DELIVERABLE D4.1:
PRELIMINARY CONTROL SYSTEM AND SCADA DESIGN REQUIREMENTS

ADVANCED TIDGEN® POWER SYSTEM
US DEPARTMENT OF ENERGY AWARD: DE-EE0007820

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Ocean Renewable Power Company, Inc.
254 Commercial Street, Suite 119B
Portland, ME 04101
Phone (207) 772-7707
www.orpc.co

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1 Purpose

This document is the technical report deliverable, D4.1, for the Advanced TidGen®, which fulfills milestone 4.1 for the project:

Award No.:	DE-EE0007820, effective 11/1/2016
Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

The document provides details regarding the control system and SCADA system preliminary design for Task 4 of the Advanced TidGen® project. Milestone and deliverable descriptions are below. **Note that simulation files are not applicable due to the development approach ORPC has adopted for the project.**

4.1	Milestone	Preliminary control system and SCADA design for tidal system operation completed, with control system models supporting capability to maintain maximum power point operation through tidal and turbulence ranges.	8	3

3	**Task 4: Software & SCADA Design and Integration**	M4.1	Report	**D4.1:** Technical report on control system development, supporting simulations and SCADA system requirements	pdf	Protected	<50MB	None	MHK-DR
3	Task 4	M4.1	Data: simulation files	**D4.1:** Supporting MATLAB simulation files	Matlab /Simulink files	Protected	<10MB	Requires software license	MHK-DR

2 Control System

This Project will investigate and analyze advanced turbine control schemes with the objective of increasing the energy harvested by hydrokinetic turbines in tidal environments.

Previous projects focused on control approaches evaluated four types of controllers which were tested in simulation, emulation, a laboratory flume, and the field.[1] Trends in simulation were verified through experiments, which also provided the opportunity to test assumptions about turbine responsiveness and control resilience to varying scales of turbulence. The clear message was that the feedforward $K\omega^2$ controller out-performs feedback controllers in almost all aspects and modes of evaluation. The controllers proved a substantial improvement over the baseline performance of the TidGen® turbine, in terms of energy capture.

2.1 Theory

This project will focus on the theory and implementation of two types of controllers:

1. $K\omega^2$ – a nonlinear feedforward controller
2. Adaptive $K\omega^2$ – a nonlinear feedforward controller

These controllers will be tested in simulation. If adaptive control shows benefit in simulation, it may be tested in the field along with the base controller.

Nonlinear feedforward ($K\omega^2$)

Derived from the dynamic model of turbine operation, the nonlinear feedforward $K\omega^2$ controller commands a torque,

$$\tau_c = K\omega^2 = \frac{1}{2}\rho A R^3 \frac{\eta(\lambda)}{\lambda^3}\omega^2$$

which brings the turbine to a desired operating point on its performance curve ($\eta(\lambda)$). In the case where K results in the turbine operating at peak efficiency, this optimal gain is referred to in this report as K^*. K values larger or smaller in magnitude than K^* result in operation to the “left” or “right” of the peak (slower or faster than optimal λ, respectively). Optimal performance requires a well-defined performance curve and accurate

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[1] EE0006397_ORPC_FINAL_TECHNICAL_REPORT

measurement of ω. Note that unlike a feedback controller, the control torque equation does not explicitly prescribe a fixed set-point. Rather it controls the turbine to a set-point based on the estimate for the plant dynamics. This controller is shown schematically in Figure 1.

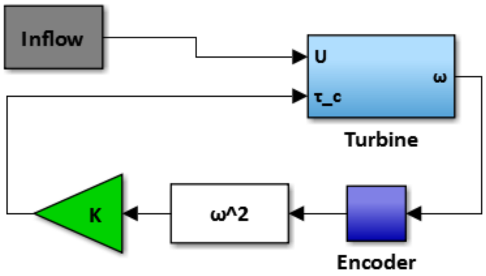

Figure 1: Kω^2 controller schematic. This feedforward controller creates a torque command based on the speed of the turbine and the plant characteristic k.

Adaptive nonlinear feedforward (adaptive Kω^2)

An adaptive version of Kω^2 control can be used when a turbine's performance curve is subject to parameter variation (e.g., efficiency is a function of both tip-speed ratio and free-stream velocity). A model of this variation with free stream velocity is employed so that

$$\tau_c = K(U)\omega^2 = \frac{1}{2}\rho A R^3 \frac{\eta(U,\lambda)}{\lambda^3}\omega^2 ,$$

in which controller action depends on measurement of U. As with the standard formulation for this controller, its performance depends on the quality of turbine performance space. The controller is shown schematically in Figure 2.

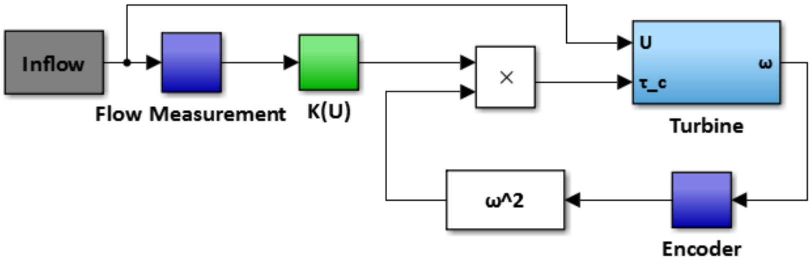

Figure 2: Adaptive Kω^2 controller schematic. The plant characteristic value, K, can be adapted for a specific value of U, or any other desired parameter.

Simulation of turbine systems

Numerical turbine simulations were implemented in MATLAB Simulink and Python. The controller produces a command torque signal based on an estimate for the rotation rate (ω). This control torque and actual free stream velocity act on the turbine, changing its rotation rate. The simulation integrates the turbine dynamic equation forward in time using a variable-step integrator. Uncertainty in the rotation rate passed to the controller is simulated by a logic block that can add noise to the actual rotation rate (representing an inaccuracy in the controller's inherent estimate for rotation) and attempt to improve the estimate through filtering.

In simulation, the turbine response to inflow conditions is deterministic and performance evaluations are rapid, enabling a low-cost exploration of parameter spaces. However, the simulated dynamics parameterize a number of aspects of turbine operation and may not be fully representative of real systems. Field operation of controllers demonstrates their true effectiveness, though uncertainty is higher than in simulation, owing to the mechanical response of the turbine being obscured by the power train since only rotation rate and electrical power are known, rather than mechanical torque and structural loads.

The performance of each controller and filter strategy is considered in terms of the range of tip-speed ratios at which it could operate stably, variability of command torque and power output, and ability to hold a set point.

In a tidal environment, the mean currents will change continually from slack to peak flow. Initially, to maximize power, an adaptive Kω^2 controller might need to be employed if the turbine's efficiency is a function of both velocity and tip-speed ratio. All test work from previous projects shows that a properly tuned adaptive Kω^2 controller can maintain optimal efficiency for a time-varying inflow velocity. Beyond the turbine's rated speed, the control objective would shift from maximum efficiency to maintaining a constant torque or power output. The Kω^2 controller can be used to achieve this by adjusting *K* to a value away from *K**. This is another form of an adaptive Kω^2 controller.

From prior projects it can be concluded that commercial products will not require real time water velocity measurements, assuming the turbines are properly characterized.

The lowest tip-speed ratio for which stability was achieved for each controller is summarized in Figure 3. In this regard, the Kω^2 controller is superior to the other architectures.

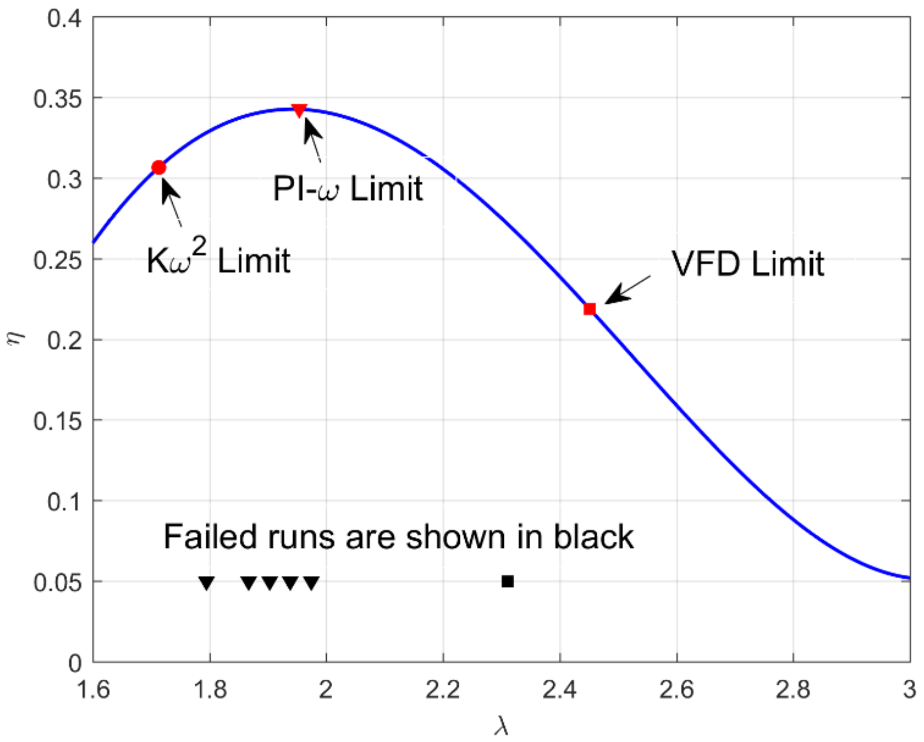

Figure 3: The stable regions of operation for each controller. Regions to the right of the marked point are stable for the controller corresponding to the point: circle for Kω^2, triangle for PI- ω, and square for the built-in VFD speed controller.

3 Control System Implementation

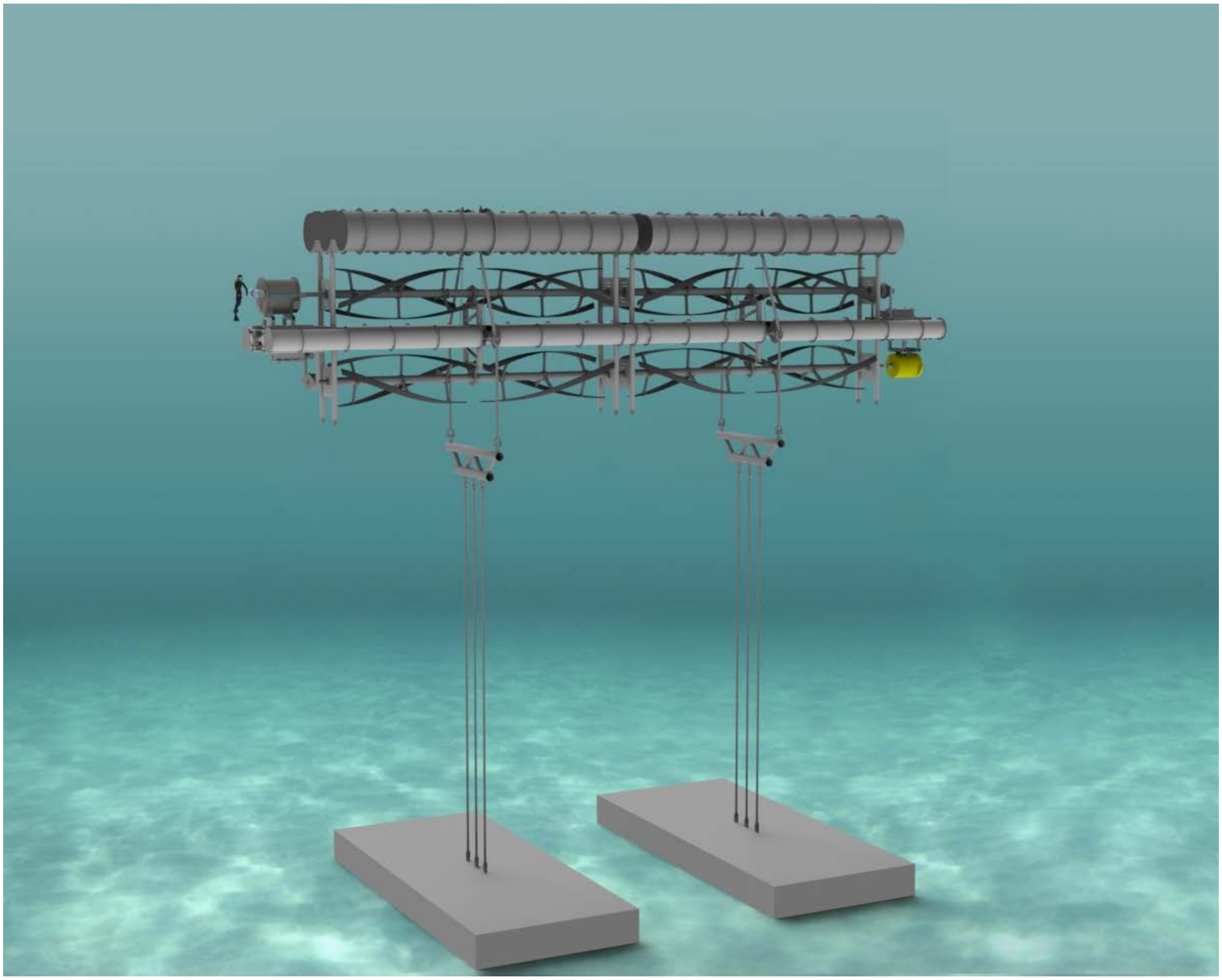

Figure 4: Conceptual illustration of Advanced TidGen®

Given that there are two rows of turbines, each with its own generator, control is implemented independently for each generator and row of turbines. Active control is implemented directly in the power conditioning module for each generator.

The TidGen 2.0 control system is designed as a bridge between the autonomous normal operations and condition monitoring system and the operator. The TidGen 2.0 turbines are designed to work in a bi-directional flow, significantly reducing the required control system inputs compared to conventional axial flow tidal turbines. Due to this reduced complexity, the control system is reduced to commands of: Start, Prepare to Stop, and Stop. The bulk of the responsibilities of the control system is to manage the condition monitoring system, storing and managing raw data files, monitoring for system faults and reporting data back to shore for review.

3.1 Normal Operations

Control of the normal operations are driven by the Rolls-Royce Marine or IKM generator installed on the system. The system will always be in one of three states: normal state, parking brake, and tripped.

Normal State

While the system is in a normal state, the generators are given a starting RPM to bring the turbines up to speed before switching over to a running state and producing power. While in a normal state, the generator health is monitored by the converter box and if any failure or over limit, such as RPM, occurs the generator will switch to a tripped state. At any time during operation, the user can perform an emergency stop and the system will move to the tripped state as well.

Parking Brake

The system enters a parking brake state after the system slows to a sufficient RPM (around 2 RPM) and a short circuit is engaged. Even with the parking brake engaged, the system will spin at a few RPMs when relying on the generator short-circuit torque alone. A secondary electro-mechanical brake is provided to ensure the ability to brake the system if the generator is unable to perform that function.

Tripped

The system can enter the tripped state in one of two ways: the operator can issue an Emergency Stop command, or a fault is detected in the condition monitoring system. Upon entering the tripped state, the system is left in a free-wheel condition until the parking brake can be engaged. Alternatively, the secondary electro-mechanical brake can slow the free-wheel system down until the generator is able to engage the parking brake.

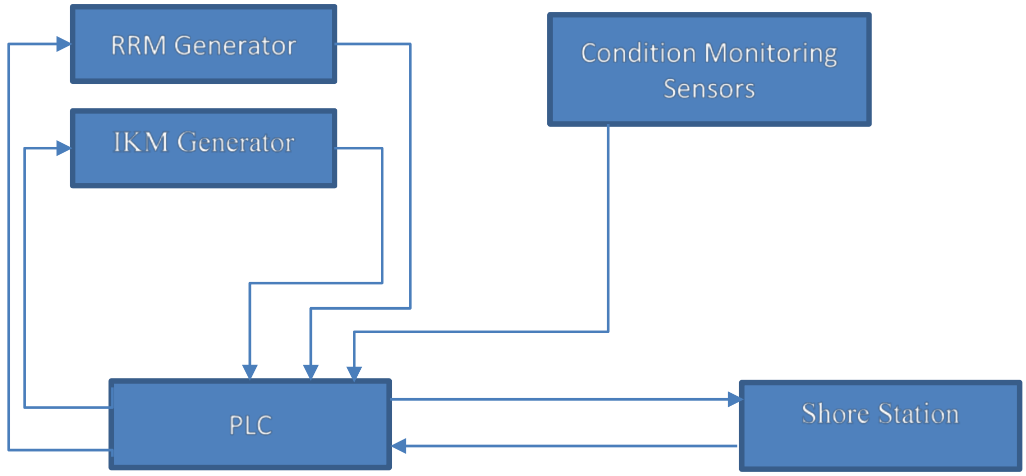

Figure 5: Control System Schematic

3.2 Drive logic and behavior

The drive state can be inquired and controlled by an external system using CAN bus A. The CAN bus specification describes how the CAN packages are built up and how to communicate with the drive on the CAN bus. This section describes the working principle of the control logic.

3.3 Design principles

Interruption of potential energy flow

Since the generator is of the permanent magnet type, it will generate voltage whenever it is rotating. An opening contactor is situated between the generator and frequency controller (inside the converter cabinet) to interrupt the potential flow of energy in fault situations.

A free-spinning generator will generate a voltage up to 1350 V (worst case: 110 RPM and cold magnets). Although this voltage is sustainable by the system, such operation should be minimized to limit premature degradation of the system.

"Parking brake" functionality

The short circuit torque is sufficient to limit the rotation to a few RPMs when the turbine is already at rest. At 2 RPM, a short-circuited generator will apply approximately 25 kNm at 150 A. Both the current and torque depend linearly on the speed up to this point. A short circuit will automatically be applied to the turbine when the generator is free-spinning at low speed (below ca. 2 RPM and the opening contactor is open).

Bring the turbine to standstill

The system does not provide any means to dissipate enough energy for bringing the turbine to rest in cases where the normal energy flow is not OK (e.g. grid failure, converter failure). The design is based on a UPS (provided outside of the converter box) system having enough power to wait for slack tide before the "parking brake" is engaged.

3.4 Drive state machine

The drive state machine is comprised by various logic states such as regulator mode and rotor state. A state diagram is shown in Figure 5. The logic variables can be changed by commands or they may change by various other events such as fault monitoring.

Two separate state logics, one for the parking brake (short circuit contactor) and one for the inverter stage describe the global state machine logic.

3.5 Parking brake circuit

The short circuit brake circuit is referred to as a "parking brake" as an analogy to emphasize that it is used in a similar way to a parking brake on a car: it is used to keep the generator at rest, and it can only be applied once the generator is at standstill. It is not dimensioned to bring the turbine down from speed. The parking brake is engaged automatically by electro-mechanical logic and a voltage-monitoring relay. This makes the logic work independently of the control software. The logic is obtainable by studying the circuit diagram, but will also briefly be described here.

There is an electromechanical inter-lock in place ensuring that the main disconnecting contactor (called "motor contactor" in the software) and short circuit contactor is not engaged simultaneously. Both the main contactor and short circuit contactor provide feedbacks to the control circuit, ensuring that the inverter is not activated in forbidden states. The table below summarizes the brake logic.

State of main contactor	State of short circuit contactor	Description
OPEN	CLOSED	“Parked” state with generator at rest. The parking brake may be disengaged by closing the main contactor (software controlled), bringing the turbine to the released state.
CLOSED	OPEN	“Released” state. In this state, the converter is connected to the generator. This is the state of the brake during normal production. Note that the short circuit contactor will not close in this state due to the electromechanical inter-lock, hence the brake logic will never go directly from released to parked.
OPEN	OPEN	“Park pending” state. The inverter is disconnected from the motor. In this state, the main contactor has been opened but the short circuit contactor has not yet engaged. The short circuit contactor may engage from this intermediate state, this logic is controlled by the voltage monitoring relay. The electrical parking brake is engaged automatically when the rotor is stationary (provided 24 V aux. power is available).
CLOSED	CLOSED	This is a forbidden state that will cause a fault in the drive. A faulty 24V power or contactor coil may cause it.

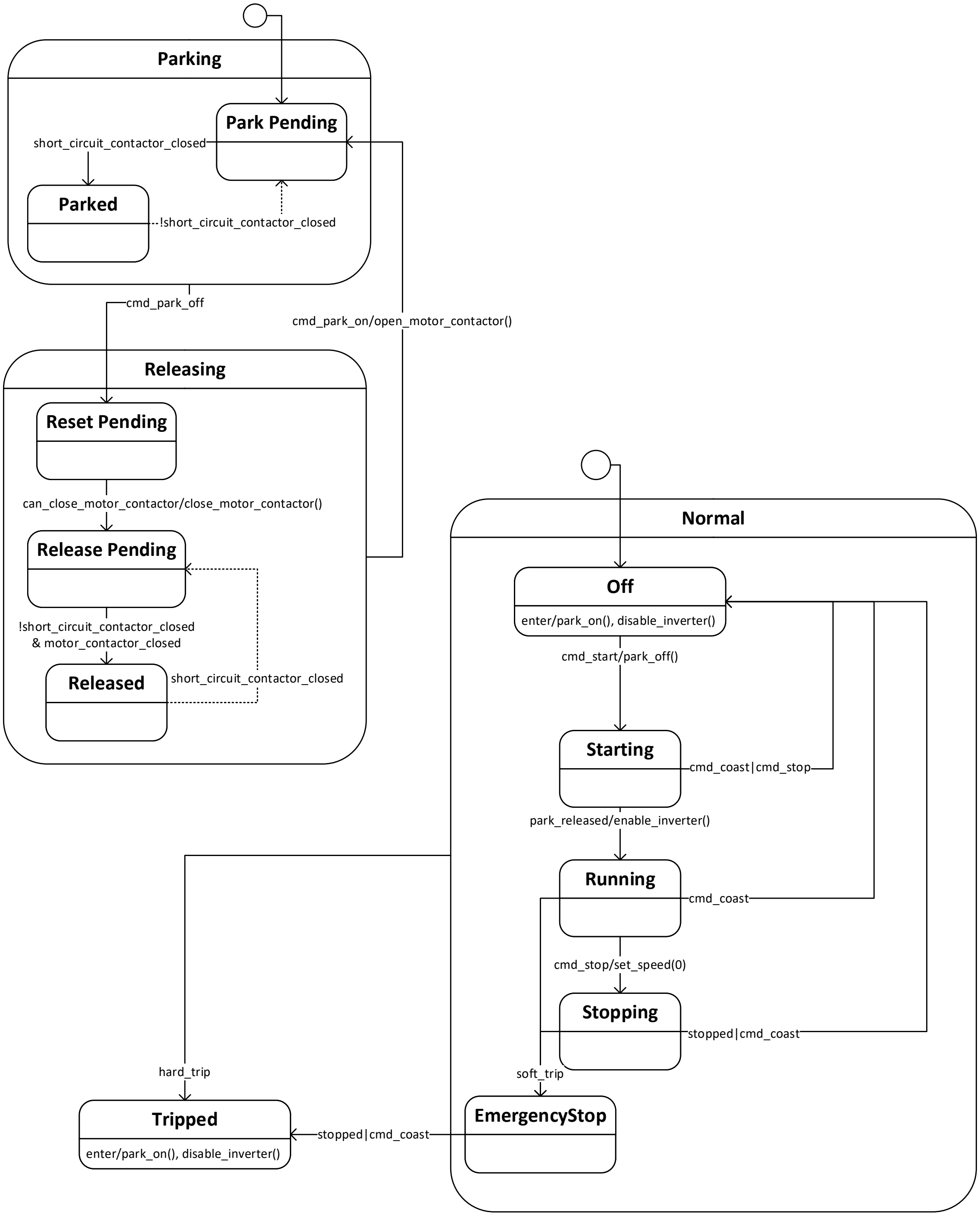

Figure 6. State diagram of the drive

3.6 Starting the generator

The inverter state logic is controlled by the software and commands that are given to the drive.

Starting the generator would typically be done using the *speed regulator mode*. This will start the machine in open loop speed mode. A speed reference of e.g. 15 RPM is set. If the regulator does not go into the closed loop speed mode after a given time, the start has failed, probably due to a stuck rotor, too small current vector, or too fast ramping of the speed. A new reference of e.g. 40 RPM is set when in closed loop speed mode. When the generator is running, the regulator can be changed as needed.

Note that starting may be inhibited if the inverter is given a start command in the “park pending” state, if the speed is too high for the inverter to engage.

3.7 Watchdog timer

The drive state machine automatically commands a controlled stop if the watchdog timer value reaches zero. The watchdog value must therefore be updated with a new counter value (user selectable) at a desired rate. See CAN spec.

3.8 Drive regulators and limits

The inner current regulator is used for both open and closed loop.

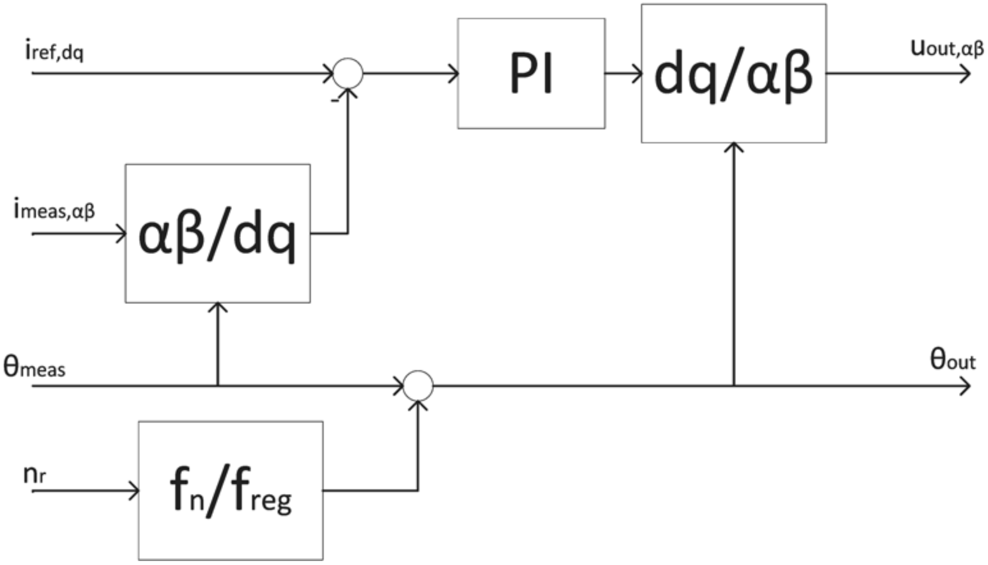

Figure 7. Current regulator block diagram

The open loop speed regulator uses the previous dq output angle to generate the next “measured” angle. This rotates the current vector with the given speed reference. The open loop speed reference has a feedback from the high pass filtered output active power to dampen rotor oscillations. The current reference is given by fixed parameters giving a rotating output current vector with fixed magnitude.

The closed loop regulators use the estimated dq angle and speed of the flux model. The d current reference is normally 0, but can be negative to field weaken the generator for high speeds. The q current is given either by an outer regulator in the speed and dc regulator mode, or calculated directly from the torque, power or k-omega-square reference. The q current reference is limited by limit calculated from the torque, power, speed and dc voltage.

The speed reference is ramped using a reference filter limiting the acceleration and braking, these limits are individual for the open and closed loop.

Table 1. Description of acceleration and brake limits

Measurement	**Acceleration limit**	**Brake limit**
Torque	General maximum acceleration torque, useful to limit motor currents.	General maximum braking torque, useful to limit motor currents.
Power	Maximum acceleration power. Gives a torque limit calculated as power over the speed.	Maximum brake power. May be useful to limit temperature of a brake chopper.
Speed	Limits acceleration torque when speed is above the speed limit to avoid overspeed. Useful in e.g. torque mode.	Limits braking torque when speed is below a speed limit. Useful to avoid stopping the motor and failing due to invalid flux model.
DC voltage	Limits acceleration torque when dc voltage dips below a limit to avoid dc undervoltage and overtaxing the dc source.	Limits braking torque when dc voltage rises above a limit to avoid dc overvoltage. Very useful if brake chopper is not installed.

The reference for each regulator mode can be set individually using the CAN bus interface. The limits can also be set.

If the generator is overspeeding, the drive will trip, and the generator contactor be opened. This fault can then be acknowledged by the system and the drive restarted when the speed has dropped below the overspeed limit again. The speed measurement is not dependent on the inverter being active. Restarting the system when overspeeding will cause a new fault without closing the contactor.

4 SCADA

The SCADA system will provide supervisory control for the system as well as monitoring and logging data. Condition monitoring will be integrated with the SCADA system.

4.1 SCADA Hardware

RedLion Graphite Controller have been selected as the hardware for the SCADA system. These allow for PLC & Data Logger to appears as a web server at shore station from which we can create easy HMI for control and monitoring of device, and download of data.

Figure 8. SCADA hardware

4.2 Condition Monitoring System (CMS)

The CMS monitors the structural, electrical and relevant environmental condition of the TidGen 2.0 system from deployment through decommissioning. All external sensors mounted on the system route to the Sensor Integration Module (SIM) where a high-speed data acquisition system is located. The SIM performs two functions:

1. Continuously monitor vital sub-systems for failure and if a failure occurs indicate to the control system to perform an emergency stop.
2. Record and store all operational data for future review of system performance to allow for diagnosis of any failures that occur and better understand the operational loading conditions.

The CMS continuously acquires and stores all sensor data tentatively for 24 hours, subject to change depending on sampling interval, storage capacity and logging practice. If at any time the operator requests historical data, the CMS sends a data file to the shore station for the specific times requested provided the data is stored on the CMS. The operator may also request real-time data streaming of most sensors. High-data rate sensors such as hydrophones and accelerometers are limited to averages and frequency responses at discrete time intervals.

4.2.1 Fault Monitoring

Components critical to the safe operation of the TidGen 2.0 are given allowable ranges for warnings and alarms. If any sensor records values outside the normal operating range, a warning is triggered immediately logging the last XX hours of data. A message is sent to the operator indicating an alarm while the system continues in normal operations. If any sensor records values outside the warning range, an alarm is triggered, and the last YY hours of data are logged. A message is sent to the operator indicating the fault and the system issues an emergency stop, triggering the tripped state.

The system cannot be re-started until the fault is cleared. In most scenarios, the fault is cleared automatically when the flow speed is reduced to slack tide. If the fault occurs due to a communications or sensor failure, a reboot can be issued to attempt to rectify the problem or the device will need to be recovered and repaired. Under no condition shall the operator be able to override a fault in a system critical component.

4.2.2 Operational Monitoring

Secondary to fault monitoring, additional sensors are integrated into the CMS to monitor the overall system performance, providing additional data for fault diagnosis and verifying system analysis models. Many of these sensors are specific only to the R&D model of the TidGen 2.0 and are not necessary for the safe operation of the commercial system. This includes, but is not limited to, depth and motion of anchors, mooring line inclination, and TidGen 2.0 rigid-body motion.

4.3 Sensor List

Initial sensor selection is detailed below.

Key	R&D Only	Commercial system						
Intrumentation Descrption & Use								
Intrument Type /Name	Use Description	SCADA Integrated or Stand-Alone		QTY	Acquisition Frequency	Reporting Frequency	Part of Safety Circuit?	Alarm
100 - Substructure and Foundation								
Load Cell (Mooring Line)	Actively measure mooring line tension	Integrated		2	1 Hz	Hourly	Yes	Yes
Pressure (Anchor)	Measure sea floor depth to determine TGU height in water column	Integrated		1	Per minute	Hourly	No	No
Inclinometer (Mooring Line)	Measure mooring line angle and TGU position	Integrated		2	Per minute	Hourly	No	No
USBL/LBL (Anchor)	Measure anchor location and sliding	Integrated		2	Per Minute	Hourly	Yes	Yes
210 - Turbine								
220 -Mechanical Drivetrain								
Hydrophone (bearings)	Measure vibrations in bearing for health monitoring	Integrated		2		Hourly	No	Yes
Accelerometer (bearings)	Measure vibrations in bearing for health monitorig	Integrated		10	1000kHz	Hourly	No	Yes
Temperature (bearings	Measure temperature of PCD bearing for health monitoring	Integrated		10	Per Minute	Hourly	Yes	Yes
RPM (driveshaft)	Provide independent measurement of driveshaft RPM	Integrated		2		Hourly	Yes	Yes
230 - Chassis and Buoyancy								
Heading (System)	Determine heading TidGen	Integrated		1	Per Hour	Hourly	No	No
Tilt, Roll Sensor (System)	Determine relative orientation of TidGen during deployment and operation	Integrated		1	Per Hour	Hourly	No	No
Humidty	Measure humidty in buoyancy tanks to detect moisture (leaks)	Integrated		6	Per Minute	Hourly	Yes	Yes
Pressure Sensor (Hull)	Measure water depth through pressure	Integrated		1	Per Hour	Hourly	No	Yes
Accelerometer (System)	Determine acceleration of TidGen during deployment and operation	Integrated		3	1Hz	Hourly	No	No
Pressure Sensor (Buoyancy)	Measure pressure of buoyancy tanks to detect leaks	Integrated		6	Per Minute	Hourly	Yes	Yes
240 - Generator and Electrical								
Winding Temperature	Measure winding hot spot temperature in select coils for health monitoring	Integrated into Generator		3		Hourly	Yes	Yes
Encapsulation Temperature	Measure encapsulation hot spot temperature in select coils for health monitoring	Integrated into Generator		3		Hourly	Yes	Yes
Accelerometer (Connector Box)-3 axis XXXHz	Measure accelerations in side connector box for health monitoring	Integrated into Generator		1		Hourly	No	No
Oil humidity	Measure oil humidty for health monitoring and leak detection	Integrated into Generator		1		Hourly	No	Yes
Magnetic force sensor	Used for magnetc health assesment and as speed sensor	Integrated into Generator		3		Hourly	No	Yes
Oil Level	Measure oil level in compensator	Integrated		1		Hourly	Yes	Yes
Oil temperature	Measure oil temperature for health monitoring	Integrated into Generator		1		Hourly	Yes	Tes
DC Link Voltage	Measure output DC voltage of the converter box	Generator CAN Bus						
Output Real Power	Measure output real power at the converter box	Generator CAN Bus						
Output Apparent Power	Measure output apparent power at the converter box	Generator CAN Bus						
Heat sink Temperature	Measure heat sink temperature for condition monitoring	Generator CAN Bus						
Motor RPM	Measure RPM of the motor	Generator CAN Bus						
Estimated Torque	Measure torque seen by the motor	Generator CAN Bus						
Motor Current	Measure peak line current at the motor terminals	Generator CAN Bus						
Motor Voltage	Measure peak phase voltage at the motorterminals	Generator CAN Bus						
Controller card Temperature	Measure controller card temperature for condition monitoring	Generator CAN Bus						
NTC1 Temperature	Measure output NTC temperature of the converter box	Generator CAN Bus						
NTC2 Temperature	Measure output NTC temperature of the converter box	Generator CAN Bus						
NTC3 Temperature	Measure output NTC temperature of the converter box	Generator CAN Bus						
250 - SCADA and Controls								
Temperature (SIM Enclosure)	Measure temperature of SIM enclosure for health monitoring	Integrated		1	Per Minute	Hourly	No	Yes
Humidity (SIM Enclosure)	Measure humidity to detect leaks in SIM enclosure	Integrated		1	Per Minute	Hourly	Yes	Yes
300 - Electrical Infrastructure								
Voltage Transducer	Measure incoming TidGen line voltage	Integrated		1	>= 1 Hz	1-10min mean	No	No
Current Transducer	Measure incoming TidGen line current	Integrated		1	>= 1 Hz	1-10min mean	No	Yes
400 - Environmental Monitoring								
500 - Deployment System								
Load Cell (Line)	Measure tension in winch lines for deployment							
USBL	Measure device location during descent							
Differential GPS	Accurately measure ship position during deployment							
Compass	Accurately measure ship heading during deployment							

5 Development Path

The next step of development leading from this project would be to further develop the adaptive $K\omega^2$ controller on a tidal turbine to verify expected performance benefit by simulation.

The SCADA system specification will be completed.

6 Revision History

Revision	Date	Description	Author	Reviewer
00	10/25/17	Initial	J. McEntee	-