x 0.1 mm^2 (2 wires) **DU 5** 2 m, 2 x 0.1 mm^2 (2 wires) **DU 6** 2 m, 2 x 0.25 mm^2 **DU 10** 2 m, 2 x 0.25 mm^2 grey PVC, oil proof	**DU 6 E** 2 m, 3 x 0.25 mm^2 **DU 10 E** 2 m, 3 x 0.25 mm^2 grey PVC, oil proof
Weight (cable included)	**DU 3.5** 17 g **DU 6** 72 g **DU 5** 17 g **DU 10** 116 g	**DU 6 E** 72 g **DU 10 E** 116 g
CE-marking	Yes	-

Dimensions

Type	U mm	L mm	H mm	W mm	A mm	B Ø mm	C mm	D mm	E mm	F mm	G mm	I mm	J mm	K mm	M mm	N mm	O Ø mm	P Ø mm
DU 3.5	3.5	15	19.2	10.2	5	2	10.5	6.85	17	10	5	Ø 1.1	2	2000	1			
DU 5	5	15	19.2	10.2	5	2	9	6.85	17	10	5	Ø 1.1	2	2000	1			
DU 6	6	30	26.8	16.4	10	2.3	10.1	20	10	11	15.25	2.2	17	2000	9	12.5	6.5	4.2
DU 10	10	45	44.5	25.6	17	4.5	17	32	13	15	20	2.95	24	2000	10	20	8.5	4.1



DU 3.5 - DU 5



DU 6 - DU 10

Specifications are subject to change without notice (20.08.01)

Phoenix Contact PSR-SCP-24DC-RSM4X1 Technical Data Specifications

12 Technical data and ordering data

12.1 Technical data

Input data	
Nominal input voltage	24 V DC
Permissible range (based on U_N)	0.85 - 1.1
Typical current consumption at U_N	100 mA
Voltage at input, start, and feedback circuit	24 V DC
Typical response time (K1, K2) at U_N	15 ms
Typical release time (K1, K2) at U_N	12 ms
Recovery time	1 s
System response time	Depends on the frequency, see page 47

Output data		
Contact type		4 enabling current paths
Contact material		Silver nickel 10 (AgNi10) 5 µm gold-flashed
Maximum / minimum switching voltage		250 V AC/DC / 10 V AC/DC
Limiting continuous current		5 A[1]
Maximum / minimum switch-on current		6 A / 1 mA [2]
Maximum interrupting rating	24 V DC 48 V DC 110 V DC 220 V DC 250 V AC	Ohmic load t = 0 ms, inductive load t = 40 ms On request
Minimum switching capacity		0.1 W
Mechanical service life		≥ 50 x 10^6 switching cycles
Switching capacity according to DIN EN 60947-5-1/VDE 0660 Part 200	Switching cycles: 360/h	24 V (DC13) 5 A; 230 V (AC15) 5 A
Short-circuit protection of the output circuits		6 A gL (automatic device C8)
Current carrying capacity of signal outputs FO, MO1, and MO2		100 mA, short-circuit-proof

[1] Total current on request.

[2] Up to a maximum switching current of 0.3 A

General data	
Ambient temperature range	-20°C ... +55°C
Nominal operating mode	100% operating time
Air and creepage distances between the circuits	DIN EN 50178/VDE 0160: 1998-04, basic insulation[1]
Rated voltage	250 V
Rated surge voltage	4 kV [1]
Pollution degree	2
Surge voltage category	III
Mounting position	Any

[1] Safe isolation, reinforced insulation, and 6 kV between the input circuit and the output contact current paths.

Dimensions	Screw connection	Spring connection
W / H / D	45 mm / 99 mm / 114.5 mm	45 mm / 112 mm / 114.5 mm

Connection data	Screw connection	Spring connection
Conductor cross section	0.2 mm^2 ... 2.5 mm^2 (24 - 12 AWG)	0.2 mm^2 ... 1.5 mm^2 (24 - 16 AWG)
Stripping length	7 mm	12 mm

Safety characteristics according to IEC 61508	
SIL	3
PFH (probability of a dangerous failure per hour for the entire module)	7.9×10^{-9}

Safety characteristics according to EN 62061	
SIL claim limit	3
PFH (probability of a dangerous failure per hour for the entire module)	7.9×10^{-9}

Safety characteristics according to EN ISO 13849-1	
Category	4
Performance level	e

12.2 Ordering data

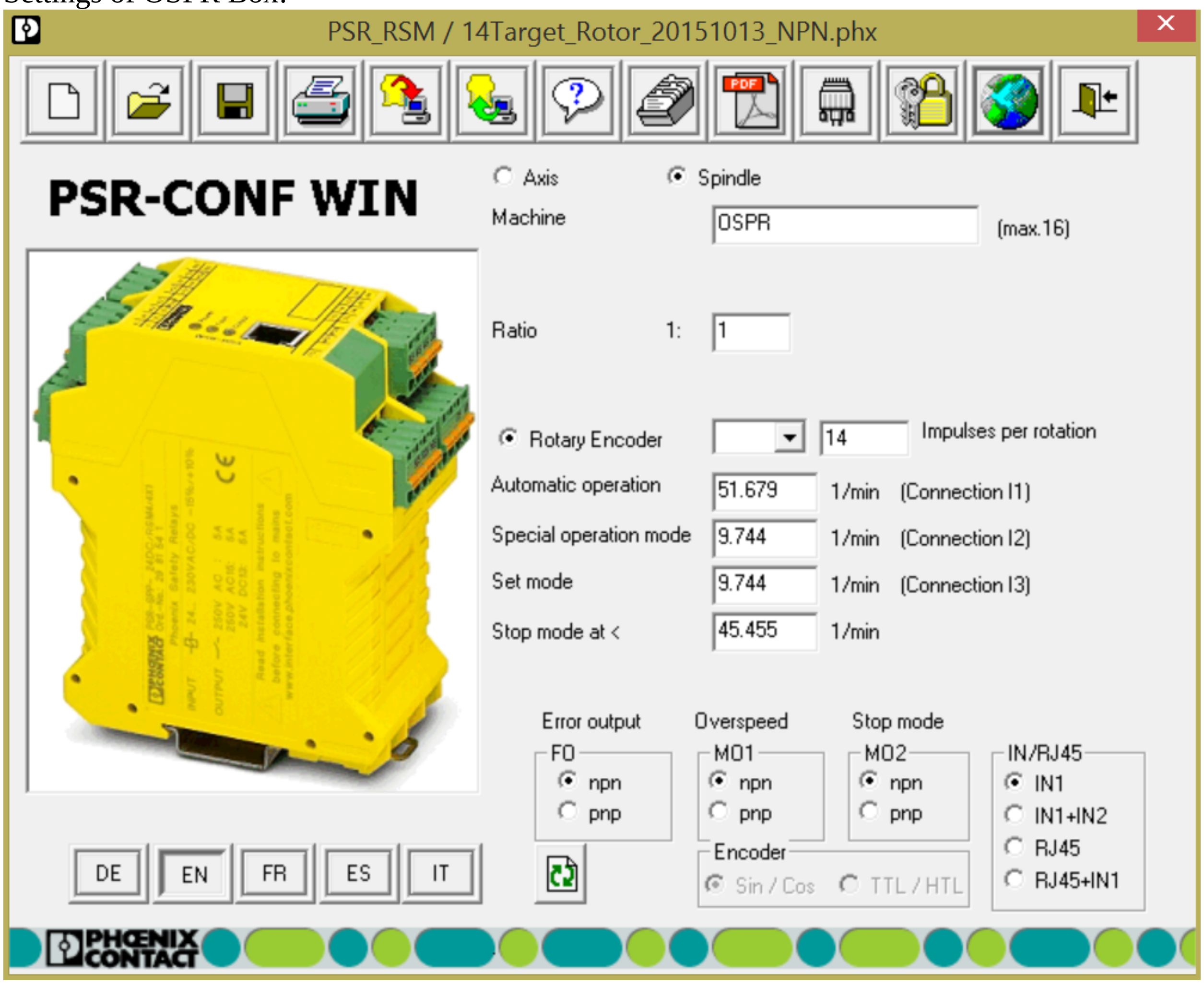
Products

Description	Type	Order No.	Pcs. / Pkt.
Safe speed monitoring with screw connection	PSR-SCP-24DC/RSM4/4X1	2981538	1
Safe speed monitoring with spring connection	PSR-SPP-24DC/RSM4/4X1	2981541	1

Accessories

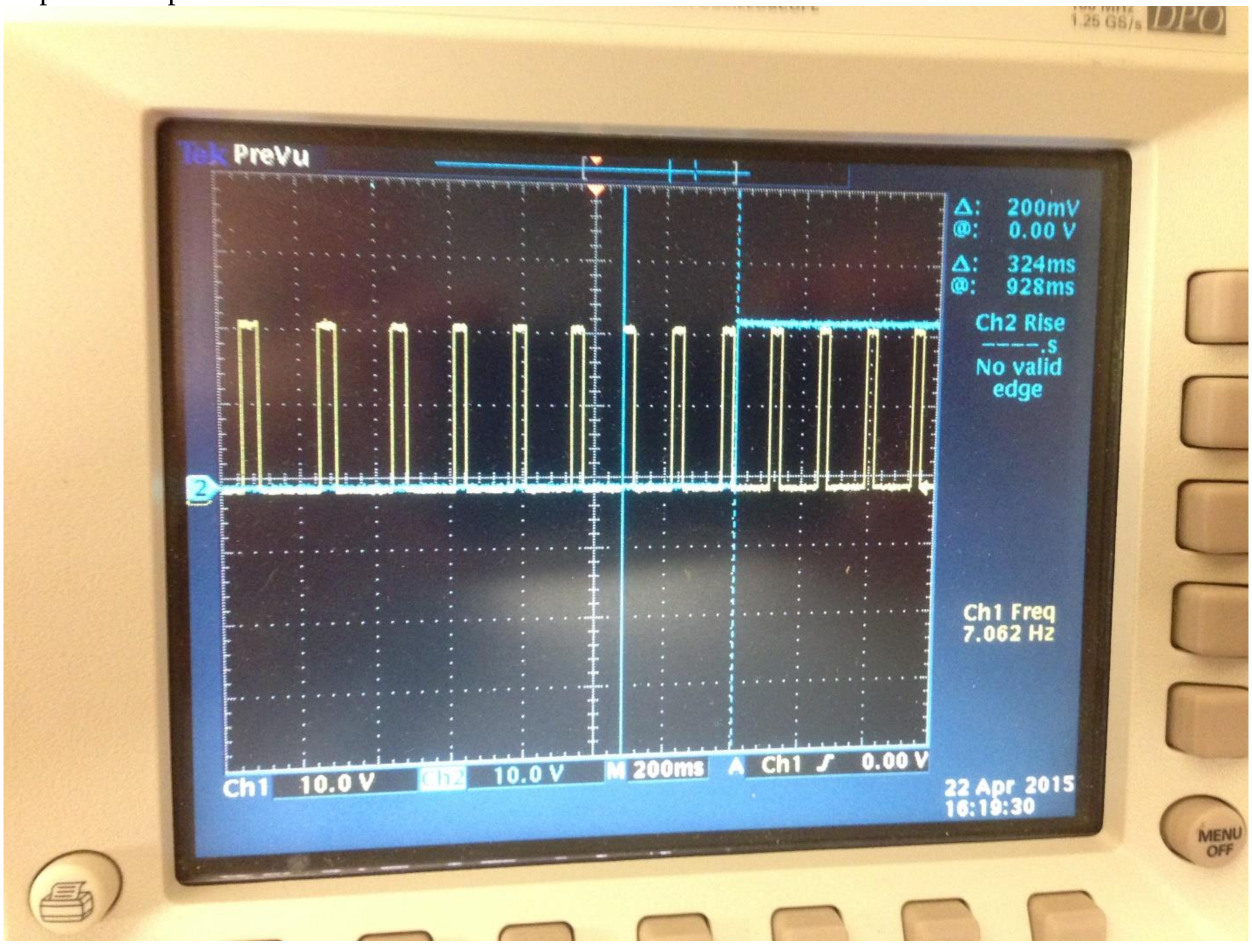
Description	Type	Order No.	Pcs. / Pkt.
PSR configuration software with connecting cable, for configuring the PSR-RSM4 safety relay, language: German, English, French, Italian, and Spanish	PSR-CONF-WIN1.0	2981554	1
Cable adapter for PSR-RSM4 Cable length: 2.5 m	See "Adaptation to existing drive systems" on page 25		
Adapter for PSR-RSM4, hardware interface for HTL encoder - signal conditioning	PSR-RSM-HTL-ADAPTER	2981897	1

Settings of OSPR Box:



Note: the setting of overspeed, "Automatic Operation," at 51.679 RPM (18.26% over nominal RPM of 43.7) is the closest setting the box will allow based upon the 14 target per rotation resolution. This ensures the box does not trip over the 52.7 RPM limit.

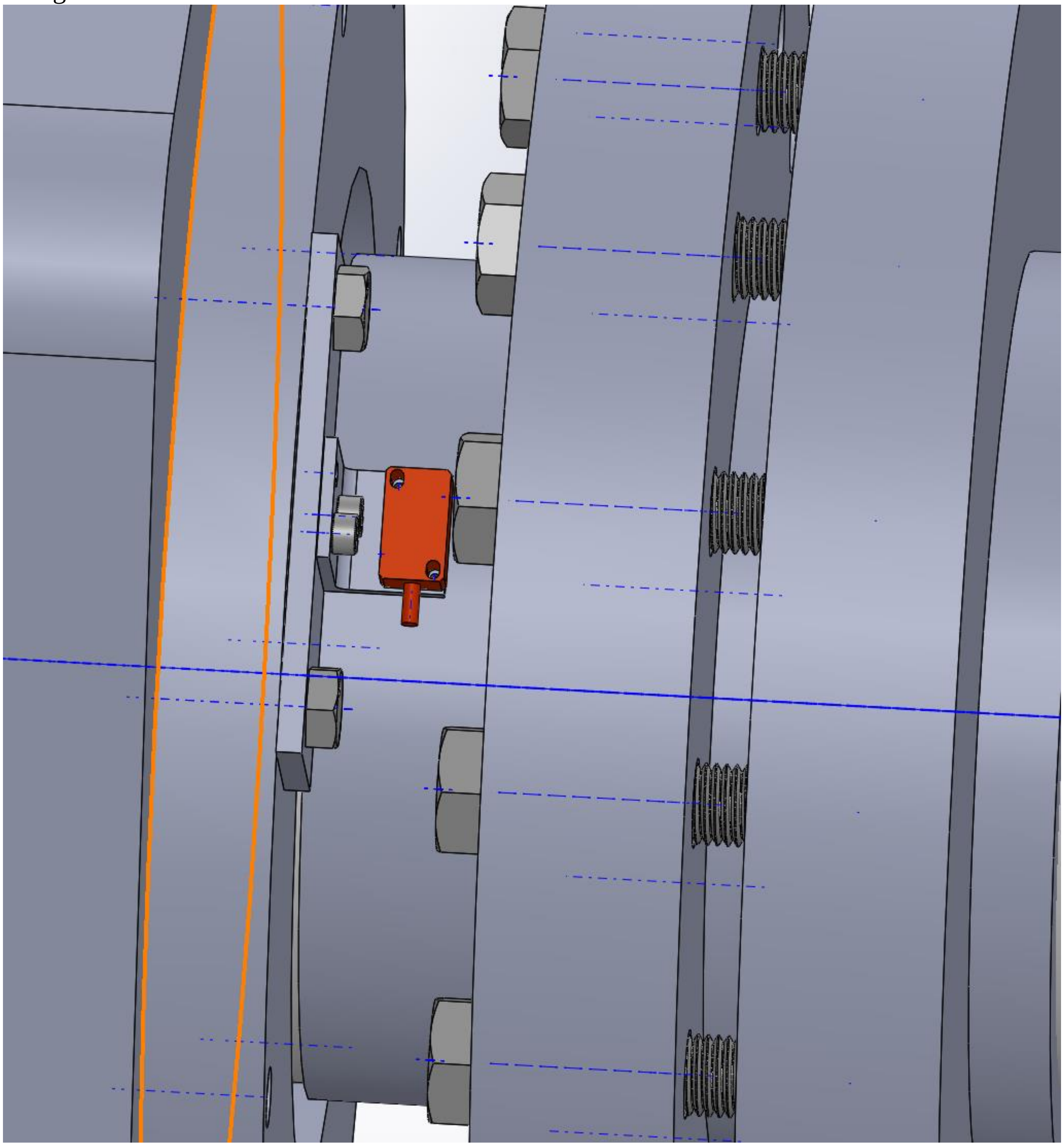
Expected response time of OSPR: 324 ms at 7 Hz.

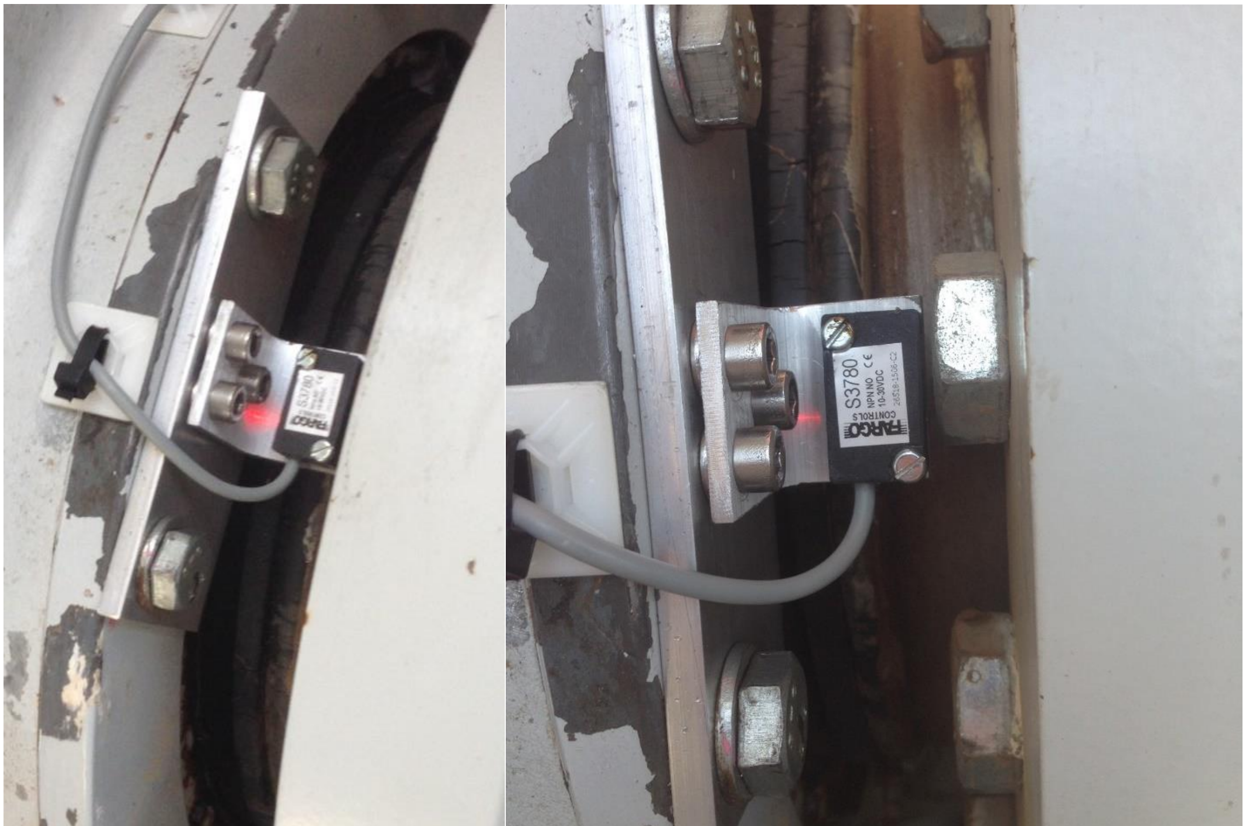


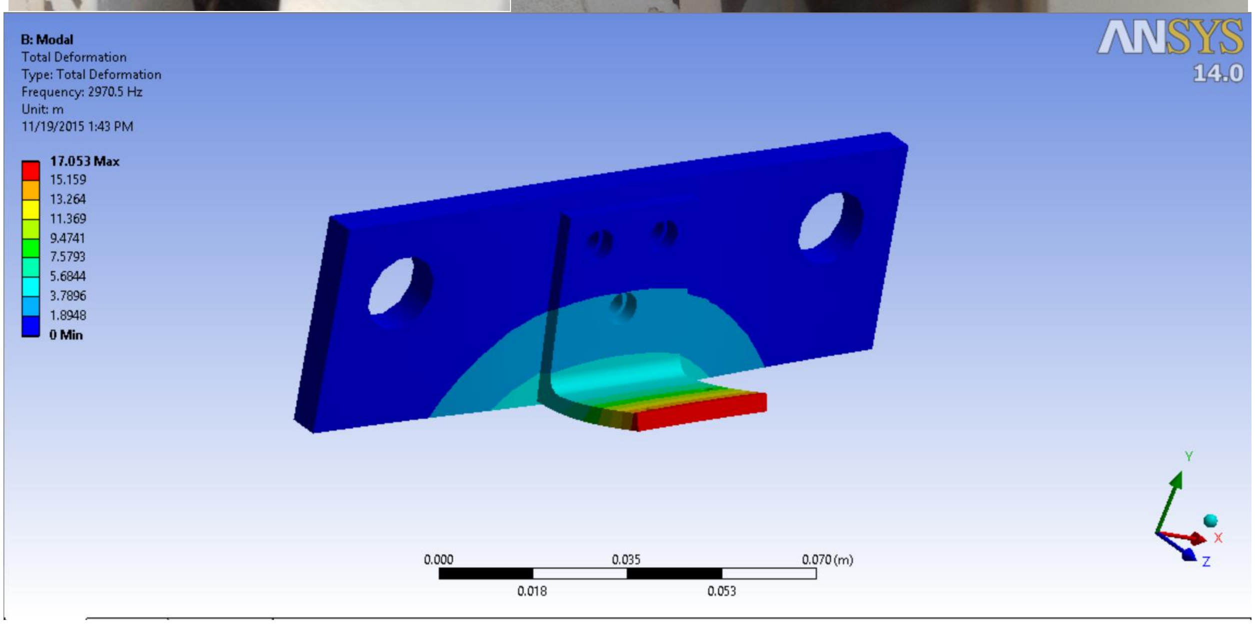
The sensor is set to trigger at 12 Hz on the turbine during a high speed event, so will respond faster than this test which was at 7 Hz. Testing was performed prior to knowing the amount of targets that will be measured per rotation of the shaft, causing the mismatch in frequencies during testing. The system response time will be measured in greater accuracy for the entire emergency system during commissioning procedures.

APPENDIX B: OSPS INFORMATION

Design of OSPS Sensor Bracket:

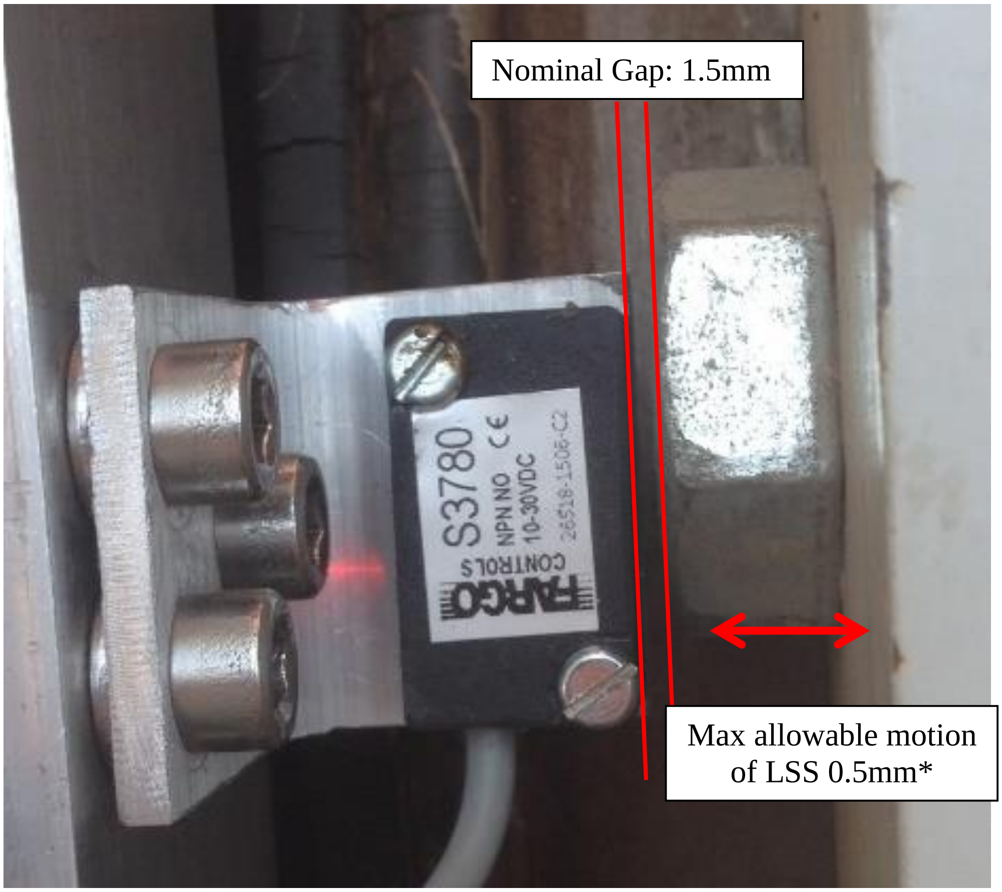






First mode of vibration of OSPS Bracket: 2970 Hz. Bracket is considered stiff in all operating ranges of the turbine. The sensor adds a small amount of mass to the bracket, so will drop the frequency a couple of Hz, which still exceeds any operational frequency of the turbine.

Sensor Clearances:



Sensor Operating Distance: 2mm *Minimum distance required to trigger sensor.
*Source: SWiFT Mechanical Manual Section 8.3.2
Sensor output is monitored by the controller. If the sensor goes “dead” for any reason, including being struck, the controller will see the dropout of the sensor and trigger an Emergency Stop.

Sensor Info: Fargo Controls, INC. S3782

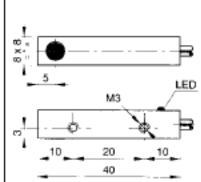
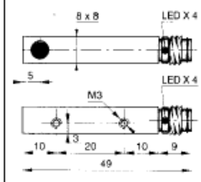
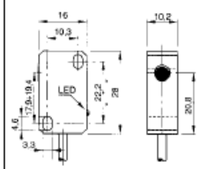
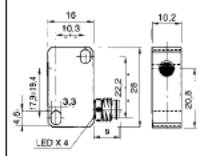
FARGO CONTROLS, INC.

Inductive

Rectangular DC 3 Wire

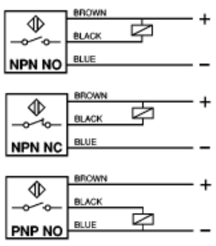
FEATURES:

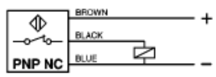
- Short circuit & reverse polarity protection
- Protection degree IP67: dust tight and protection from the effects of immersion
- LED function indicator
- 3.5, 5, 7.5 and 10 meter cable lengths available upon request

		MODEL			
Output Function	NPN, NO	S3160	S3164	S3780	S3784
	NPN, NC	S3161	S3165	S3781	S3785
	PNP, NO	S3162	S3166	S3782	S3786
	PNP, NC	S3163	S3167	S3783	S3787
Dimensions: mm 1 mm = .03937" CE					
Operating Distance (Sn)		**2mm**	**2 mm**	**2 mm**	**2 mm**
Power Supply		6 - 30 Vdc			
Max Switching Current		200 mA			
Power Drain (24Vdc)		< 12 mA			
Voltage Drop (sensor ON)		< 1.8 V			
Short Circuit Protection		Yes			
Operating Frequency		2 kHz		1 kHz	
Repeatability (%Sn)		≤ 3%			
Hysteresis (%Sn)		< 10%			
Case		Anodized Aluminum		Plastic	
Flush Mounting		Yes			
Protection Degree		IP 67			
Operating Temperature		- 25 to +70 °C *			
Output Connection		Cable PVC: L = 2 m	Connector C1	Cable PVC: L = 2 m	Connector C1

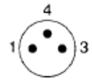
* +100° C high temperature version available upon request

WIRING:





CONNECTOR:



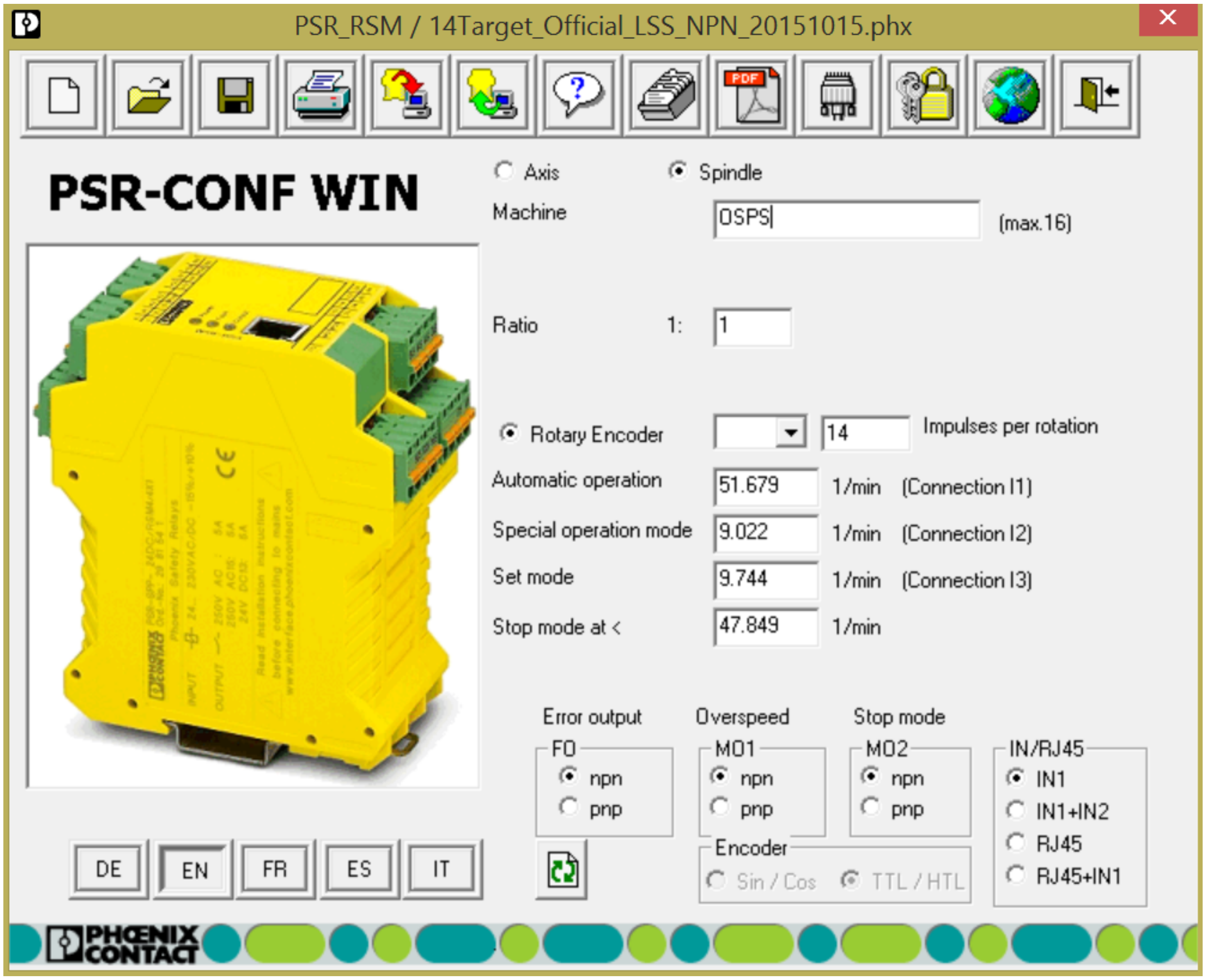
Male connector C1
1=Brown/+
3=Blue/-
4=Black/output NO-NC

MATING CONNECTORS:

ID#	Type	Description
S3480	C1	right angle w/ 5 meter cable
S3481	C1	straight w/ 5 meter cable

 732 389-3376 Fax 732 542-3553 www.fargocontrols.com

Setup of OSPS:


PSR_RSM / 14Target_Official_LSS_NPN_20151015.phx
PSR-CONF WIN
Axis
Spindle
Machine
OSPS
(max.16)
Ratio
1:
1
Rotary Encoder
14
Impulses per rotation
Automatic operation
51.679
1/min
(Connection I1)
Special operation mode
9.022
1/min
(Connection I2)
Set mode
9.744
1/min
(Connection I3)
Stop mode at <
47.849
1/min
Error output
Overspeed
Stop mode
FO
npn
pnp
MO1
npn
pnp
MO2
npn
pnp
IN/RJ45
IN1
IN1+IN2
RJ45
RJ45+IN1
Encoder
Sin / Cos
TTL / HTL
DE
EN
FR
ES
IT
PHOENIX CONTACT

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APPENDIX C: WATCHDOG

ABB CM-WDS- Cycle monitoring time of 150 milliseconds

ABB Cycle monitoring relay with watchdog function

6

Cycle monitoring relay
w/watchdog function

Phone: 800.894.0412 - Fax: 888.723.4773 - Web: www.clrwtr.com - Email: info@clrwtr.com

Cycle monitoring relay with watchdog function
Ordering details

CM-WDS

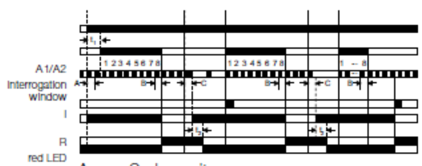
Description

The cycle monitoring relay CM-WDS (watchdog) observes if a regularly intermittent pulse is applied to its pulse input "I". It is, for example, possible to connect the output of a programmable logic controller (plc), which is set and reset regularly (e. g. once each cycle). The connected cycle pulse must be generated by suitable programming of the plc/ipc. Now, the CM-WDS monitors if the cycle time of the plc/ipc program is smaller than the cycle monitoring time setted by means of the front-face selector switch "time value (ms)".
The output relay 11-12/14 of the CM-WDS energizes and the red LED is switched off, if there are minimum 8 successive regular pulses on input "I". When the pulse signal stays out or is not regular, the output relay de-energizes and the red LED is illuminated.
In case the monitoring time is too short or too long, this can be adjusted by a modified programming of the plc/ips or by modified setting of the monitoring time "time value (ms)".
A fault recognized and stored with the CM-WDS can be reset by an H-impulse (0-1-transition) on the reset input "R(9)", so that the cycle monitoring is again released. The reset impulse can be generated by means of a reset button or by suitable programming of the controller (plc/ipc).

Ordering details

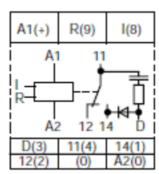
Rated control supply voltage	Reference code	Catalog number	Weight (1 pce) kg (lb)
24 V DC	CM-WDS	1SVR430896R000	0.15 (0.33)

Function diagram CM-WDS



A = Cycle monitor
B = Cycle is correct, no cycle error
C = Cycle failure 1: pulse > monitoring window
Cycle failure 2: pulse stays out
t_1 = 300 ms
t_2 = 260 ms

Connection diagram CM-WDS

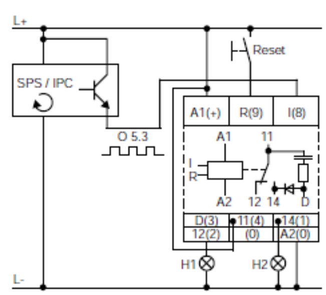


A1/A2	Rated control supply voltage
I	Cycle pulse input
R	Reset input
11-12/14	Output relay
D	Protected output (freewheeling diode)

Characteristics

- Cycle monitor for monitoring the function of programmable logic controllers or industrial pcs
- 4 selectable cycle monitoring time ranges from 0.5 to 1000 ms
- 24 V DC supply
- 1 c/o contact
- 2 LEDs for status indication

Example of application - circuit diagram



Application

The CM-WDS is designed for the external monitoring of the correct function of programmable logic controllers (plc) and industrial pcs (ipc).

Cycle monitoring relay with watchdog function

Technical data

Type		CM-WDS
Input circuit		A1-A2
Rated control supply voltage U_S - power consumptionA1-A2		24 V DC - approx. 1 W
Tolerance of the rated control supply voltage U_S		-30 % - +30 %
Duty time		100 %
Measuring circuit		I
Monitoring function		cycle monitoring
Measuring voltage		24 V DC
Current consumption at the measuring input		approx. 5 mA
Setting range of cycle monitoring time		selectable: 0.5-150 ms, 0.5-260 ms, 0.5-500 ms, 0.5-1000 ms
Response time		approx. 0.5-1000 ms
Accuracy within the supply voltage tolerance		ΔU ≤ 0.5 %
Accuracy within the temperature range		ΔU ≤ 0.06 % / °C
Timing circuit		
ON-delay		approx. 2.2-10 s
Indication of operational states		
Control supply voltage		U: green LED
Output relay de-energized / cycle error		F: red LED
Output circuit		11-12/14
Kind of output		1 c/o
Operating principle [1]		Closed-circuit principle
Contact material		AgCdo
Rated operational voltage U_e	IEC/EN 60947-1	250 V
Minimum switching voltage / Minimum switching current		
Maximum switching voltage		250 V AC, 250 V DC
Rated operational current I_e (IEC/EN 60947-5-1)	AC12 (resistive) 230 V	4 A
	AC15 (inductive) 230 V	3 A
	DC12 (resistive) 24 V	4 A
	DC13 (inductive) 24 V	2 A
AC rating (UL 508)	Utilization category (Control Circuit Rating Code)	B 300
	max. rated operational voltage	300 V AC
	max. continuous thermal current at B 300	5 A
	max. making/breaking apparent power at B 300	3600/360 VA
Mechanical lifetime		10 x 10^6 switching cycles
Electrical lifeteime (AC12, 230 V, 4 A)		0.1 x 10^6 switching cycles
Max. fuse rating to achieve short-circuit protection	n/c / n/o contacts	10 A fast-acting / 10 A fast-acting
General data		
Dimensions (W x H x D)		22.5 x 78 x 100 mm (0.89 x 3.07 x 3.94 in)
Mounting position		any
Degree of protection	enclosure / terminals	IP50 / IP20
Ambient temperature range	operation / storage	-20...+60 °C / -40...+85 °C
Mounting		DIN rail (IEC/EN 60715)
Electrical connection		
Wire size	fine-strand with wire end ferrule	2 x 2.5 mm² (2 x 14 AWG)
Standards		
Product standard		IEC 255-6, EN 60255-6
Low Voltage Directive		2006/95/EC
EMC Directive		2004/108/EC
Operational reliability (IEC 68-2-6)		4 g
Mechanical shock resistance (IEC 68-2-6)		6 g
Electromagnetic compatibility		
Interference immunity to		EN 61000-6-2
electrostatic discharge	IEC/EN 61000-4-2	Level 3 (6 kV / 8 kV)
radiated, radio-frequency, electromagnetic field	IEC/EN 61000-4-3	Level 3 (10 V/m)
electrical fast transient / burst	IEC/EN 61000-4-4	Level 3 (2 kV / 5 kHz)
surge	IEC/EN 61000-4-5	Level 3 (2 kV L-L)
conducted disturbances, induced by radio-frequency fields	IEC/EN 61000-4-6	Level 3 (10 V)
Interference emission		EN 61000-6-4
Isolation data		
Rated insulation voltage between supply-, control- and output circuit (VDE 0110, IEC 60947-1)		250 V
Rated impulse withstand between all isolated circuits (VDE 0110, IEC 664)		4 kV / 1.2-50 µs
Test voltage between all isolated circuits		2.5 kV, 50 Hz, 1 min
Pollution degree (VDE 0110, IEC 664, IEC 255-5)		3/C
Overvoltage category (VDE 0110, IEC 664, IEC 255-5)		III
Environmental tests (IEC 68-2-30)		24 h cycle, 55 °C, 93 % rel. 96 h

[1] Closed-circuit principle: Output relay de-energizes if a cycle error occurs

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APPENDIX D: BRAKE THERMISTOR

Sensor: Uchiya UP62 T150 1300

UCHIYA UP6 SERIES

UCHIYA THERMOSTAT

providing SAFETY to SOCIETY worldwide

SAMPLE APPLICATIONS OF UP6

- TRANSFORMER PROTECTOR
- PROTECTION OF ELECTRONIC CIRCUITS
- LIGHTING BALLAST PROTECTION
- MOTOR PROTECTOR
- SUPPLY MODE POWER SUPPLY
- SOLENOID PROTECTOR

The UP6 Series is the smallest enclosed Thermal Protector produced by Uchiya Thermostat for AC applications up to 2.5A (250V) and 4A (125V).

The compact size and unique design of the UP6 Series allows it to fit into tight spaces in applications and to be mounted onto PCB Boards.

The PBT enclosure offers both thermal conductivity and electrical insulation with no need for additional insulation sleeves.

SAFETY APPROVAL

VDE	EN60730-2-9	2.5(1.6)A 250V AC
	EN60730-2-2	250V AC
	EN60730-2-3	**1A 250V AC (NEW)**
UL/c-UL	UL873	4A/2A 125V/250V AC
	C22.2 No 24	4A/2A 125V/250V AC

FEATURES

- PBT Enclosure
- Snap Action Bimetal Technology
- Solid and Insulated LeadWire Available
- Worldwide Safety Approvals
- Not Current Sensitive

PRODUCT DESCRIPTION

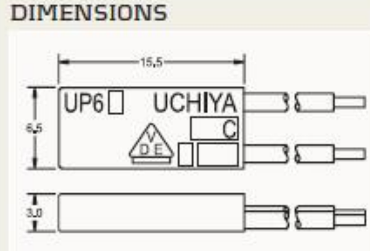
- Thermal Cut-Out
- Thermal Motor Protector
- Thermal Protector

STANDARD SPECIFICATION

SPECIFICATION	UP6 SERIES	
Switch Temp.	60C ~ 150° C*	
Open Tolerance	+/- 5K	
Standard Differential	30K ~ 40K	
Reset Tolerance	+/- 15K	
Current	2.5(1.6)A	4A
Voltage	250V AC	125V AC
Cycles	10,000*	
Contact	NORMAL CLOSED (NC)	
Contact Resistance	< 50mΩ	
Impregnation Resistance	SUITABLE**	
High Voltage Resistance	> 2.5kV AC (10mA)	
Insulation Resistance	1,000V DC (100MΩ)	
Protection Class	1	
Minimum Leadwire Size	AWG24	

* See Approvals Table for more information ** Please contact Uchiya for further information

DIMENSIONS



SERIES VARIATIONS

UP61	Solid Leadwire
UP62	Insulated LeadWire

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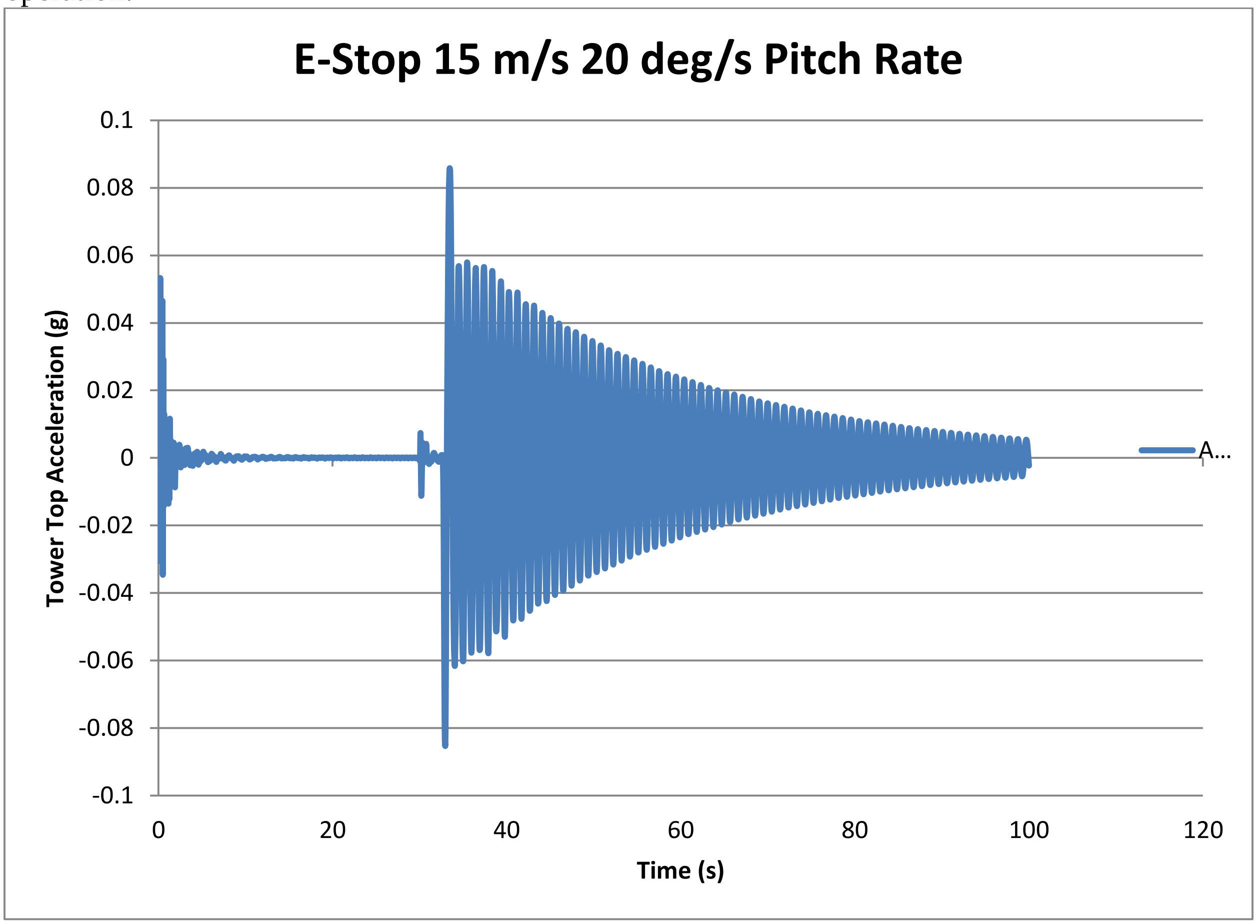
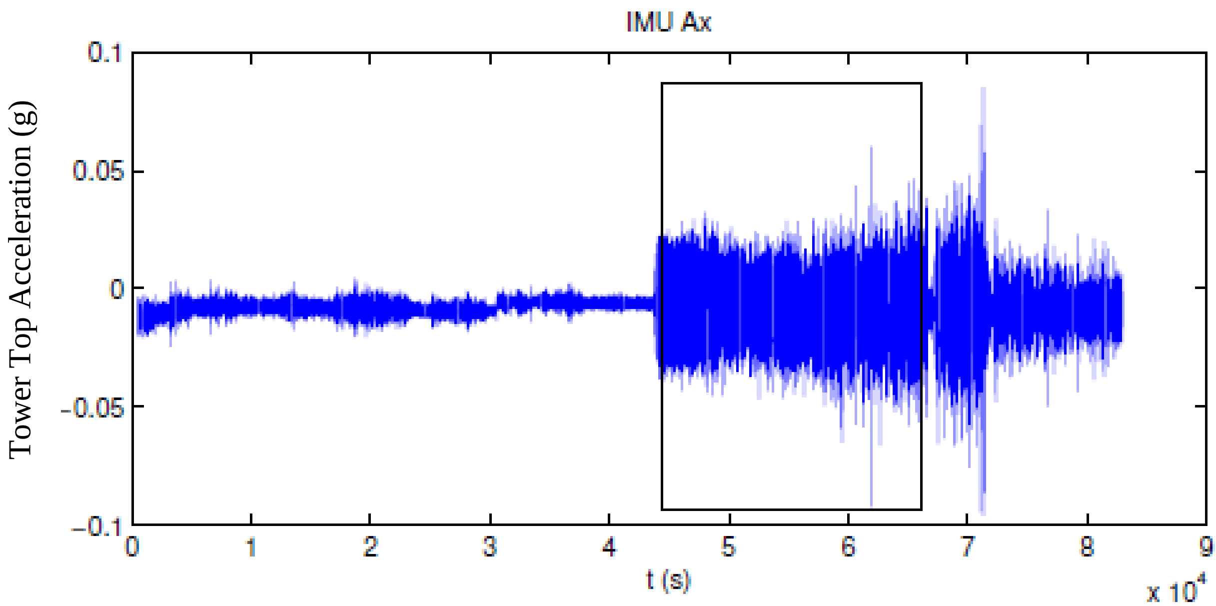
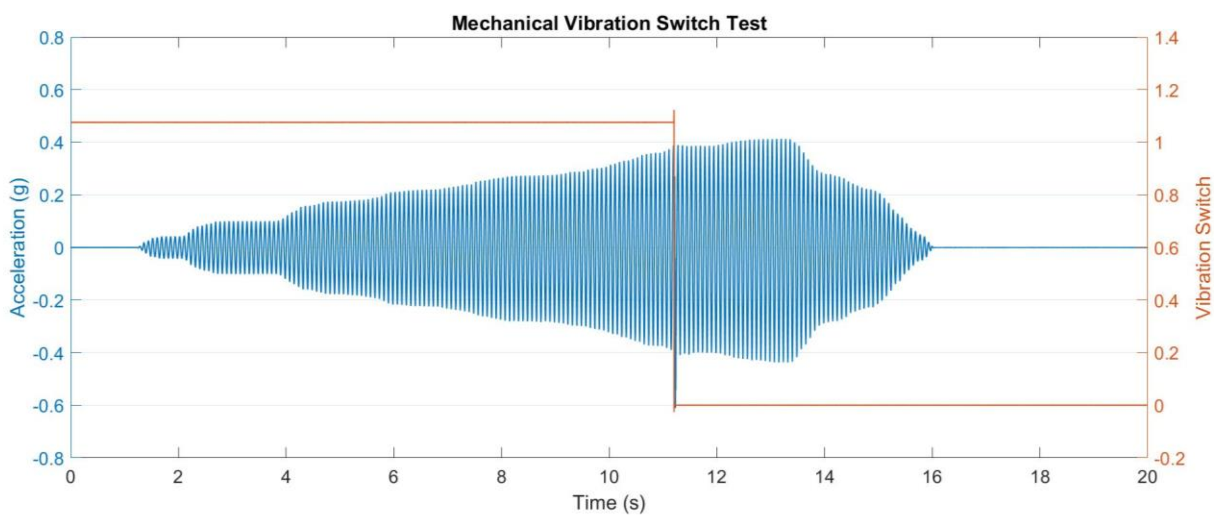
APPENDIX E: MECHANICAL VIBRATION

Sensor: IMI 685A08 Mechanical Vibration Switch
Set to 0.4 G
The below figure is the predicted tower top acceleration during an Emergency Stop due to an overspeed event at 15 m/s wind speed, cut out, with a functioning pitch ram. This scenario should represent a relatively high vibration event which the turbine may encounter during operation.



During initial commissioning testing at SWiFT, tower top acceleration was recorded from one of the turbines onsite during operation, shown below. The peak acceleration during a recorded stop was approximately 0.09 g. The turbine will regularly see events on the order of 0.1g acceleration. In order to prevent unnecessary tripping of the vibration switch, the switch is set to trip at approximately 0.4 g, well below a level that could cause significant damage to the turbine from vibration and not high enough to not react to an actual vibration issue.


IMU Ax
Tower Top Acceleration (g)
t (s)
x 10^4


Mechanical Vibration Switch Test
Acceleration (g)
Vibration Switch
Time (s)

Model Number		Revision: NR
685AX8	**MECHANICAL VIBRATION SWITCH SPECIFICATIONS**	ECN #:

	ENGLISH	SI
PERFORMANCE		
Vibration Range	0 to 7g peak	0 to 68.7 m/s^2 peak
Frequency Response	0-6000cpm	0-100Hz
ELECTRICAL		
Alarm Function	Latch	Latch
Alarm Relay (SPDT)	5A Form C 480VAC/2A Resistive, 1A Inductive @ 30VDC	5A Form C 480VAC/2A Resistive, 1A Inductive @ 30VDC
ENVIRONMENTAL		
Operating Temperature Range	-40 to +140°F	-40 to -60°C
Ingress Protection	IP50	IP50
PHYSICAL		
Size (Width x Height x Depth)	6.38 in x 4.88 in x 5.63 in	162 mm x 124 mm x 143 mm
Conduit Hole	1/2-14 NPT	N/A
Weight	4.5 lbs	2.04 kg
Mounting Thread	Thru Hole	Thru Hole
Mounting Holes (4)	0.38 in	10 mm
Sensing Element	Magnet	Magnet
Sensing Geometry	Inertial Element	Inertial Element
Housing Material	Aluminum Alloy	Aluminum Alloy
Electrical Connector	Removable Screw Terminals	Removable Screw Terminals
Screw Terminal Wire Size	14 AWG	2.5 mm^2
Rating	Explosion Proof	Flame Proof [1]
INDICATOR/CONTROLS		
Alarm Setpoint	Control Screw	Control Screw
Reset Function	Pushbutton Switch	Pushbutton Switch

OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

685AX8

- □ 0 No remote reset (base model)
- □ 1 Remote reset, 350 mA @ 24VDC
- □ 2 Remote reset, 350 mA @ 115VAC

NOTES:

Hazardous Area Certification

[1] Class I, Div. 1, Group C & D.
[2] 1697235
[3] 516U

[1] [2]   [1] [3]

All specifications are at room temperature unless otherwise specified.

ICP® is a registered trademark of PCB Group, Inc.

In the interest of constant product improvement, we reserve the right to change specifications without notice.

Form DD030 Rev.F 2/23/99

Drawn: [illegible]	Engineer: [illegible]	Sales: [illegible]	Approved: [illegible]	Spec Number:
Date: 9-18-06	Date: 9/18/06	Date: 9/20/06	Date: 9/25/06	33523

IMI SENSORS
A PCB PIEZOTRONICS DIV.
3425 Walden Avenue, Depew, NY 14043 800-959-4464 Fax (716) 684-3823 E-Mail: imisales@pcb.com

APPENDIX F: GRID QUALITY / ISLANDING PROTECTION

Provided by Mark Ralph, SNL
IEEE 1547 / UL 1741 Islanding Protection Requirements
IEEE 1547 requires DER to detect and stop generating under the following conditions

	Condition	Must Disconnect Time	at 480/277 V nominal
Over Frequency	freq > 1.008 pu	10 cycles, 167 ms	60.5 Hz
Under Frequency	freq < .988 pu	10 cycles, 167 ms	59.3 Hz
Over Voltage – slow	V > 1.1 pu	1.0 s	528 / 305 V
Over Voltage – fast	V > 1.2 pu	10 cycles, 167 ms	576 / 333 V
Under Voltage – slow	V < 0.88 pu	2.0 sec	422 / 244 V
Under Voltage – fast	V < 0.5 pu	10 cycles, 167 ms	240 / 134 V

Set points to “manufactures stated accuracy”.

Relay Set Points & Results

Bender Relay

	Relay Symbol	**Set Point**		**Observed trip point**			Meet Standard
				R1	**R2**	**R3**	
Under Voltage	U <	422 / 244 V	0.88 * 277V	245.2 V(l-n) 424.2 V(l-l)	244.9 V(l-n) 423.7 V(l-l)	245.8V(l-n) 425.2V(l-l)	X
Over Voltage	U >	Off	1.1 * 277V	-	-	-	
Hysteresis	Hys	5%					
Asymmetry	Asm	30%					
Under Frequency	Hz <	59.3 Hz	0.988 * 60 Hz	59.45 Hz	59.45 Hz	59.45 Hz	X
Over Frequency	Hz >	60.5 Hz	1.008 * 60 Hz	60.5 Hz	60.55 Hz	60.55 Hz	X
Freq Hysteresis	FHys	0.2 Hz					
Phase Sequence	PHS	Off					
Reconnect	V and freq normal		Requires manually cycling control power to reset relay				

Voltages were measured line to neutral for each phase.

ABB Relay, nominal 415.7 V

	Condition	Time	Measured Time**	Meet Standard	Comment
Over Frequency	freq > 60.5 Hz	100 ms	0	X	Tripped at 60.47 Hz
Under Frequency	freq < 59.3	100 ms	0	X	Tripped at 59.35 Hz
Over Voltage – slow	V > 525V	950 ms	971 ms	X	
Over Voltage – fast	V > 540V	100 ms	120 ms	X	More restrictive than required
Under Voltage – slow	V < 415.7 V*	1.95 s	1.97	-	This test is less restrictive than the standard requires
Under Voltage – fast	V < 240 V	100 ms	120 ms	X	
Reconnect	V and freq normal	5 min	5.02 m	X	

* 415.7 V is the maximum settable value for low voltage detection.
** Measure times start after 1 cycle (16.7ms) of the rms calculation. The manufacture may calculate rms values over a longer or shorter period. Assume times are +/- 16.7 ms.

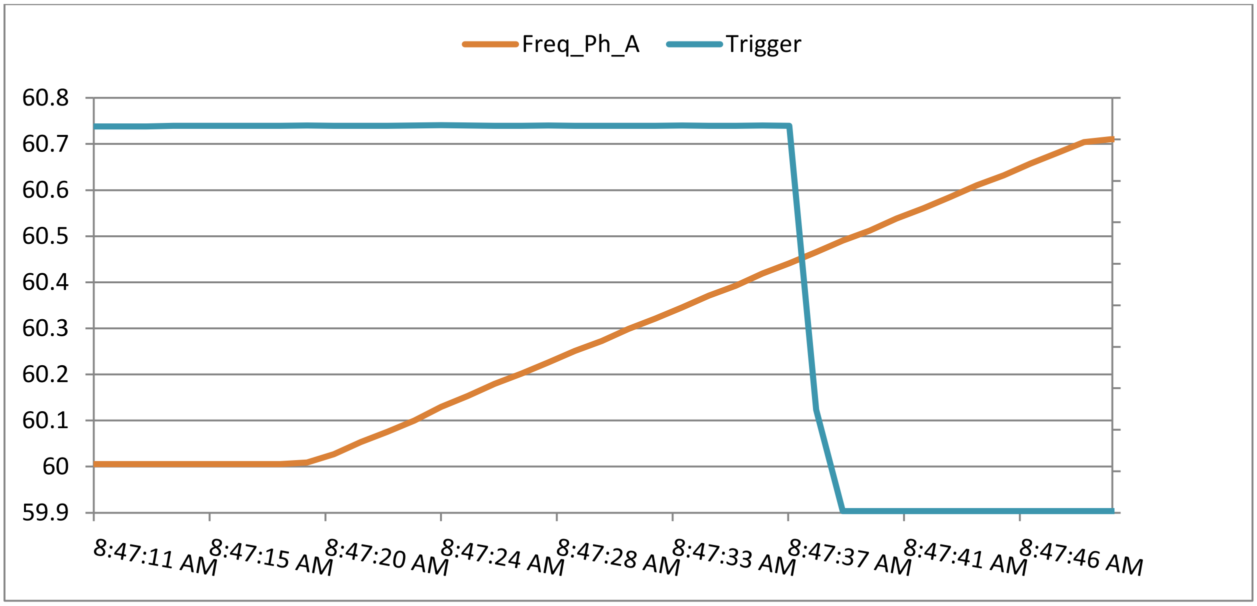
Verifying Set Points for ABB CM-UFD.M33 Relay

The ABB CM-UFD.M33 relay is being considered for anti-islanding protection for the SWiFT turbines to meet requirements in IEEE 1547. The ABB CM-UFD.M33 relay is designed for the European market with a maximum nominal voltage of 415Y/240V. The SWiFT turbines operate at a nominal 480V.

Over-Frequency

Time	Trigger	Freq
8:47:37 AM	46.63	60.44
8:47:38 AM	12.43	60.47
8:47:39 AM	0.198	60.49

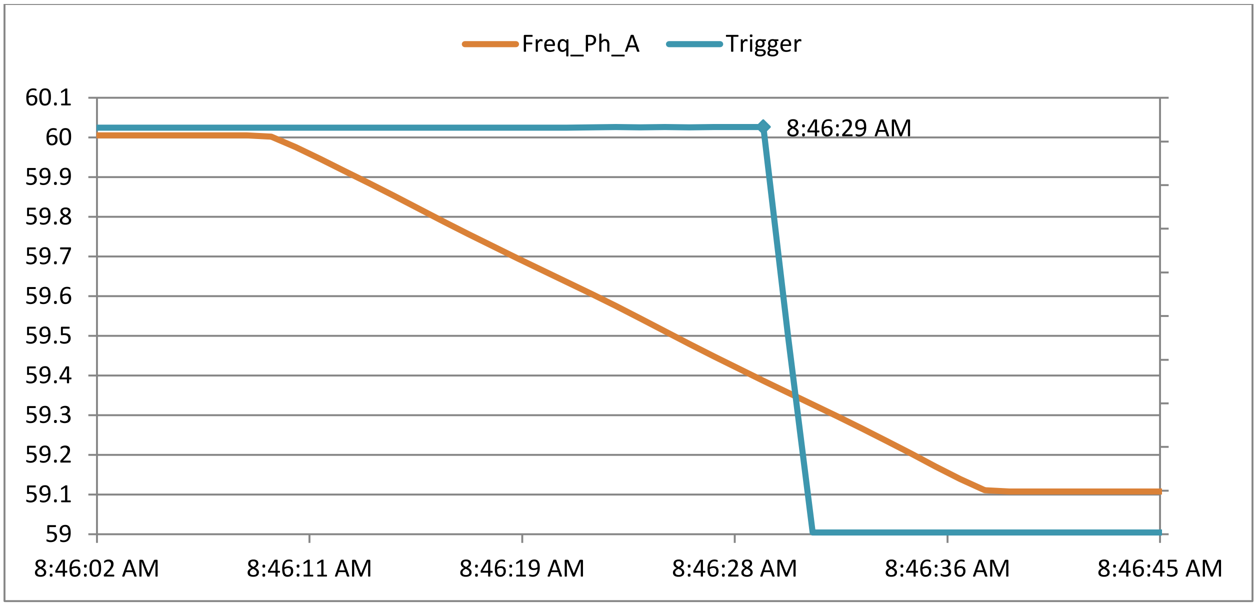
data sampled at 1 sec



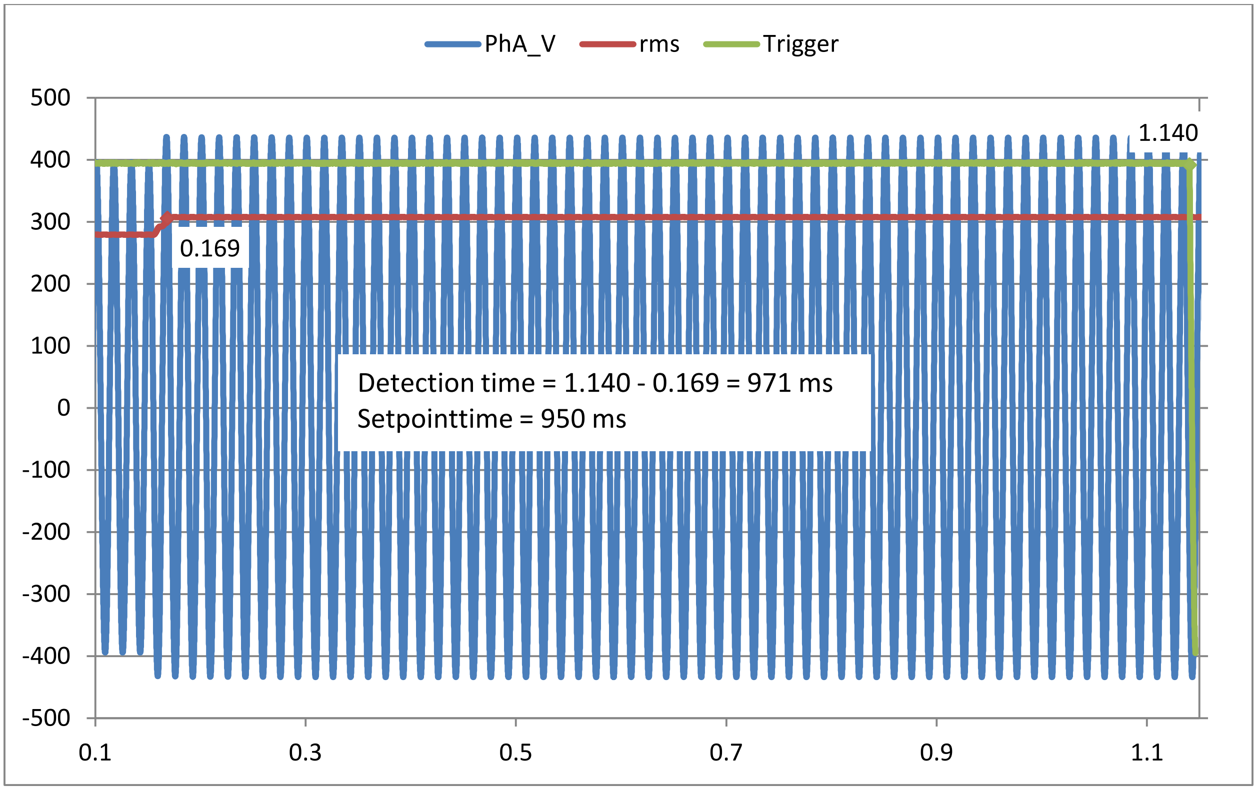
Under-Frequency

Time	Trigger	Freq
8:46:29 AM	46.6	59.39
8:46:30 AM	22.7	59.36
8:46:31 AM	0.2	59.33

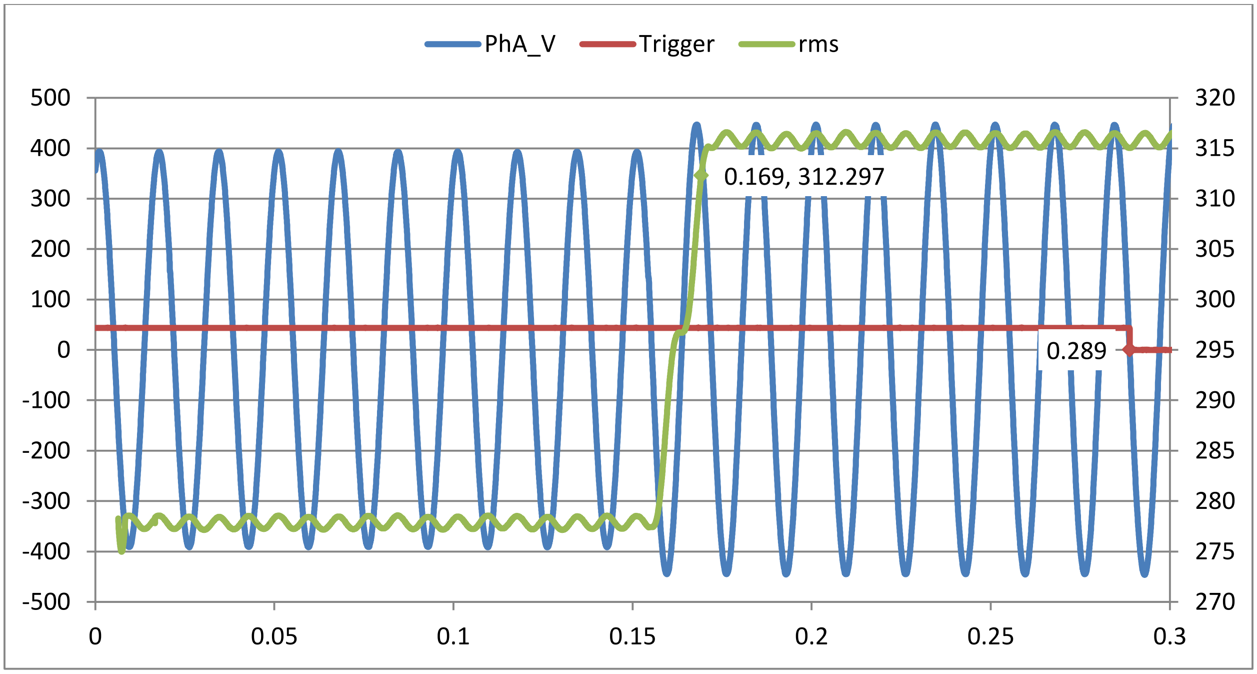
data sampled at 1 sec


Freq_Ph_A
Trigger
60.1
60
59.9
59.8
59.7
59.6
59.5
59.4
59.3
59.2
59.1
59
8:46:29 AM
8:46:02 AM
8:46:11 AM
8:46:19 AM
8:46:28 AM
8:46:36 AM
8:46:45 AM

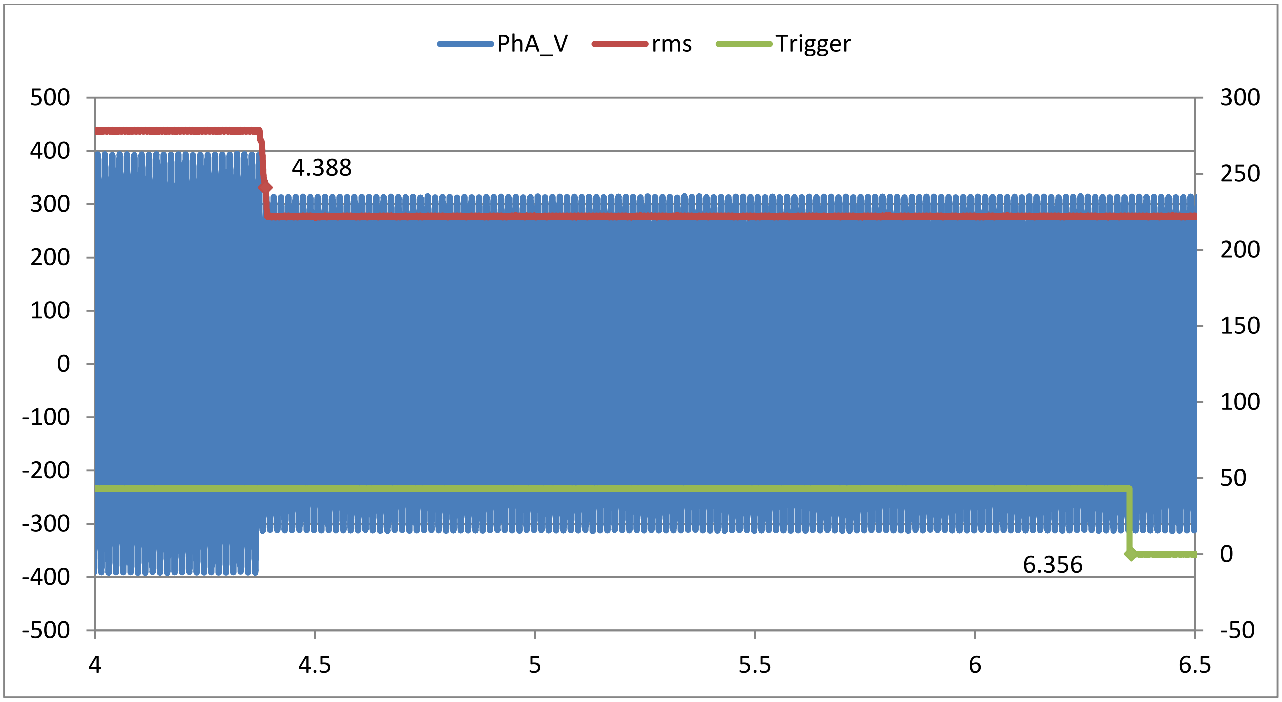
Over-Voltage detection – slow, U1



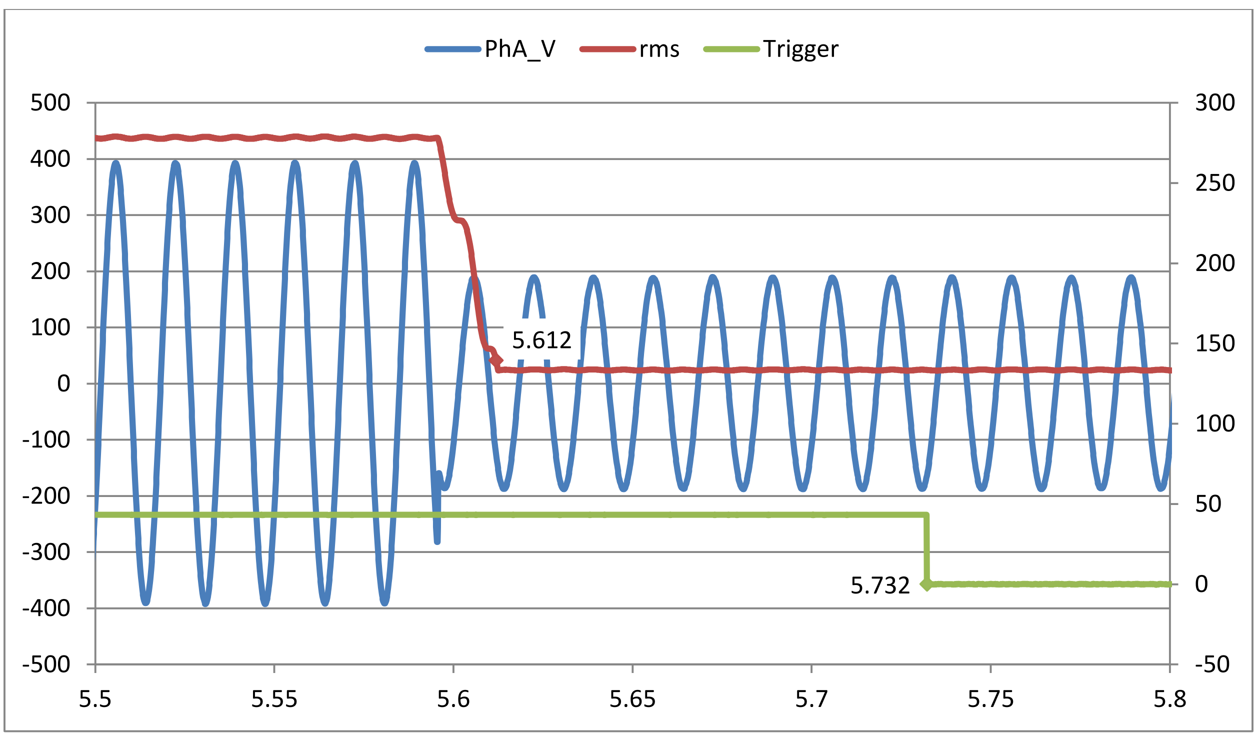
Over-Voltage detection – fast, U2



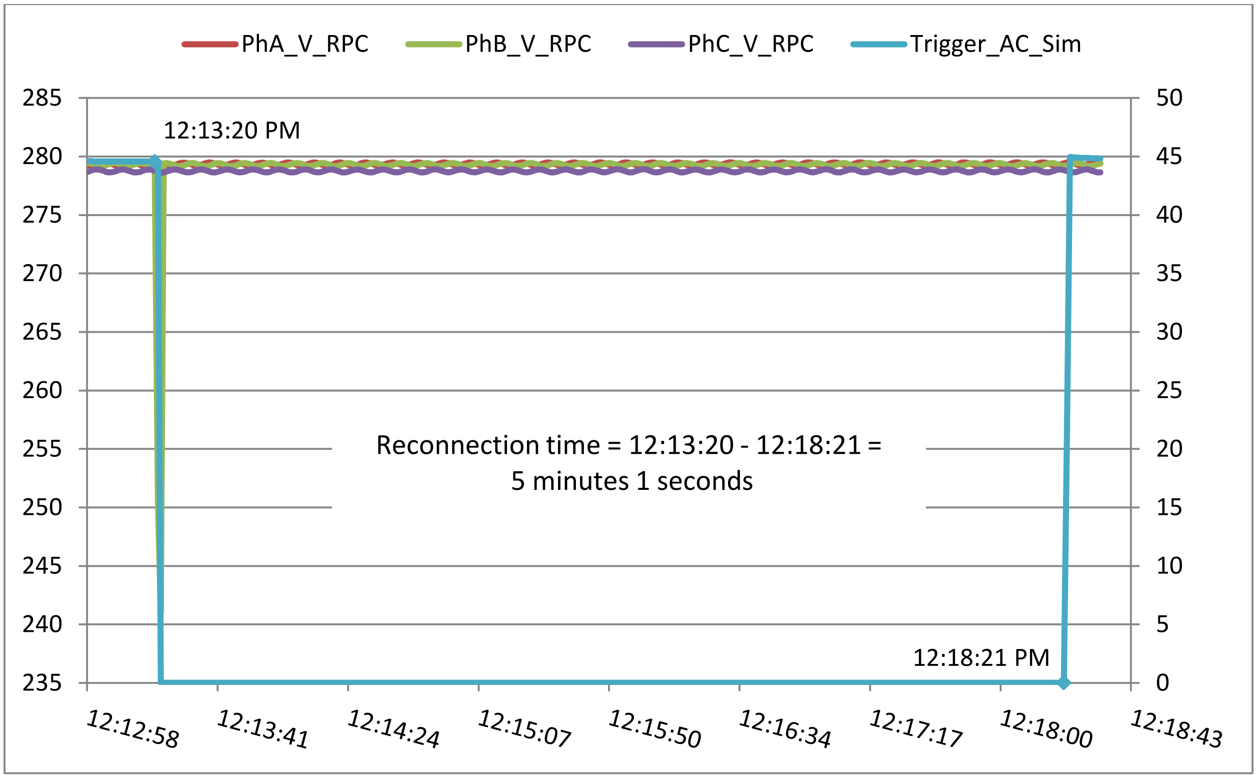
Slow Under-Voltage Detection U1



Fast Under-Voltage Detection U2



Reconnection Time



APPENDIX G: VFD BRAKING AND BRAKE CHOPPER

Cabinet-built regenerative drives ACS800-17, up to 2500 kW

Complete regenerative drive

The ACS800-17 offers you a complete regenerative drive in a single, compact cabinet-built package. The drive includes everything that is needed for regenerative operation, including line filter. The active supply unit allows full power flow both in motoring and generating modes.

Energy savings

Compared with other braking methods such as mechanical and resistor braking, the energy savings can be significant with the ACS800-17. The braking energy is returned to network, not wasted as heat. Handling of waste heat may also be a problem if braking power is significant. As no external braking devices are needed with the ACS800-17, installation work is simpler and the space requirement for installation is less.

High performance

The ACS800-17 is especially suitable for demanding applications. Transition between motoring and generating is fast due to the DTC control method. The active supply unit is able to boost output voltage, which guarantees full motor voltage even when the supply voltage is below nominal.

The active supply unit combined with the DTC control can even compensate for fast variations in line voltage. There is no risk of fuse blow or component damage due to voltage drops in the network.

Extensive range of features

Adaptation to different application requirements is possible by selecting from a wide range of standardized configurations. The cabinet-built drive series enables having a significant amount of features and accessories as built-in options.

Main standard features

- Compact design
- IP21 protection degree
- LCL line filter inside
- EMC filter for 2nd environment, unrestricted distribution according to EN 61800-3 (option in frame size R6) (category C3)
- Main switch with aR fuses (in frame sizes R6-R8i)
- Line contactor (in frame sizes R7i-R8i, option in frame size R6)
- Withdrawable air circuit breaker (in frame size n×R8i)
- Common mode filters for motor protection (in frame sizes R7i-n×R8i)
- du/dt filters (in frame size n×R8i)
- Coated boards
- Extensive, programmable I/O
- Long lifetime cooling fan and capacitors
- Inputs galvanically isolated
- I/O and fieldbus extension slots inside
- Alphanumeric multilingual control panel with startup assistant feature

Accessories for the ACS800-17

- Analogue and digital I/O extension modules
- ATEX approved motor protection
- Cabinet heater
- Customer terminal block
- du/dt filters (in frame sizes R6-R8i)
- Earth fault monitoring for unearthed network
- EMC filter for 1st environment, restricted distribution according to EN 61800-3 (category C2)
- Fieldbus modules
- IP22, IP42, IP54 or IP54R protection degrees
- Marine construction
- Output for motor fan
- Pulse encoder interface module
- Safe torque-off (STO)
- Safely-limited speed (SLS)
- Top entry and exit of cables
- 1 or 2 thermistor relays
- 3, 5 or 8 Pt100 relays
- Emergency stop categories 0 or 1
- UL or CSA certified design

Plus tailor made accessories through ABB's application engineering.

28 ABB industrial drives ACS800 single drives | **Catalog**

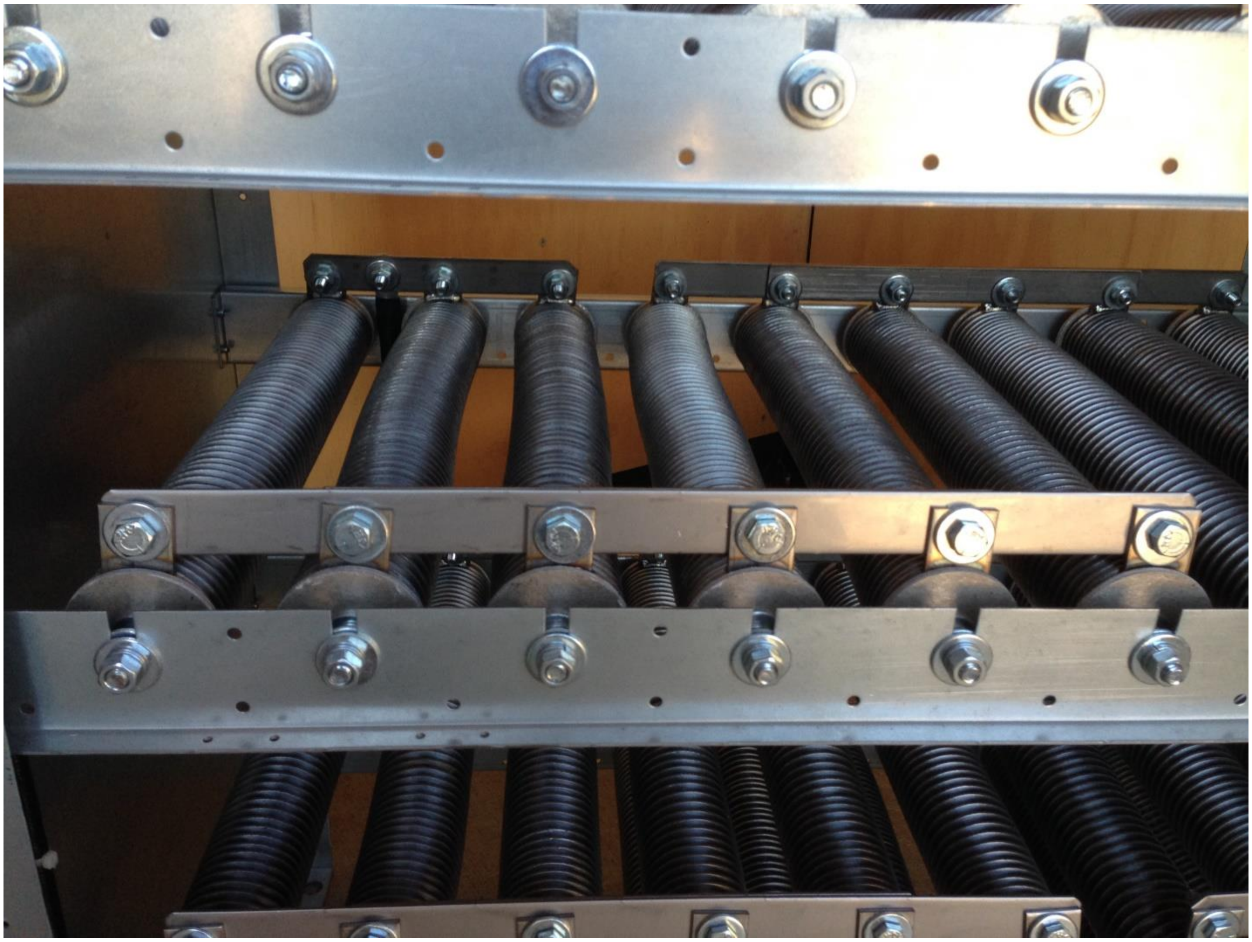
The stopping ramp time for initial testing of the SWiFT turbines will be set to 30 seconds, and tuned in based upon witnessed stopping times for normal operating conditions. For more in depth information for the ABB Variable Frequency Drive please consult the SWiFT Electrical Manual.

TABLE 2 General Specifications for 600 amp Type BM Braking Modules

Powerohm Part Number	Nominal AC Line Voltage	RMS Continuous Load Current	Turn ON Voltage	Max Peak Current
BM208-600	208	600	336	900
BM240-600	240	600	390	900
BM380-600	380	600	612	900
BM415-600	415	600	670	900
BM480-600	480	600	775	900
BM600-600	600	600	970	900
BM690-600	690	600	1090	900
BM720-450	720	600	1120	900

POWEROHM RESISTORS, INC.

Wired Brake chopper and resistor bank.


1.5 ohm resistor cabinet rated for over 600 Amp current.

DISTRIBUTION

1	MS1124	Bruce LeBlanc	06121
1	MS1124	Joshua Paquette	06121
1	MS1124	Jonathan White	06121
1	MS1124	David Minster	06121
1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories