Planning and optimising the construction and O&M strategy of tidal stream turbine arrays

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Abstract

The offshore operational costs of installing and maintaining tidal stream turbine arrays are considerable and are of great importance to the viability of the industry. Garrad Hassan (GH) has built on industry standard tools for the offshore wind industry to create two tools. The O2C tool has been developed for the analysis of environmental delays and the optimisation of a construction sequence. The O2M tool is used to optimise an operations and maintenance (O&M) strategy.

This paper is split into two sections, describing the different tools and a case study that was performed for each, with results, discussion and conclusion in each section.

The O2C model breaks the construction down into discrete operations that are simulated against an environmental time series to obtain duration distributions of individual operations. A Monte Carlo analysis is used to obtain project durations from the operation duration distributions.

The O2M model balances the cost of lost production due to turbine downtime and the cost of the resources for a maintenance strategy, to find an optimum strategy. It is used here to find the optimum number of crews and spare nacelles for a device with a removable and replaceable turbine.

Keywords: operations and maintenance, construction, tidal stream turbine arrays

1. Introduction

Tidal stream technology is now at the stage where several of the main developers are gearing up to begin deploying large arrays. On 16th March 2010, the Crown Estate announced the leasing of the seabed in the Pentland Firth for 600MW of tidal energy. With farm sizes ranging from 66 to 200 devices, optimising the installation and maintenance of these arrays is a significant step to improving the viability of these farms. The fast currents required for an effective tidal array site can severely limit access. In addition to the currents, there is also wind and waves to be contended with, creating a harsh environment to perform operations in; an environment considerably harsher than that of offshore wind turbines for which these tools were originally developed.

Operating in these environments requires specialised and expensive equipment. Effective use of resources will be the difference between a successful project and one that runs over budget. To produce an effective strategy, the risk to access posed by the site environmental factors, needs to be assessed and the assessment used to inform the strategy.

Harsh environmental conditions pose the risk of delay to construction projects. These site conditions will be dependant on the time of year; wave conditions in the UK are likely to be considerably more onerous during the winter. Additionally, if work is only performed during daylight, project progress can become very slow during the winter, where there may only be one tidal current window of opportunity for site access. During summer, with longer daylight hours and less onerous wave conditions, developers may get 3 windows of opportunity (slack water) to perform work.

Past studies by Garrad Hassan ([4], [5], [6]) in the offshore wind industry have shown that maintenance can make up a large proportion of the total lifetime cost of a farm. Maintaining turbines in such a harsh environment is costly and requires a well thought out strategy to do it effectively. In addition to the cost of the resources needed to repair the turbine, there is also the cost of downtime when the turbine is not generating any power.

Garrad Hassan have developed two tools which provide advanced analysis of construction and maintenance to aid tidal farm developers in developing strategies.

2. Construction

For every construction project there will be an optimum strategy for any given level of resourcing and building constraints. This section presents the O2C model methodology. A specific case study, using the O2C model is them described and a discussion of the results is provided.

2.1 Model methodology

The construction model consists of two parts. The first part is used to create duration distributions for the multiple operations that are required for the completion of the project. The overall project construction process is broken down into the main repeating operations of which it consists. Major operations are then further broken down into sub-operations, a series of smaller operations that are assumed to occur in series. The sub-operations are characterised by their ideal duration, their sea state limitations and whether they can be paused for bad weather or need to be completed in a single weather window. The ideal duration is the time it would take to complete the sub-operation without any weather constraints, rounded to the nearest hour. The sea state limitations are the maximum conditions the operation can take place in. Examples of operations would be installing the turbine foundations, or laying the subsea cables. Sub-operations are the further break down of the operations, such as loading of vessels, transit to site etc.

The operations are simulated against hourly environmental data for the site in the time domain. For each sub-operation the model tests the limiting conditions against the current sea state conditions from the time series. If the environmental conditions exceed the maximum conditions for the operation, then the sub-operation is either paused with progress so far recorded or it is stopped and progress is reset (depending on its characteristics) until the conditions allow it to continue again. When all the sub-operations are complete, the model records the operation as complete and logs its duration.

A database of durations of the simulated operations is built up, with the durations broken down into months to capture the seasonal variation in environmental conditions. These operation duration distributions can be used as an initial guide for as to the optimum time to conduct specific parts of the project, e.g. performing the most costly operations when conditions are likely to be best so the operation can be completed with minimum delays.

However, the main purpose of the monthly operation duration distributions is to provide inputs into the second stage of the model.

In the second stage of analysis, the operation duration distributions are combined with a set of sequencing rules to produce total project durations. Sequencing rules are applied to the model to cover a number of different features. A project may only have one vessel suitable for performing a group of operations. If this is the case, the next operation can not be started until the previous one is complete. Sequencing restrictions will also apply where an operation is physically dependant upon the previous operation being completed, for example, a turbine nacelle cannot be put in place until the foundations installed. Health and safety related restrictions that need to be adhered to are also included. For example, in the UK there are CDM zones, which may allow only one operation to take place on a turbine at once. In order to simulate the duration of a project, the model requires a start date and then builds the array based on sequencing restrictions and the duration distributions. Each operation length is taken from the relevant monthly duration distributions from the first part of the analysis.

A Monte Carlo analysis is run to take random P values (the duration from the distribution that a given percentage of the simulations are less than) from the different operation duration distributions. Once simulations are run, all with randomised P values, a project duration distribution for the proposed project is created. The project duration distribution allows developers to assess the risk of the project, with regard to likely duration and delays.

The project plan can then be altered, either by changing sequencing rules or having a different start date and the Monte Carlo analysis repeated, building up a database of duration distributions associated with different project strategies'. This database can then be queried to look at the results from any of the simulations to find an optimised solution.

2.2 Case study description and assumptions

For this paper, a comparison between two arrays consisting of different technology types has been performed. It focuses on a turbine with a gravity base and a turbine with a type of base that requires piles. In each case the analysis is performed for a farm size of 30 turbines, and one sub station.

The chosen site for this study was the Pentland Firth, given the recent leasing out of large areas by the Crown Estate. Unfortunately no long term measured environmental data was available for use in this study. However, a tidal time series was created harmonically from information in [1]. A representative wave time series from a different site was used.

To set up the model, operations required for the turbine installation needed to be defined. It was assumed that the operations were common to both turbines, with the exception of the installation of piled foundations. The assumption was that the gravity base device would have the turbine and foundations installed as a single operation, represented by the Turbine Installation, rather than as two operations as for the piled foundation device. The simulated operations are given here in sequential order:

- Array Cable Installation (CI)
- Export Cable Installation (CI)
- Foundation Installation (FI)
- Turbine Installation (TI)
- Array Cable Termination (CF)
- Export Cable Termination (CF)

- Array Cable Testing (CT)
- Export Cable Testing (CT)
- Turbine Commissioning (TO)

Each of these operations was defined by multiple sub-operations.

For the second stage of the analysis the turbines were grouped into small zones to reduce the set up time of the analysis. Sequencing rules were applied so that only one operation could be performed in each zone at once. Sequencing rules were also applied so that each operation could only be performed in one zone at a time. These were based on the assumption of having a single vessel per operation.

2.3 Results analysis

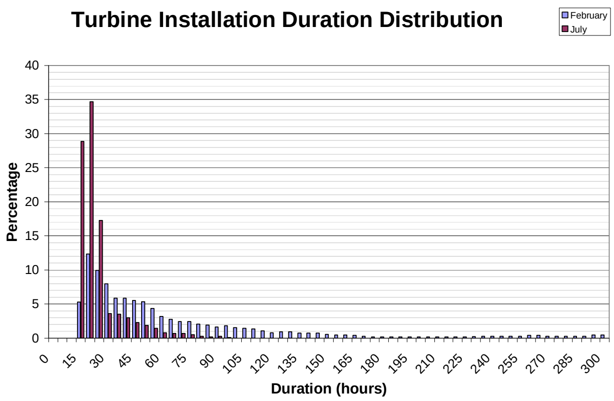

Figure 1: Duration distribution for turbine installation for February and July

Fig. 1 shows the duration distribution for the Turbine Installation operation in February and July. The simulated projects for July all took under 100 hours, compared to the simulations performed for February where 20% were over 100 hours. The duration distribution clearly demonstrates the advantages of construction in the summer months.

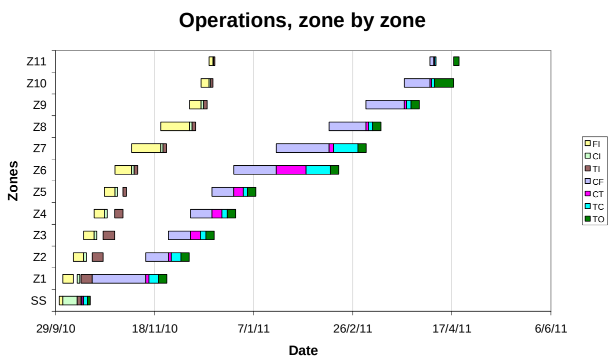

Figure 2: Visual breakdown of a simulation of project construction

The database from the second stage Monte Carlo analysis allows breakdowns of any of the simulations to be viewed. Fig. 2 provides an example graphical breakdown. It can be used to gain a better understanding of dependencies and also look at the critical path of the project. In Fig. 2, it can be seen that there is an increasing delay that occurs between the Turbine Installation (brown) and the Cable Termination (violet), as a result of the accumulated delay from the previous zone Cable Termination. One way to alleviate this sequencing delay would be to assign an extra vessel to the project. An extra vessel would change the sequencing requirements, for example zone 6 to zone 11 could have their dependency on zones 1 to 5 being completed removed. This should result in the earlier completion of the project. A limitation of the graphical breakdowns is that an averaged breakdown does not fit visually - i.e. average operation lengths will not line up and show dependencies accurately.

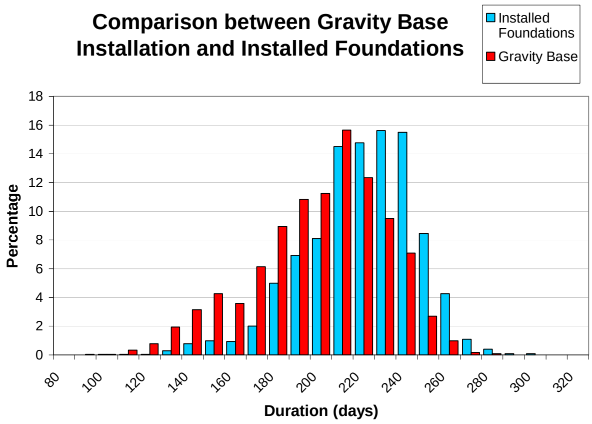

Figure 3: Duration distribution for compete project for gravity base and piled foundation turbine

Fig. 3 compares the project duration distributions. The gravity base device is shown by the O2M model to take less time to install. The difference between the two projects is notable, although perhaps not as significant as might be expected. The piled foundation device also appears to have a less spread distribution, with 60% of the distribution spread over 40 days between 210 and 250 days. In comparison, the gravity foundation device has approximately 60% distributed over 50 days between 190 and 230 days.

2.4 O2C discussion

Running the model for some of the "continuous" sub-operations (those that need to be performed in a single weather window without interruption) proved to cause considerable problems. The main tidal cycle is a 12 hour cycle, meaning that within 12 hours, you will get 2 fast flows – the flood and the ebb. In a harsh environment, such as the Pentland Firth, these flows could regularly exceed 3m/s. The result of this is that there may never be a long period of time where some continuous operations can be completed. There are two solutions to this. The first is to increase the operating characteristics of the vessel or operation. This may require more advanced vessels such as large dynamically positioned vessels, which are able to remain still in very high flows, although this does not address the problems of keeping equipment steady as it is moved into position under water. The second option is to change the operation. This could either be so that it can be paused and resumed, or making it fast enough to occur in the slack water time window.

The periodic nature of tidal flows means that at energetic sites the windows for construction at low flow speeds are small. For operations which need to be continuous (i.e. need to be completed in a single effort without interruption) it was necessary to conduct the operation in the presence of high flow rates. This highlights the need for robust and efficient construction and installation techniques.

The sequencing rule applied in this model was that a separate vessel was required for each operation. This is likely to be realistic for many operations as they are likely to be vessel specific. However, the sequencing rules could be altered to represent the same vessel being used for multiple operations, if the project so required.

3. Operations and Maintenance

The O2M model has been developed to optimise an O&M strategy. O&M strategy refers to what resources are employed to operate and maintain a tidal farm. The optimum strategy will balance the cost of deploying a resource strategy with the cost of lost production due to turbine downtime. This section presents the O2M model methodology. A specific case study using the O2M model to compare different turbine types, reliability profiles and maintenance resources is described and a discussion of the results is provided.

3.1 Model methodology and assumptions

The O2M model performs time domain simulations of a turbine farm and its support system. All the turbines are assigned a reliability profile based on the mean time between failures (MTBF), a common measure of reliability. The model iterates through time and at each time step, a random number is generated and used to determine whether a turbine fails. If a turbine fails, it stops producing energy and its downtime is logged.

Once a turbine fails, the model attempts to assign resources to repair it. These resources take the form of crew and vessels. Vessels are given characteristics. They have a maximum wave height (Hs) and a maximum tidal current speed that they are able to operate in. The operations a vessel can perform may also be varied. Different vessel contracting strategies can be modelled, from ownership to chartering vessels only when a failure occurs.

Crews are assigned shift working hours. This allows the model control over operating hours, enabling it to represent daylight only operations, which is likely given the risks of offshore work.

Before the model is able to assign resources, it checks that they are both available and suitable. If there are crews on shift who are not already assigned to another turbine and a vessel is available, the model assigns them to the damaged turbine. The model then simulates the resources attempting to access the turbine to conduct repairs. All vessels have associated operating limitations. At each time step the model compares the current environmental conditions with limiting conditions of the resources. If the current environmental conditions exceed the resources' maximum operating conditions, then the resources are forced to wait and check again at the next time step.

When the environmental conditions allow, the resources are dispatched to the site to retrieve the turbine and return it to the base for repairs. The model does allow for repairs to be simulated on site for devices for which this is possible. However, for the case study presented in this section all turbines were assumed to return to base before repairs were performed. The tool allows for a stock of turbine nacelles to be modelled, where if a turbine breaks down, a spare working nacelle can be swapped in. The spare nacelles are treated as parts which are held in stock. If one is used, the model will simulate repairs on the one that has been removed. Once repaired, the turbine goes back into the stock. Part of this paper includes a study into how the number of stocked turbines affects the array availability.

Once a turbine has been retrieved, it is assumed to be at the base, where its repair is no longer limited by environmental conditions.

It is possible that in some scenarios the O&M resources will be insufficient. This occurs when turbines fail at a faster rate than they can be repaired for the majority of the simulation. These cases will be removed, as they do not make for a viable long term O&M strategy for an array.

Once the time domain simulations are complete, costing is applied to the results to give the cost of the maintenance strategy per annum. Lost production is assigned a cost, consisting of the cost per MWh of electricity and also the value of the ROCs that it would generate. The variables in the maintenance resource are then priced. This includes the cost of service crews, all costs associated with vessels. An average price per repair is assigned, to cover vessel fuel, parts required for turbine repair etc. If the strategy includes spare nacelles, the cost of additional nacelles is divided by the expected farm life. Spare nacelles incur an additional cost for storage. With all these factors included, it is possible to find an optimum strategy, based on the combined expense of lost production and maintenance strategy.

3.2 Setting up the model for the case study

The focus of this example is to investigate the effect of having a stock of additional nacelles that can be used to replace damaged turbines in a single operation. This is investigated for different numbers of crews, different vessel types and with different assumed power curves.

With tidal power still in an early stage of its development, there are no reliability figures available for commercial sized devices operating continuously. To allow for this, a sensitivity study has been performed on the mean time between failures (MTBF) for the turbines, varying the value from 2,500hrs to 10,000hrs.

As for the O2C tool, a long term tidal current series was required. As well as governing site access, it is also used to calculate the lost power. A full measured series was not available, so again one was modelled. The flow speeds were intended to represent those found in the Pentland Firth. [1] was used to find mean spring peak flood (MSPF) and mean neap peak flood (MNPF) flows, for the area just south of the Pentland Skerries. The following approximations were used for the two main constituents (M2 and S2) that make up the tidal harmonic:

$$M2 = \frac{MSPF + MNPF}{2}$$

$$S2 = \frac{MSPF - MNPF}{2}$$

Constituent values for the tide height at Gills Bay, the nearest referenced base, were obtained from [2]. The values given for O1, a lunar diurnal constituent, and K1, a lunisolar diurnal constituent, were scaled using the average of the scale factor for M2 and S2 (a scale factor of 4.14).

Constituent	Magnitude	Speed (°/hr)
M2	4.645	28.984
S2	1.701	30
K1	0.539	15.041
O1	0.456	13.943

Table 1: Created Constituents

A harmonic time series was synthesised using created constituents shown in **Table** 1. The created series was for the flow speed at the surface. A power law was applied to the time series to give the speed at hub height (assumed to be 20m), so that it could be used to get the power lost.

$$U_z = U_{surface} \times \frac{z}{z_{surface}}^{\frac{1}{10}}$$

The depth of the site was assumed to be 50m. This method allowed the synthesis of a long term tidal time series that could be used in the model to govern access and calculate the power lost.

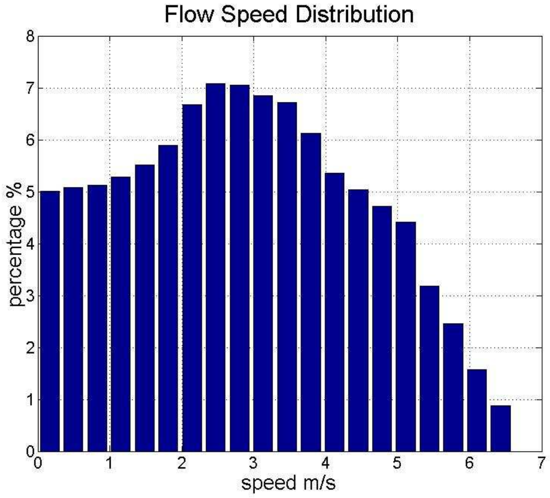

Figure 4: Modelled tidal time series – flow speed distribution (over 7 years)

As well as using the time series characterised by Fig. 4, the model requires a power curve to convert the flow speed into the power lost. For this study, two power curves are used, one for a pitch regulated device, and one for a variable speed fixed pitch (VSFP) turbine rated at maximum flow.

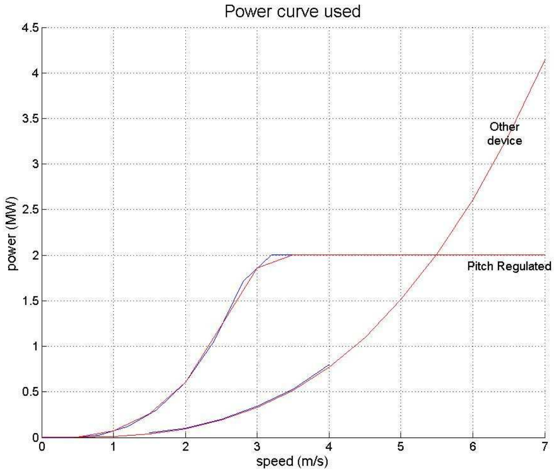

Figure 5: Device Power curves

The pitch regulated device in Fig. 5 uses the steady state 2MW rated power curve from [3]. A comparison of the effect of the different power curves is performed as part of this case study. The power generated has an associated price and for this study, it is assumed that each MWh will receive 3 ROCs.

Vessel	Hs limit	Vs Limit
Tug	1.5	1.5
Improved Tug	2	2
Barge	1	1.5
Improved Barge	1.5	2

Table 2: Vessel limiting conditions

The vessels used in the simulations are defined by the limiting environmental conditions, as summarised in table 2. It has been assumed that vessels are contracted on a long term basis to the farm. The costing is based on the price per year.

For the model, the number of vessels is tied to the number of crew, meaning there are always sufficient vessels to transport all the crew. Each crew is an idealised crew, available to work 12 hours a day, 7 days a week, without holiday. This unrealism is compensated for in the costing and optimisation, where a factor is applied to the cost of the crew to account for the fact that each ideal crew would be made up of multiple real crews on a shift system.

Several of the devices developed so far feature a turbine and rotor that can be removed from the foundations and replaced with another one; examples include Tidal Generation Ltd’s DeepGen, Hammerfest Strom’s HS1000 and Swanturbines’ cygnet prototype device. For O&M this offers the opportunity to remove a damaged nacelle and replace it with a working one in a single operation. To do this, a supply of strategic spares is required. To investigate the optimum number of spare nacelles, simulations were performed again for the 3 different reliability profiles. The optimum number of crews was used to inform the number of crews for each turbine.

3.3 O2M Results

The results presented here show how the cost of O&M varies with different numbers of crew and numbers of spare nacelles. They also illustrate the effect of MTBF.

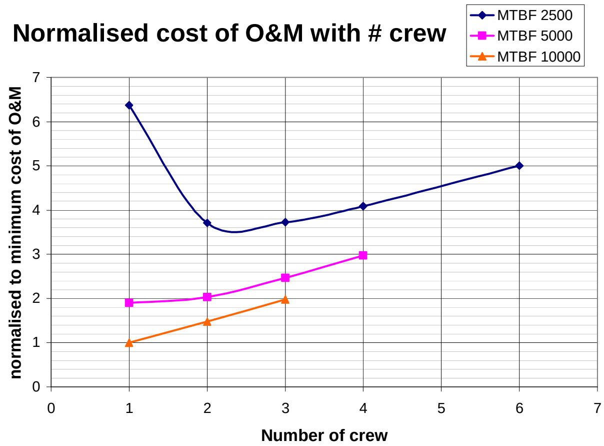

Figure 6: Graph showing effect of number of crew for 3 different reliability profiles

Fig. 6 shows the O&M strategies for the three modelled reliability profiles. Optimum strategies occur at the minimum point for each curve, where the cost of the O&M is lowest. The first point to note is that lower MTBF values (i.e. low reliability) result in farms that are more expensive to operate and maintain. A greater number of failures will lead to the requirement for a greater resource for repairs, and give a higher cost of lost production.

For a MTBF of 2500 hours, the model shows 2 crews to be the optimum number, although it was very similar to 3. With higher MTBF values, lower resources were optimum. This meant for MTBF values of 5,000 and 10,000 hours 1 crew (the minimum available in this case study) came out as the optimum.

Also of interest from the MTBF of 2500 hours, is that having more crews than the optimum produces a significantly cheaper O&M strategy than having the equivalent less than the optimum. This will be discussed further in the next section.

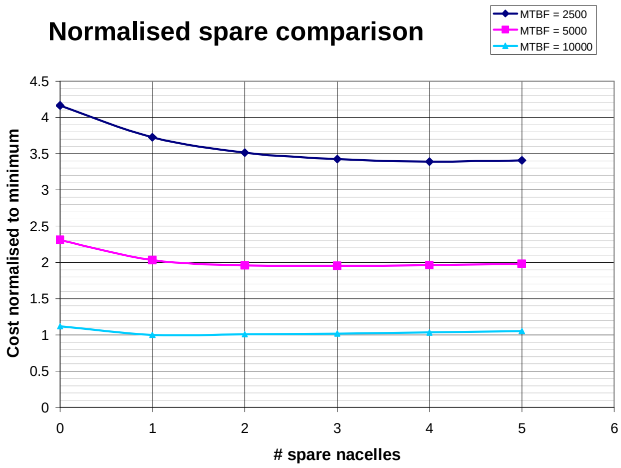

Figure 7: Graph showing effect relative to normalised cost with varying numbers of spare nacelles for 3 different reliability profiles

Fig. 7 gives the outputted annual costs for each MTBF value for varying numbers of nacelles, normalised to the lowest costing strategy. It shows that having additional spare nacelles makes a dramatic difference to the annual O&M cost. The cost of having spares over the lifetime of the farm is quite low – the investment in the extra nacelle is small when spread over the life of the array and the primary cost becomes the storage. Spares allow for broken turbines to be back online as soon as a vessel is able to get out to sea to perform a switch. This saves at least 2 days (the time taken in the model to repair the turbines) of downtime, generally more when the environmental conditions are factored in, per turbine failure when there is a spare available. The effect of having spares is greater with lower reliability turbines, where there is more downtime.

As well as being dependant on the reliability of the turbine, the O&M strategy is also reliant upon the turbine power curve. The model was used to optimise strategies for identical arrays using two different power curves.

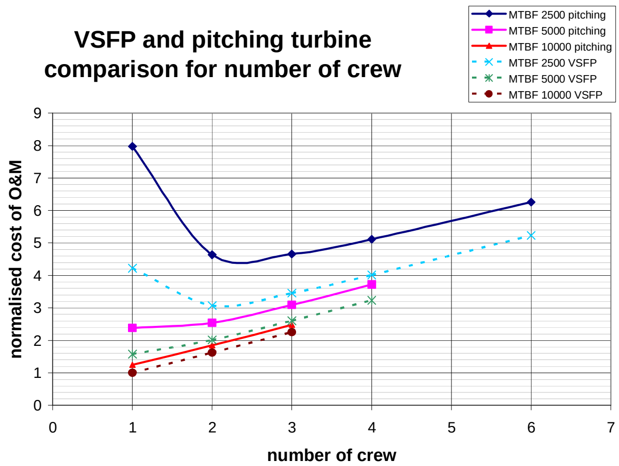

Figure 8: Comparing optimum strategies for turbines with different power curves, while varying of number of crew

Fig. 8 compares the normalised cost of O&M for different reliability profiles, and for different power curves. For each reliability case, the VSFP turbine is shown to have the lowest O&M costs. This, however, is a false saving. The VSFP turbine, on average, has a lower power output than the pitch regulated turbine. This means that there is less potential power lost when the turbine is down, and so less potential money is lost in comparison to the pitch regulated turbine.

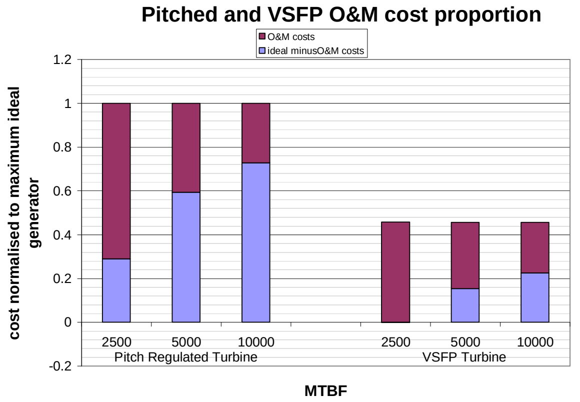

Figure 9: Normalised cost comparison between pitched and VSFP

Fig. 9 gives a better representation of the difference between the pitched and the VSFP turbine type. It shows that while the O&M costs of the VSFP device may be lower than the pitched; they are a larger proportion of the potential generated capital. Moreover, for some of the reliability profiles, for the VSFP power take off, the O&M costs exceeded the capital from the ideal generated power. This means that particular strategy would be making a loss on O&M alone. If a higher cost of energy is applied, possibly through a greater number of ROCs being allocated to the project, then the cost of the O&M will appear to increase, but will become a smaller proportion of the ideal energy generated and the strategy may become profitable.

One of the issues with the VSFP device is that it generates little power (comparatively) until it get close to its rated power. The pitch regulated turbine on the other hand is able to achieve rated power from lower speeds, generating on average more power. Fig. 9 shows that in this particular case the income generated by the pitch regulated device is similar to a VSFP device that has a fourfold increase in reliability.

3.4 Discussion

The cost of lost production makes up a significant proportion of the O&M costs and is dependent on the value of energy. Changing the value of energy, possibly through increasing the number of ROCs, changes the cost of all the strategies. It is logical that an optimum strategy would move towards having greater resources, as it becomes more worthwhile to keep producing energy. This can be inferred from Fig.8 where the downtime of the VSFP device is less costly than that of the pitch regulated one, and consequentially favours lower O&M resourcing.

With higher MTBF values, lower resources were optimum. For MTBF values of 5,000 and 10,000 hours, 1 crew came out as the optimum, as shown in Fig 6. It should be remembered that each modelled crew is an idealised crew able to work 12 hours a days, 7 days a week. This assumption is accounted for in the costing phase, where the cost per crew has a realism factor, to account for how many real crews would be required. Thus the optimum number of crews for the turbines with high reliability could be less than one modelled crew – perhaps a crew working 7.5 hours a day, 5 days a week. For this paper, this has not been investigated further, due to time restriction on the number of simulations that could be run, however the model could be run with altered crew shift lengths to investigate this.

Looking at the MTBF of 2500 hours in Fig 6, having 2 crews is shown to be the optimum; however, with 3 crews being so close to the optimum as well, there are several other factors that should be taken into consideration. Firstly, the turbine reliability has the potential to change over the life of the array. There may be a period of time at the start where initial problems need to be fixed and the reliability may be lower. Also, after several years of operation, the turbines will have accumulated wear and the reliability may drop towards the end of the farms life. This being the case, having more crews at the beginning and end of the farm life may be preferable. There is an additional benefit to having more crews. If many turbines fail in a short period of time, then more crews will allow for a quicker clearing of a backlog, helping to stabilise the number of working turbines.

One of the assumptions that the model makes with spares is that a single towing vessel can retrieve and replace a turbine in a single outing. This requires that at some point during the retrieval and replacement operation, it is handling two turbines at once, i.e. when the damaged turbine is removed, the vessel will have to control the damaged turbine and the replacement one on the surface at the same time. With larger crane vessels, this should be possible, because they are able to lift equipment onto the deck. With smaller towing vessels, this is more difficult and may require mooring points around the turbine foundations, where a turbine could be temporarily placed.

4. Conclusion

This paper has presented two tools for analysing and optimising construction (O2C) and operations & maintenance (O2M).

The O2C model highlighted the need for efficient methods of installing devices, due to the fast flow environment and small time windows available for installation of equipment. The model suggested that the project construction time was faster for the gravity base device than the pile foundation, however most of the difference was absorbed through sequencing delays.

The O2M model used time domain simulations to optimise the operation and maintenance strategy of tidal stream turbine arrays. Turbine availability using different resourcing strategies has been analysed by a cost based optimisation process. The analysis has shown the significant potential advantages of having spare turbines that can be swapped in for damaged ones, and thereby reduce the time a turbine is offline, and so increase profit from generating power.

The paper has also shown how the O2M tool can be used to optimise other aspects of the O&M resource, such as the number of crew required. The optimum strategy was shown to be array specific and the sensitivity to the assumed MTBF has been investigated.

The sensitivity to the assumed power curve was also investigated. An array which generates less energy was shown to have lower O&M costs, due to the lower energy loses during turbine downtime. A method of overcoming this was presented, whereby the cost of the O&M is put in perspective of the total ideal annual energy generation.

Acknowledgements

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