
ELEMENT: DII.2 FINAL REPORT ON OPERATION OF ELEMENT ON NOVA MI00-D

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1 INTRODUCTION

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme to develop and validate an innovative tidal turbine control system, using the tidal turbine itself as a sensor, to deliver a step change improvement in performance. This will demonstrate Effective Lifetime Extension in the Marine Environment for Tidal Energy (ELEMENT), driving the EU tidal energy sector to commercial reality. This was in response to the call LC-SC3-RES-11-2018: Developing solutions to reduce the cost and increase performance of renewable technologies.

This document relates to work undertaken as part of work package 11 and is submitted to satisfy deliverable D11.2 of the ELEMENT project.

The ELEMENT project has seen the development of a control system for a fixed pitch, seabed mounted, tidal stream turbine. The baseline for the control system was taken from Nova Innovation's M100 turbines deployed at the Shetland Tidal Array (STA), the world's first offshore tidal array operational since 2016. The control system was developed from this baseline with the aim of decreasing the levelised cost of energy (LCOE) through improvement of the turbine control system. Some aspects of the control system have remained unchanged, but most have been altered or are newly designed and developed during the project. The control system has been designed using experience and learnings from both the tidal and wind generation industries. Simulations were conducted on some of the control system modules to help validate the design and de-risk turbine operation using the control system.

The project has so far allowed for testing of the control system in Nova Innovation's RE50 turbine during onshore testing at the ORE Catapult (OREC) test facility in Blyth, UK and further in-water testing using the same turbine at Chantier Bretagne Sud (CBS) site at the Ria d'Etel estuary, Brittany, France. The onshore testing allowed validation and comparison between versions of the control system during simulated and repeatable tide flow conditions while the estuary testing allowed for further validation and performance testing of the control system in a real-world environment. The final test phase of the project was to deploy the control system on a production scale turbine to better assess the LCOE reduction that can be achieved through the new control system. One of the three latest generation M100-D turbines at the STA is being used for this final test phase, offering an improved representation of state-of-the-art turbine technology, compared to onshore and estuary testing, with commercial site conditions that the new control system can be deployed on.

This report will document how the ELEMENT control system was deployed and operated on an M100-D turbine, along with learnings obtained from this test phase. Resulting data will be presented to demonstrate the improvements made by the control system and how this data is helping further design optimisation of the control system.



2 IMPLEMENTING ELEMENT CONTROL SYSTEM ON M100-D

Most of the ELEMENT control system is software based with some defined hardware components required to assist in improved control. One of the M100-D turbines deployed in STA, turbine T4, was therefore upgraded with some new hardware during a maintenance interval. This consisted of new or improved sensors installed inside the turbine, improved communication hardware for communicating with the onboard drive system and improved networking hardware to accommodate transferring more data back to shore where it could be processed and stored to help with testing analysis.

The hardware upgrades were all tested and commissioned as part of the turbine maintenance intervention along with the associated software upgrades for connecting to the hardware. Most control software changes were made over time to the deployed turbine as the software component of the control system was further developed and improved.

The control system software code consists of multiple modules that can be written, checked and then tested by simulation on a computer before being remotely downloaded to the turbine. Some modules were new, such as those relating to the newly installed hardware, while some existing modules were modified as part of an iterative improvement process throughout the testing period. This report will cover only the modules that underwent testing within this test phase, particular focus is given to the modules within the turbine controller – the major component of the control system that controls the turbine speed, torque and export power.

2.1. Flow Velocity Measurement System

An additional hardware upgrade to the T4 turbine was the integration of hardware to the turbine to incorporate two external acoustic doppler current profile (ADCP) sensors. These were not required as part of the ELEMENT turbine control system but were installed to assist in assessing the performance of the control system. The design for the ADCP system included two Nortek Signature 500 sensors, installed onto ballasted frames that were deployed on the seabed ahead and behind the turbine – see Figure 1. A waterproof cable with waterproof connectors was then used to connect the ADCPs to the turbine. The connectors on the turbine provided power and ethernet communication to each sensor enabling the data to be routed through the turbine network back to shore via the turbine export cable where it was further processed. This provided real time flow velocity measurement of the uninterrupted tide flow towards the turbine rotor, for both flood and ebb tides.



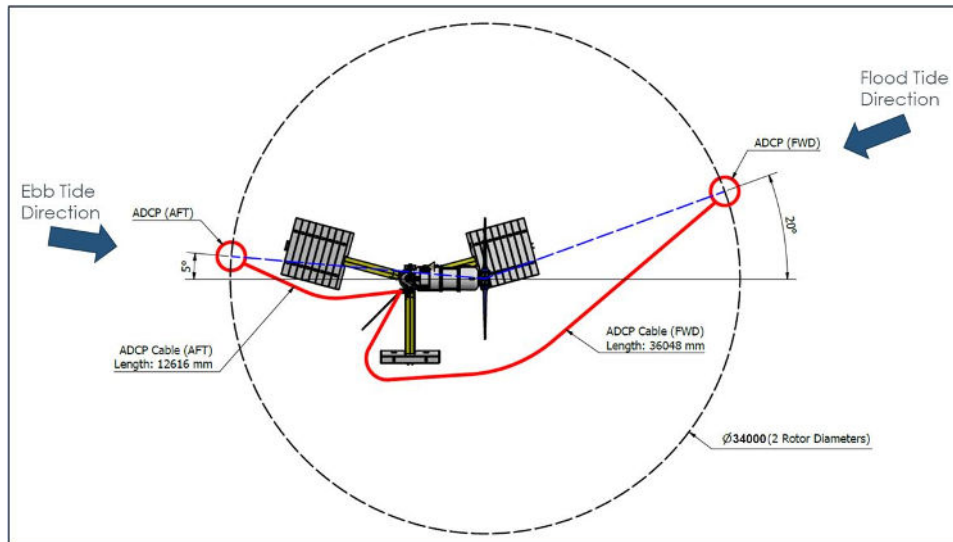


Figure 1: Plan view showing the deployed M100-D turbine and ADCP locations.

The ADCPs were initialised via a deployment file created using proprietary Nortek software. The deployment files dictate all the necessary parameters to set up the measurement schedule of the ADCP. For instance, number of cells, cell heights, frequency of measurements and environmental constants are all described by the deployment file. Often, ADCPs are deployed and left for a period before recovering the instrument and then extracting the data. As described, the ADCPs in this instance are directly connected to the M100-D turbine allowing for real time data transfer as well as modifying the deployment settings when required. Figure 2 shows the simplified flow of data from the ADCP to cloud storage.

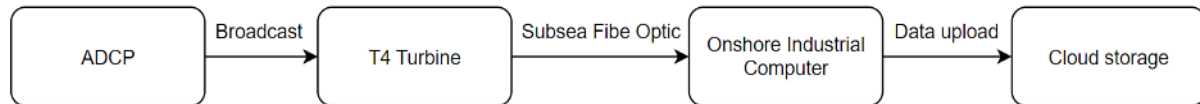


Figure 2: Data flow from ADCP's to cloud storage.

At first, the ADCP broadcasts the velocity and other data down the ethernet cables through the turbine towards shore where it is processed by software scripts running on onshore computing hardware. Separate software scripts then format the data and upload it to cloud storage. Once in the cloud, the data can be downloaded for further post processing and analysis in parallel to the time synchronised turbine operating data.

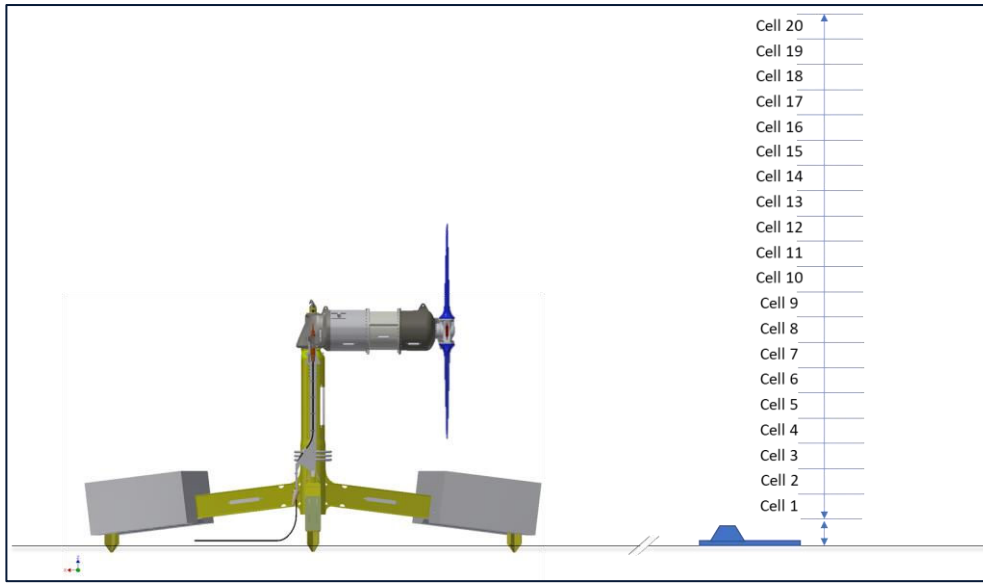


Figure 3: Side view of M100-D turbine and measurement cells in the water column for each ADCP

Figure 3 shows the side view of the M100-D turbine and the positions of the measurement cells of the ADCPs. The cells 4 to 12 inclusive cover the rotor swept area. As part of the post processing, it was necessary to calculate an effective average velocity of the incoming tidal flow across the rotor area, in both flood and ebb directions. The ADCPs provide the speed and direction of the tidal flow, and as such, the perpendicular component to the turbine blades of the tidal flow was extracted for each cell. A rotor swept area rated average velocity known as the velocity performance, was then determined using Equation 1.

$$U_{perf} = \left(\frac{1}{A} \sum_{k=4}^{k=12} U_k^3 * A_k \right)^{\frac{1}{3}}$$

Equation 1: Velocity Performance Equation

Where U_{perf} is the velocity performance, A is the rotor swept area, k is the cell number, U_k is the blade perpendicular velocity component and A_k is the swept area covered by the rotor for a specific cell. The velocity performance is an important metric that is later used for the verification and validation of damage statistics.

2.2. Turbine Auto-Start Module

As there is no flow speed sensor installed on the turbine, there is a need to create a start-up command within the turbine control system to know when to start rotating the rotor again after a period of slack tide – where the tide flow speed is too low to generate electricity. Several methods were explored within the project design work to calculate an accurate time for a turbine to start up and generate. Starting too soon results in consumption of power to motor the turbine and starting too late results in lost electricity generation. A target accuracy of starting up within +/- 5 minutes of the optimum time was defined as part of the test plan. The M100-D was used to test the developed strategies to produce this start up command automatically within the control system without relying on operator input.

2.3. Electrical Braking Module

As the turbine is constantly exporting power to the connected grid during operation, a loss of grid or other load rejection event, such as an onshore circuit breaker opening, results in the turbine losing the ability to export power. This loss of power equilibrium within the turbine drivetrain results in the shaft starting to accelerate as control is lost by the onboard drive system. For a fixed pitch turbine, this acceleration would often be countered by activating a mechanical brake that applied a large braking force on the shaft to cause fast deceleration. In the first instance, the ELEMENT control system instead uses electrical braking to prevent loss of control of the shaft speed in response to load rejection and thereafter provides a smooth deceleration of the shaft. This reduces the peak torque loading applied to the turbine in such events, resulting in a reduced load cycle count throughout the turbine lifetime. Successful performance criteria were that the drive system would retain control of the shaft speed and decelerate to near zero speed before enabling the parking brake to hold the shaft at standstill.

2.4. Turbine Controllers

The baseline turbine controller used at the start of the project was the ‘basic speed controller’. During the design phase of the ELEMENT project two new controllers were developed – the Advanced Speed Controller (ASC) and Advanced Torque Controller (ATC). These two controllers were modelled and tested through simulation that resulted in an initial phase of refinement of each. They were then further tested during the project’s onshore testing and estuary testing phases using Nova Innovation’s RE50 turbine, providing for some development and de-risking prior to testing on a commercial M100-D turbine at the Shetland Tidal Array. From observations made during testing and learnings made throughout the project, an additional controller was developed at a later stage than the original two. This controller – named the Advanced Position Controller (APC) – is an optional accompaniment to the advanced torque or speed controller. It is a novel controller and provides additional control influence on turbine operation based on the rotational position of the rotor.

Each controller was simulated specifically for the M100D turbine model and the site conditions present at the STA). Checks and tuning were conducted through simulation to ensure controller stability and to minimise torque fluctuations in the turbine that contribute to fatigue damage. This is an important stage of adapting the ELEMENT control system for a specific turbine and site. The ability to make such adjustments is a strength of the ELEMENT control system enabling it to be deployed in other tidal stream turbines and sites with only minimal adjustments.

Having the ADCP measurement system installed, provided for flow conditions to be measured alongside real world operation of the turbine with each deployed turbine controller. The test plan scheduled each controller to be tested over varying tidal flow conditions and the necessary data to be captured to assess its performance. With the cyclic nature of the peak flow speed of each tide, more time was required to generate results than that for the simulation work or onshore testing but delivered real evidence of performance from the real-world tide conditions with a production scale turbine. The three controllers were loaded into the M100-D control system and modifications made so that any controller could be selected to control the turbine power generation throughout testing.



3 TESTING RESULTS

The control system was loaded into an M100-D turbine at the STA with the features as described in Section 2. The test plan allowed for early project deployment of some lower risk modules of the control system to provide long term observation of the behaviour and performance. Other modules, such as the turbine controllers, required specific tide conditions to accommodate a period of low-risk commissioning prior to allowing them to operate autonomously across multiple tide cycles. To capture the full range of tidal conditions, typically a period of a full lunar month (28 days) is required to assess a controller fully. This period covers 2 spring tide cycles. This adds considerable time to the testing period, and so efforts were taken to overlap testing of multiple modules during the test period to maximise the effectiveness of the testing phase.

3.1. Turbine Auto Start Module Testing

The first method that was tested for this module, was to use historical turbine stop times to predict the next startup time. The turbine stops once the tide flow reduces to a speed where the turbine is no longer exporting power and the time can be calculated between this stop time and the optimum start time. Initial work was completed to calculate this time using historical stop times to predict the future start time. Comparing these predicted times with the known optimum startup time showed that this method had lower accuracy and repeatability. The accuracy was typically about ± 30 minutes, which was short of the ± 5 minutes target.

The second method that was designed and tested, was using an external water pressure sensor that was installed on the turbine as part of the hardware upgrades. This provided direct measurement of the water height above the turbine with an algorithm in the control system software calculating the rate of change of flow and creating a predicted flow speed from this. The implementation and deployment of the sensor was successful, with a sample of the measured pressure values shown in Figure 4.



Figure 4: Pressure reading, in Bar, from the external pressure sensor on M100-D over one month

Figure 5 shows the relative power output (blue) from the turbine for several tide cycles compared to the accurate pre-modelled tide (yellow) and the flow speed derived from the pressure sensor (green). The derived pressure was used to attempt to predict the optimum starts time, but there was insufficient accuracy and repeatability using this method which also fell short on the ± 5 minutes target for optimum start up times.

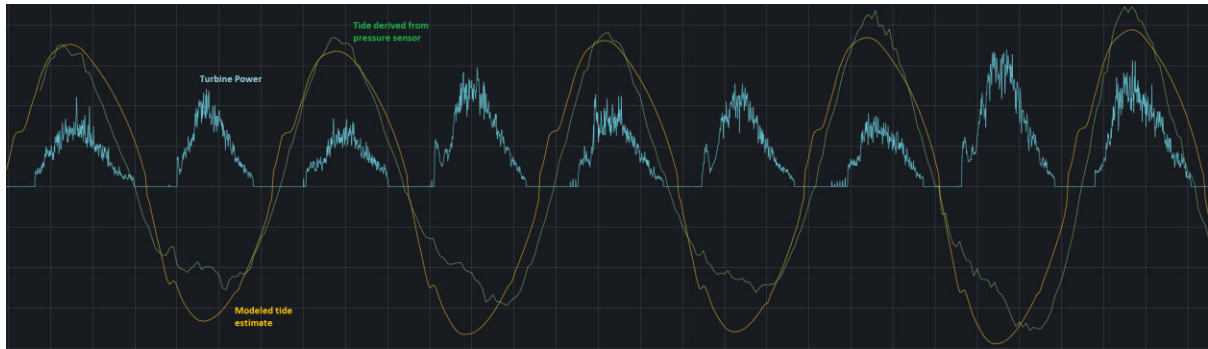


Figure 5: Tide speed derived from rate of change of sea pressure (Blue trace: turbine power output; yellow: accurate model of tide flow speed; green: calculated flow speed from pressure sensor measurement)

A final method was tested, using existing sensor data that all M100-D turbines generate – the particular sensor(s) used being a sensitive detail of intellectual property. Using this sensor data enabled a correlation to be made between the tidal flow speed and real-time sensor data within the turbine. Testing on the M100-D turbine enabled the data to be gathered over a long period of time. An algorithm was written to adaptively adjust a threshold by learning the data behaviour over time. The data and algorithm produced a threshold that was compared to a filtered component of real-time data from the turbine to generate a start command within the control system. Testing of this method required a lot of development effort, but has proven successful in operating accurately across various tide flow conditions and delivers close to the ± 5 minute target. This has resulted in an increase in turbine operation, with observed data showing the turbine typically starts when the flow speed is 0.3m/s lower than using the original startup method. This change relates to an improvement of 0.9% annual turbine energy yield. Figure 6 shows an example comparison between the original method where the turbine often missed potential generation at the start of a tide cycle, and the new method where the turbine starts earlier and harnesses more available energy at the start of a tide cycle.

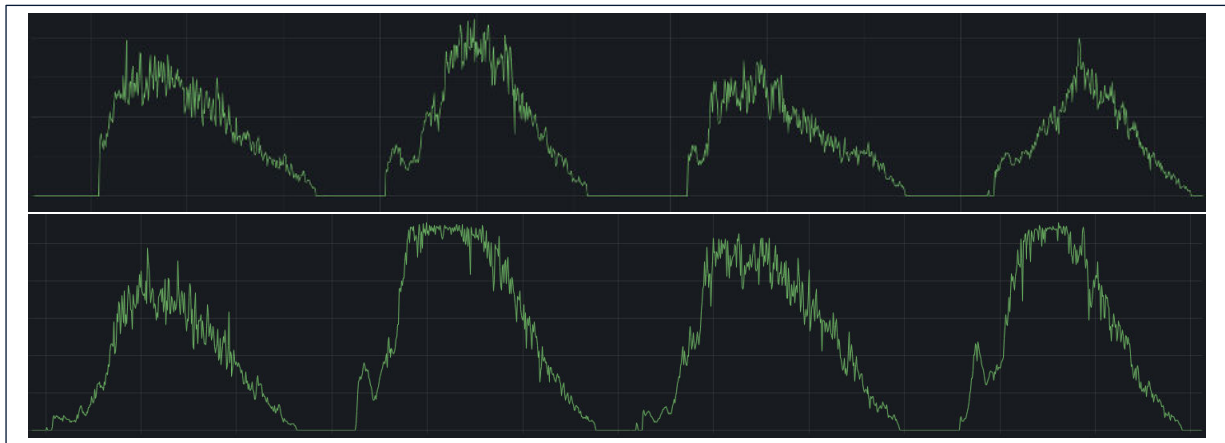


Figure 6: Comparison between original startup control (top) and startup control using sensor data learning algorithm (bottom)

3.2. Electrical Braking Modules Testing

The electrical braking module is triggered to operate when a grid loss or load rejection event occurs. Manually initiating such an event adds risk to the turbine and so during the testing of this module we relied on such an event occurring under normal operation of the turbine. With the nature of the isolated electrical grid in Shetland, grid disconnections can occur more commonly than on the Scottish mainland, and so there were several such disconnections during the testing

phase. The electrical braking module operated as designed during each event and the mechanical brakes did not need to actuate until the shaft was at near zero speed.

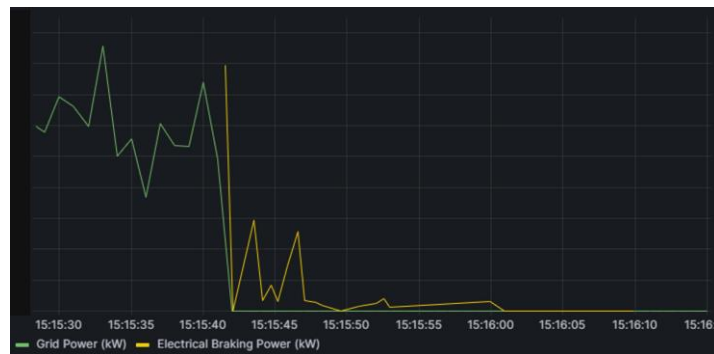


Figure 7: Grid power and electrical braking power during an example grid loss event



Figure 8: Speed and torque time series during the same grid loss event

These test results were similar to those during the onshore testing phase and validate the operation of the system as per the design stage expectations. For example, that the system does reduce peak structural loading on the turbine and substructure by reducing the number of mechanical braking events that the turbine experiences during its lifetime.

3.3. Turbine Controller Commissioning

Each of the controllers required careful commissioning on the M100-D turbine to ensure that the turbine would not be put at undue risk of damage by unexpected torque loading or resonance. Previous work during onshore and estuary testing of the RE50 helped to reduce risk of undesirable control behaviour but could not completely remove all risk due to the stronger tidal conditions and differences in the drivetrain between the two turbine models.

The advanced speed and advanced torque controllers were deployed separately on tides with increasing flow speeds. Each operation of the turbine was assessed for stability and controller performance, then refined by way of controller parameter adjustment. Each commissioning run of the turbine allowed for an increase in power up to rated power operation and provided further confidence in each controller operating with minimum risk to the turbine. Later, once the advanced torque controller was further tested, the advanced position controller was commissioned using the same method.

During commissioning and testing, high volumes of data were generated from the ADCP and turbine operating data. Analysis tools were utilised to assess the stability and performance of the controllers using this data. Constant turbine data capture was performed by Nova's historian data system (2Hz sampling) assisted by on-request data capture using Siemens TIA Portal STEP7 software (50Hz sampling) and ABB Drive Composer software connecting to the drive system

(250Hz sampling). Data was analysed using Nova's in-house historian data system for time domain analysis and MATLAB and LabVIEW for frequency domain analysis. Frequency domain analysis was used to create Fast Fourier Transforms (FFTs) and Power Spectral Density (PSD) plots to locate any undesirable frequency components or resonances and so aid design of filtering and other controller parameter changes. Any controller re-design such as parameter changes were checked through modelling and simulation for stability such as phase and gain margin analysis using Bode plots.

3.4. Turbine Controller Assessment

Advanced Torque Controller

Once the advanced torque controller was commissioned, it could be operated with improved understanding and reduced risk to the turbine. This then enabled a period of testing and tuning to commence where the turbine operating data could be gathered and analysed to identify further improvements that could be made to the controller. This process was conducted iteratively to refine the controller during the testing period to improve the controller performance. One of the many balances that was sought in the controller performance assessment was between favouring tight control of the turbine power and shaft speed while also trying to minimise torque fluctuations that add to turbine damage. Once these tuning steps were completed, the controller was operated for over a month to allow data gathering from the turbine in parallel with synchronous ADCP flow data. This data was post-processed using tools developed during the project that used the flow velocity to create summary turbine operating data across various flow speeds in both the flood and ebb tide directions. This summary data was then used to generate electricity yield and fatigue equivalent damage ratings for each flow speed.

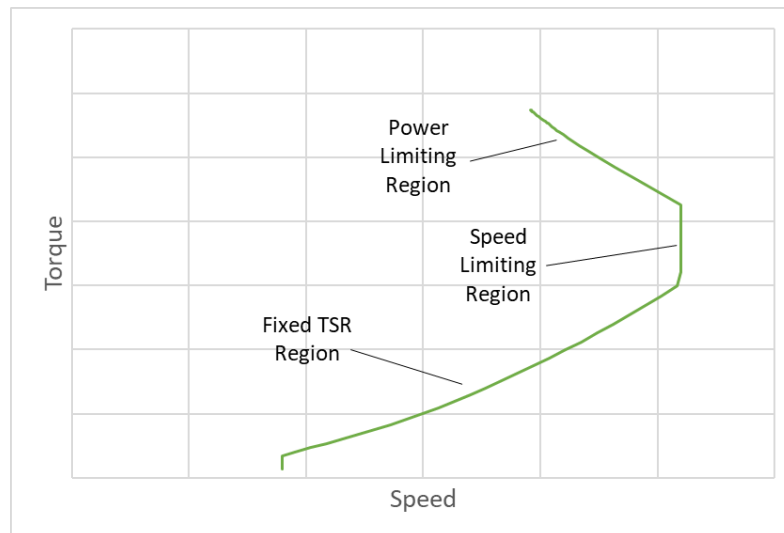


Figure 9: Optimum operating curve for a fixed pitch stall control turbine

The ATC was proven to provide a good level of control of the turbine once the tuning was completed and the controller operated over the subsequent month. Some of the controller performance was best assessed by experienced Nova Innovation engineers analysing the time series data from the turbine operation and using in-house metrics to assess the performance. Additionally, statistical analysis was conducted to allow quantitative assessment of the performance, some of this is shown below. The controller was observed to provide very good level of control on maximising power during the fixed TSR region (see Figure 9) of operation, by keeping very close to the optimum operating curve as shown in Figure 10. The graph shows a small deviation at lower speeds, but

this has a very minor impact on power production. Otherwise, the controller adjusted very well to changes in the flow speed by adjusting the turbine operating torque to maintain operation close to the optimum operating curve.

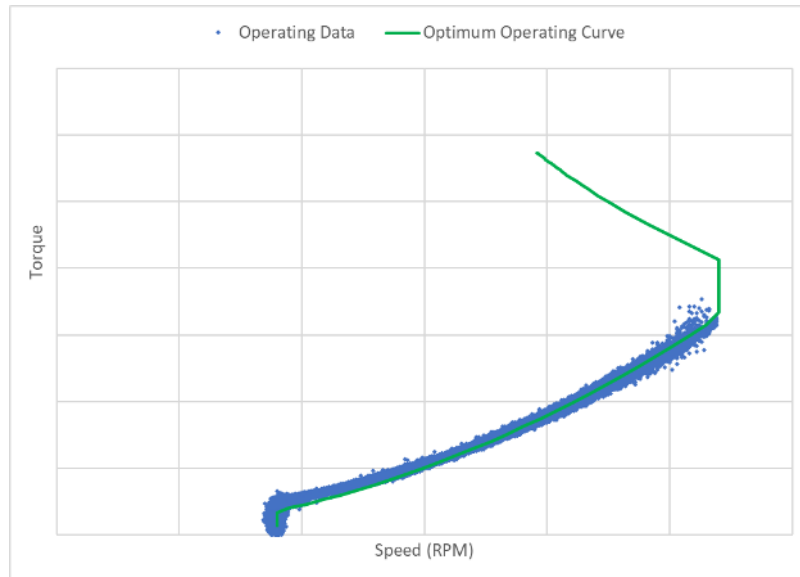


Figure 10: ATC operating data for fixed TSR operation

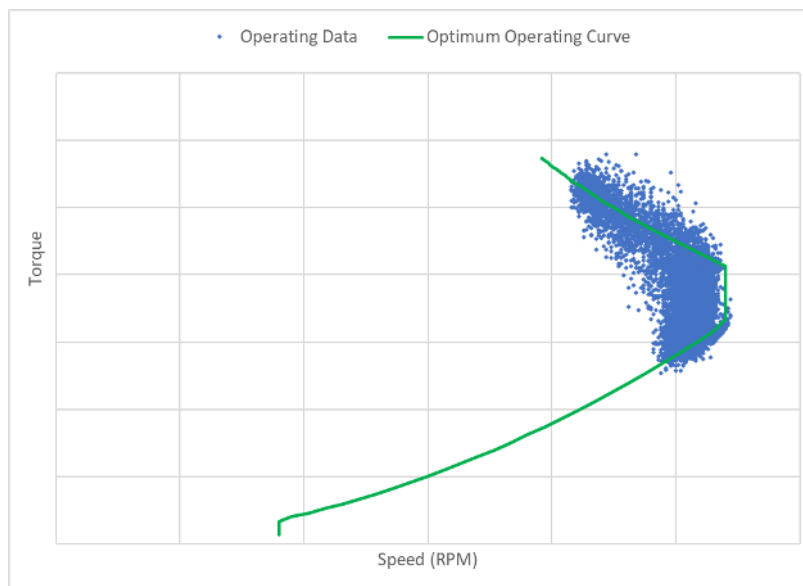


Figure 11: ATC operating data for speed limiting and power limiting regions

Figure 11 shows operation at the speed limiting region and power limiting region for the ATC. The controller was adjusted to allow more speed tolerance – as can be seen by the spread in the operating data – at the speed limiting region as this was found to reduce torque fluctuations. The maximum speed limit was consequently reduced slightly to keep the upper speed values below the upper speed limit. This reduction in speed resulted in only very minor reductions of power – the rotor torque increases as the speed is reduced in this region – but reducing speed to accommodate higher speed variation results in a reduction of torque fluctuation. The stall control, or power limiting, region, is where the turbine produces most of its energy yield and is therefore the region that most of the tuning adjustments were focused on. The controller was able to stay close to the optimum curve, but deviations are a natural consequence of a feedback control loop where the

turbine must always respond to changes in flow speed only once they have been observed in the turbine generated power. In this region, the focus was on minimising power and torque peaks and large fluctuations that increase fatigue damage to the turbine. To achieve the operation shown above, tuning was applied to the controller to balance maximum power production whilst minimising torque fluctuations by studying data sets from each parameter adjustment.

To assess the performance of the controller: speed, torque and power data was collated for the turbine operation and used to calculate yield and fatigue equivalent load damage rating. This data could then be compared to data for the baseline controller to show the improvement from the new controller. As part of this comparison, sampled ADCP data was compared to the existing flow speed model that was used to assess the baseline controller performance earlier in the project. Figure 12 shows an outline of this method using a conversion model generated from ADCP data and modelled flow data for the same period. This conversion is not suitable for conversion of short-term time series, as it cannot account for short term turbulence and flow variations, but it is reliable for longer term time averaged data such as that used in assessing several weeks' worth of data from the baseline and the M100-D testing data.

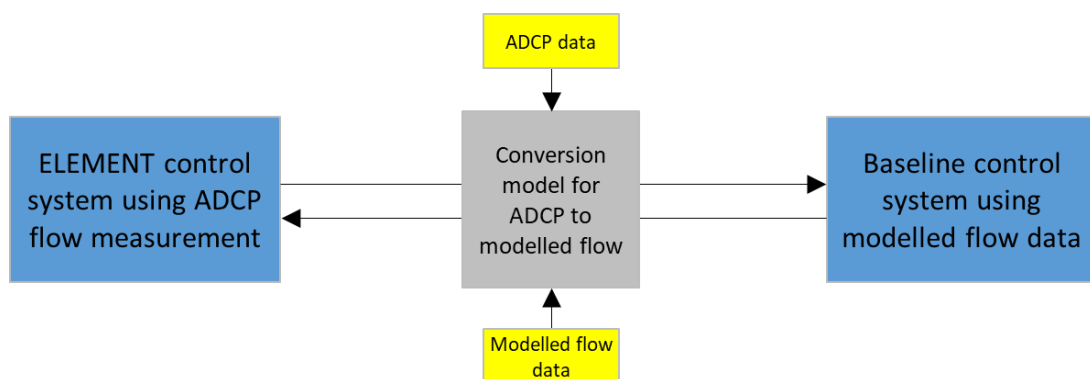


Figure 12: Conversion method to allow comparison of ADCP flow speed data with modelled flow speed data

Using the ADCP data, the operating data from the advanced torque controller was categorised into bins of similar average flow speeds. For each flow speed bin in both flood and ebb tide direction, the average operating speed, torque and power was calculated as well as fatigue damage equivalent loading using a rain-flow counting algorithm. This provided typical operating and performance assessment of the controller at various flow speeds in each tide direction. The next step of processing was to multiply the data in each flow speed bin by the occurrence (in hours) of that flow speed occurring over one year at the STA site. This resulted in a distribution that represented the annual metrics that the controller could be expected to produce, with the yield and fatigue damage being of most benefit to allow comparison with the baseline controller.

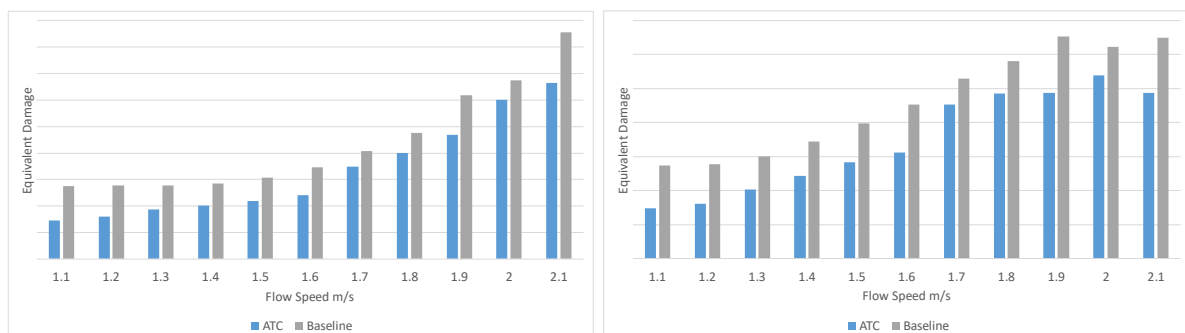


Figure 13: Comparison for ATC and baseline controllers across flow speeds for fatigue damage ratings (L); additional weighting by flow speed occurrence (R)

Figure 13 shows an output from the above analysis method, where the fatigue damage equivalent loads are shown across a subset of flow speeds for both the ATC and baseline controllers. The right-hand graph demonstrates the importance of further weighting this data by occurrence of each

flow speed and shows that while fatigue damage is worse at the highest flow speeds, the overall turbine fatigue damage is more evenly distributed across flow speeds once flow occurrence is accounted for. Regarding the comparison data shown in Figure 13, the ATC shows consistent reduction in fatigue damage across the flow spectrum when compared to the baseline controller, confirming the benefits of the controller in reducing torque fluctuations that were also observed by the test engineers viewing the time series data during testing.

Similar analysis was conducted on the turbine yield, and again used occurrence weighting to demonstrate the change in annual electricity production (AEP) that could be expected from the turbine when using the ATC in comparison to the baseline controller over a year of operation. Figure 14 shows the results of this analysis and indicates that improvements can be achieved across the full subset of flow speeds when using the ATC instead of the baseline controller.

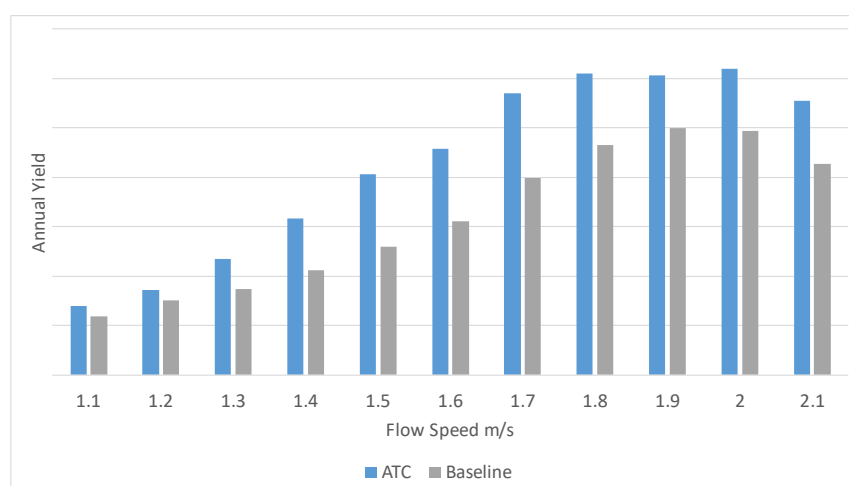


Figure 14: Comparison of expected annual yield for a range of flow speeds for ATC and baseline controllers

The above data presents the conclusion that the advanced torque controller is able to increase yield and decrease fatigue damage when compared to the baseline controller, across the range of operating flow speeds. Figure 15 and Figure 16 show the conclusions of applying this analysis across the full lifetime of a M100-D turbine operating at STA. A 25% overall reduction in lifetime damage caused by fatigue is achieved, with a higher contribution from improvements in the flood tide direction than the ebb tide direction. Figure 16 shows a 34% improvement in lifetime yield from using the ATC, again with improvements on the flood tide contributing more than the ebb tide improvements.

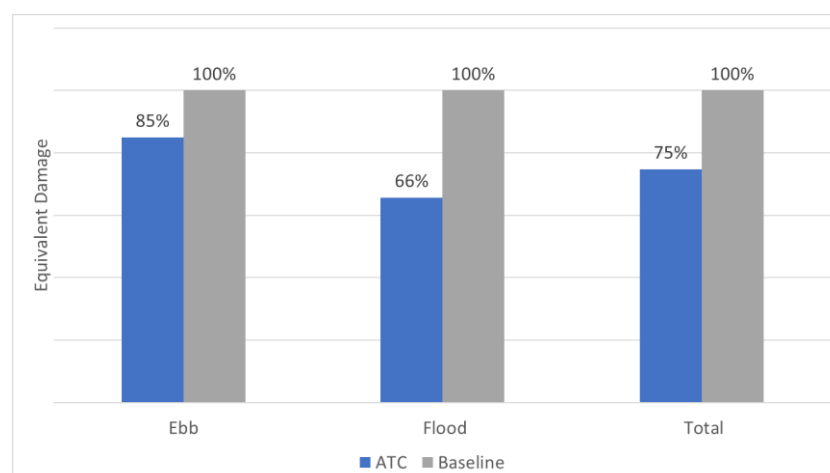


Figure 15: Comparison of fatigue damage ratings for ATC and baseline controllers (normalised to baseline value).

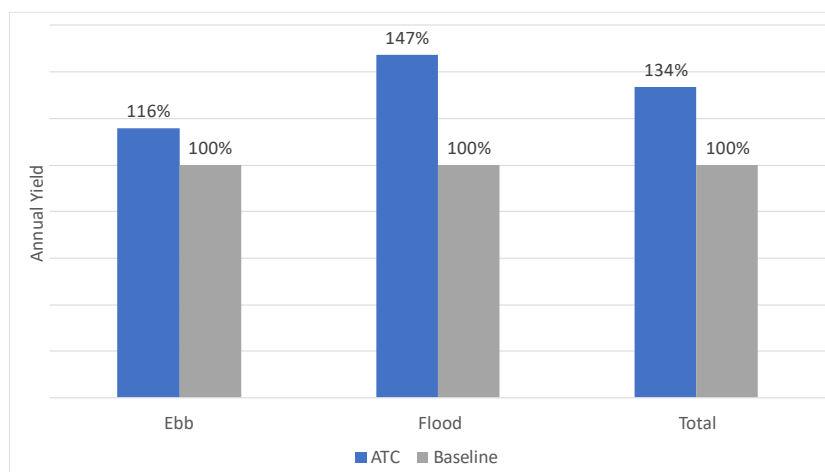


Figure 16: Comparison of expected annual yield for ATC and baseline controllers (normalised to baseline value).

The results of testing the ATC support the project objectives of reducing LCOE through increase in yield and reduction in damage caused by fatigue. These real-world results are consistent with what the onshore testing phase had concluded was possible and is validation of both the onshore testing and the design work simulations that proposed that such improvements could be realised in a real-world environment.

Advanced Speed Controller

The testing phase also included testing the advanced speed controller on an M100-D turbine at the STA. Initial commissioning showed the controller to be stable however further assessment and tuning of the controller during faster flow conditions, showed the turbine shaft speed and torque were liable to oscillate. While the magnitude of oscillation was relatively low and the turbine was operating within its operating limits, the presence of any oscillation is undesirable and could potentially lead to unstable control and excursion of speed and torque beyond the turbine design limits. Figure 17 shows an example of the observed oscillation where the lower frequency changes in torque are a result of the flow turbulence and the higher frequency that is common throughout the data set was unexplained oscillation.

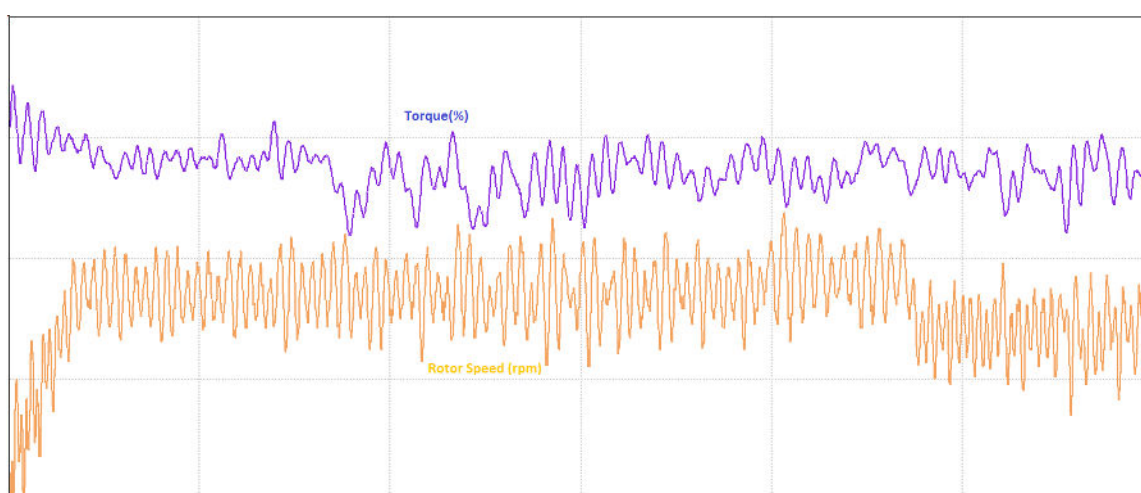


Figure 17: Example of oscillation on turbine speed (orange) and torque (purple) during ASC operation

Consultation was made with the drive manufacturer, ABB, who are a project partner, which resulted in changes to the drive operating parameters to attempt to remove this oscillation. The oscillation was still present after these adjustments and further analysis provided no clear cause. To make best use of the remaining time and available tidal conditions in the test phase, the decision was

taken to pause testing of the advanced speed controller and progress to testing the Advanced Position Controller which at this point had been fully developed.

Advanced Position Controller

The advanced position controller (APC) was designed to reduce some of the twice per revolution (known as 2P, where P is the rotor rotation frequency) torque fluctuation caused by tower shadow and the shear profile of the water column. The ATC and ASC have some capability to reduce these, but the APC adds an additional function to further reduce these 2P torque fluctuations. This 2P torque cycling effect is known to be a major contributor to turbine fatigue. Also, the resultant peak torque values can potentially cause the turbine to reduce power output as a protection function to prevent operating torque exceeding the turbine's torque limit.

The APC was tested after its commissioning stage was completed as per the described commissioning method above. This controller is different from the ATC and ASC in that it does not provide control for all regions of operation of the turbine across the range of flow speeds. Instead, the controller is designed to be deployed in parallel with either the ATC or ASC and only influences the turbine control during the stall operating region of the turbine where the turbine output power is being limited. Based on the progress of testing the standalone ATC and ASC earlier in this test phase, the APC was tested by deploying it with the ATC that was previously tuned and fully tested.

Testing of the APC commenced initially at low flow speeds to minimise risk of damage to the turbine. As a novel and sophisticated controller, it was only possible to fully verify its stability and fine tune it using real-world operating data. The controller was initially only operated while being fully supervised by Nova Innovation engineers and so the testing was restricted to daytime hours when the tide was at the relevant speeds needed for testing. Data was gathered from the testing to allow for tuning of the controller. After some iterations, the turbine began to demonstrate a reduction in the peak torque values during the stall operating region.

Figure 18 shows an example of a period of turbine operation with the APC switched on and off. The graph shows that the APC can reduce the magnitude of most of the 2P cycles. The lower frequency variations are due to the changes in tide flow speed. The 2P variation is caused by the turbine tower shadow and the shear effect of the water column. Importantly, the magnitude of the 2P variation has reduced resulting in less fatigue damage being caused and an increase in headroom between peak torque values and the turbine's operating torque limit.

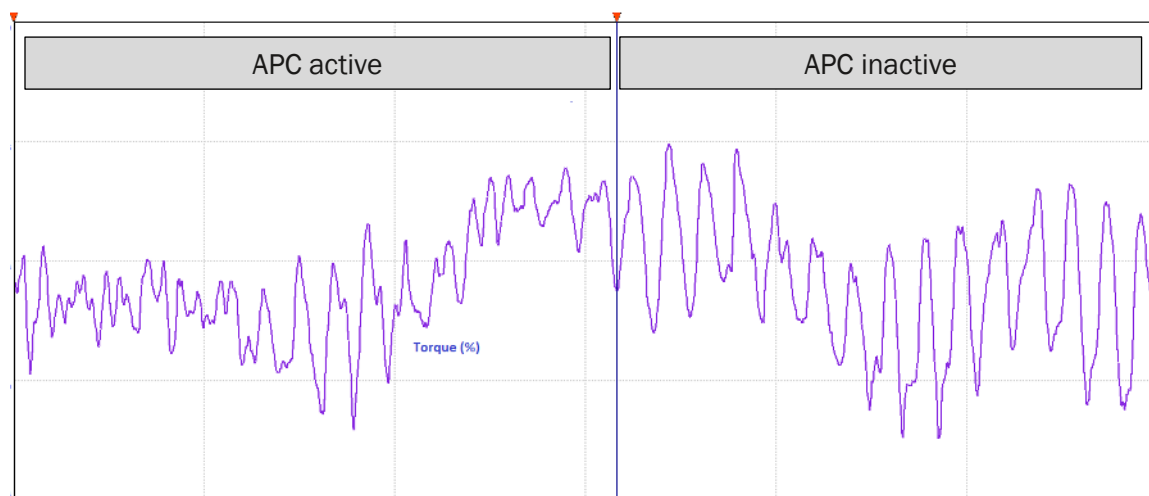


Figure 18: Turbine torque time series showing comparison between APC controller being active and inactive – note smaller amplitudes.

The APC testing was conducted at the end of the test phase, and the time limit of the project meant that a full suite of testing the APC across all tide flow conditions continues. The testing is continuing

on the M100-D turbine at the STA to assess the full performance and benefits of the APC but from the initial testing that has been done to date, it is expected that the turbine yield can be increased slightly by holding the output power more stable. From a very small dataset of the initial testing, comparison shows the yield is similar to when the APC is operating but the damage from fatigue was reduced by 25%. More test data over a longer period is needed to allow further conclusions to be generated about the lifetime improvement from operating the APC but this initial finding suggests a positive and significant improvement in fatigue reduction is achievable.



4 CONCLUSIONS

The development of a tidal turbine control system under the ELEMENT project has been demonstrated to have advanced significantly further through the deployment and assessment of the control system in real-world conditions on a production scale in-sea M100-D turbine. The control system turbine auto-start and electrical braking modules were successfully tested and demonstrated to provide improvements to the control system by allowing improved accuracy at start-up and reduced peak loading during shutdown events for load rejection scenarios. The auto-start module was demonstrated to achieve an 0.9% improvement in annual yield without any additions in turbine capital or operating costs.

The testing of the advanced speed controller identified oscillations in the turbine speed and torque that could not be identified and removed from operation of the controller. Analysis of the controller design does not indicate that the controller itself is the source. Additionally, the controller was operated during onshore and estuary testing on the RE50 turbine where this oscillation was not apparent. This highlights the importance of testing of the controller on a deployed turbine in real-world flow conditions in identifying issues that cannot always be predicted through modelling or even through risk reduction testing onshore or at a smaller scale. The initial advanced speed controller commissioning and testing has demonstrated that the controller can be deployed on a turbine and manage the turbine power production.

The advanced torque controller was demonstrated to deliver substantial improvements in turbine yield and fatigue damage. The controller tuning proved very successful in producing tight turbine control along the fixed TSR region as well as keeping the turbine speed below the upper speed limit, yet minimising torque fluctuations that would give a tighter speed control but increase fatigue damage. The power limiting region control was very similar to the initial modelling and simulation work at the design stage for the controller, provided confidence in the design methods used as well as validating the power production that can be achieved through stall control. These improvements were proven to significantly contribute to the project objectives of reducing predicted turbine loads, maximising energy yield and reducing the cost of tidal energy.

The novel advanced position controller added to the performance of the advanced torque controller by providing a reduction in peak torque values as well as reduced fatigue damage. The test time available allowed partial quantification of the advanced position controller performance, the initial results demonstrating that a reduction in fatigue damage was achievable as well as a reduction in peak torques. These gains help to extend turbine lifetime by reducing fatigue loads and peak torques. The turbine is therefore less likely to have to shut down or curtail operation in highly energetic tide conditions and will thus produce an increased energy yield.

The open points on the advanced speed controller and further assessment of the advanced position controller give direction on future controller development that is ongoing even beyond the ELEMENT project.

Real-world evidence has been produced that shows the ELEMENT control system can deliver substantial gains in reducing the levelised cost of energy for tidal stream turbines through improved control. The testing activities presented in this report support the project objectives in realising this reduction and moving tidal energy towards commercialisation.



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