Generic Dynamic Modelling for Grid Integration of Ocean Energy Devices

D Mollaghan, D O 'Sullivan, A Blavette, D Cashman, R Alcorn, M Egan, Antony Lewis

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D. Mollaghan[1], D. O'Sullivan[1], A. Blavette[1], D. Cashman[2], R.Alcorn[1], M. Egan[2], A.W. Lewis[1]

[1] Hydraulic & Maritime Research Centre,
University College Cork,
Pouladuff Road, Cork City, Ireland
E-mail: hmrc@ucc.ie

[2] Department of Electrical Engineering,
University College Cork,
College Road, Cork City, Ireland
E-mail: eleceng@ucc.ie

Abstract

As ocean wave and tidal stream technologies approach commercial readiness, grid operators need to assess the impact a wave or tidal device will have on the electrical grid under both normal and fault conditions. In order to achieve this, it will be necessary for each device developer to supply dynamic models of their device to the grid operator.

A generic modelling approach is proposed to facilitate the integration of ocean energy devices into the electrical grid, from the perspective of both device developers and grid operators. This paper outlines issues surrounding dynamic modelling for ocean energy devices, and proposes a generic model structure based on data obtained from a recent survey of device developers. The proposed model structure would simulate the power flow through a device using generic parameters which can be obtained from empirical test data and equipment specifications.

Keywords: dynamic modelling, generic modelling, grid integration, ocean energy

1. Introduction

In order to connect an electricity generating plant to the electricity grid (network) there are a series of rules and guidelines that must be adhered to. One of these is that the generator must provide a dynamic electrical model of their system that is compatible with the network operator's software. This model must take time series resource inputs (e.g. wave, tide conditions, network signals) and output electrical power and other dynamic characteristics, during normal and faulted operation. These models are a requirement as they are used by the network operator to ensure that any new generation on their system is:

- Stable under normal and fault conditions
- Does not affect other users/generators
- Produces acceptable power quality
- Does not overload existing protection circuitry and power lines
- Allows Load Flow analysis to be performed

Currently, the only sustainable energy system models available are of those for wind and hydro. These existing models are highly confidential, proprietary and fully commercial. The ocean energy industry will require dynamic electrical models in order to procure grid connections and to demonstrate their technology at large scale. They also need to know how their technology interacts with the grid, and what, if any, remedial design work needs to be carried out in order to procure a grid connection.

In this paper, the requirements and criteria for a successful dynamic model are examined, and lessons from the experience of wind energy development are summarised. The specific difficulties in the dynamic modelling of wave and tidal energy devices are outlined and the generic modelling approach is detailed. A methodology for the development of a generic device model for wave and tidal energy is presented. This methodology has been devised based on data from a comprehensive survey of wave and tidal energy device developers, performed under Annex 3 of the International Energy Agency Ocean Energy Systems (IEA-OES) Implementing Agreement. The outputs from this survey are presented and a generic device model structure is proposed.

2. Grid Integration of Ocean Energy

The technology for ocean energy conversion is still in its relative infancy. The installed capacity of ocean energy devices supplying to national grids worldwide is less than 10 MW as of 2010[1]. There are many challenges which must be overcome for wave and tidal energy to be both feasible and economical enough to compete with or complement more mature renewable sources such as wind energy[2, 3]. There are a multitude of designs for wave and tidal energy devices, at various stages of development, employing many means of energy conversion. Each device has its own particular advantages and disadvantages, but there is as of yet no clear indication which technology type or group of technologies will emerge as viable from an engineering and economic point of view.

Globally there are only a few devices that have exported power to national grids. Some examples of these are:

- Marine Current Turbines (tidal) in Strangford Lough, N. Ireland
- Pelamis Wave Power (wave) in Aguçadoura, Portugal
- Pico Power Plant (wave) in the Azores islands
- Wavegen Power Plant (wave) in Islay, Scotland

Figure 1: Grid Connected Devices

Clockwise from top-left: Marine Current Turbines[4], Pelamis[5], LIMPET[6], Pico Power Plant[7]

However, quite a few pre-commercial developers are now approaching the point where they are investigating the grid connectivity of their technology. Simultaneously, electricity network operators and others are looking to assess the potential future impact on distribution and transmission networks of the large scale integration of ocean energy [8, 9].

Dynamic models provide a grid operator with a means of assessing the impact of renewable energy generators on the local and national grid from the point of view of system stability, dynamic voltage variation, and fault performance and ratings [10, 11]. Without such a model, device developers will be unable to procure a grid connection. Moreover, the process of developing a grid connection dynamic model also furnishes the device developer with a design tool to assess the grid compatibility of their technology.

3. Model Complexity

Modelling techniques employed by developers tend to focus on a high level of accuracy and are targeted at device and performance optimisation. These models would typically involve some form of hydrodynamic study of the device. A fully descriptive and exact dynamic model would require much of the following information, and more:

- Hydrodynamic coefficients in all degrees of freedom
- Hydrodynamic and thermodynamic models of the primary power capture stage
- Full geometric device information
- Prime mover dynamic pressure and flow characteristics
- Full knowledge of control strategy.

Constructing a model in this manner would obviously be quite a complex and time consuming process. Also, the level of detail in this type of model is not necessary for the purpose of dynamic modelling for grid connectivity. Furthermore, it is most unlikely that such information will be available either from developers, or even within the capability of some developers. It is much more likely that empirical information, test results, and characteristic curves will be available.

4. Dynamic Model Requirements

A successful dynamic model should have the means to accept a time series resource input and provide a real and reactive power time series output to a connection point in a power systems simulator package, initially for a single device, but ultimately for an aggregated farm of devices. It is anticipated that two levels of modelling will be required for operation under both normal conditions and grid fault conditions.

Under normal conditions, the dynamics of the power transfer from the ocean to the prime mover will be dominant over the electrical power dynamics. However, under fault conditions, the electrical power dynamics change rapidly and the system must respond accordingly. The fast electrical power dynamics means that the input power from the ocean has less of an effect on the overall system dynamics. Also, grid codes specify that faults must be dealt with within a specified time (typically 3 seconds) [12], either by implementation of a fault ride-through mechanism or else disconnect from the grid. Thus to model a system under fault conditions, a higher order model is required, but over a much shorter time scale.

A distinction needs to be drawn between a grid connection dynamic model and a design level model, which usually includes full hydrodynamic parameters and full electrical dynamics and harmonics. This type of model strives to be highly accurate in its representation of device dynamics. As previously discussed, this level of detail is not required in a dynamic model for grid connection. However, power output variation, protection mechanisms, and generator and prime mover dynamics need to be modelled to a reasonable level of accuracy. Dynamic models exist for wind turbines [10,11,13-16] (which are of similar structure to tidal flow turbines); however, apart from some initial studies [17], models for wave energy and oscillating tidal devices are not widely available.

Furthermore, experience from the wind industry has highlighted a number of issues surrounding dynamic modelling in terms of implementation and transmission system operator (TSO) usage [18]:

1. In order to protect commercially sensitive technology, the source codes for most dynamic models may not be made available to the TSO; this can lead to issues in diagnosing problems within the model.

2. Specific models from numerous developers can lead to uncoordinated computer programming.

3. Initialisation stabilities can lead to a large increase in simulation time or the model may even reach an unintended equilibrium point.

4. Grid codes often specify integration step sizes; for instance Irish grid codes specify step sizes must not be less than 5ms [12]. Numerical instabilities can occur if models with time steps of less than 5ms are incorporated into a large model.

Therefore, in addition to describing the main characteristic of a device, a dynamic model must also be compatible with the TSO's simulation requirements and diagnostic procedures.

Furthermore, the model will need to be validated against physical testing results to ensure the model's outputs are accurate. The validation stage will need to be taken into consideration in the model to ensure the choice of model parameters will not inhibit the validation process.

5. Generic Modelling

One option for overcoming the difficulties in creating a dynamic model, from the perspective of developers and TSOs, is through the development of generic dynamic models. A generic model would reduce the computational requirements of a developer, and ease the model's integration into the TSO's testing procedures.

The IEA-OES are attempting to impose some order on the process of creating a dynamic model by guiding developers towards a *generic* model structure. This 'framework' or 'group of frameworks' would then be parameterised by individual device developers.

A generic model should be capable of describing the main dynamic characteristics of a device using a minimum number of parameters. The following approach is used for the creation of a generic model:

1. *Categorise* the majority of devices according to their energy capture mechanism.

2. *Divide* power conversion train into a number of generic blocks

3. *Define* the appropriate level of detail at each block stage.

Wave and tidal devices can be categorised in quite a number of ways. The most suitable for the purpose of modelling was to categorise devices according to their primary energy capture mechanism.

The following categories were selected for wave energy devices:

- Oscillating Water Column
- Point Absorber
- Submerged Point Absorber
- Attenuator
- Overtopping Device
- Oscillating Wave Surge Convertor

The following categories were selected for tidal energy devices:

- Tidal Turbines
- Oscillating Hydrofoils
- Tidal Sail Devices
- Venturi Effect Devices

Despite the wide variation of power take-off methods in these wave and tidal energy devices, a common power conversion process is observed in most devices (outlined in Fig. 2):

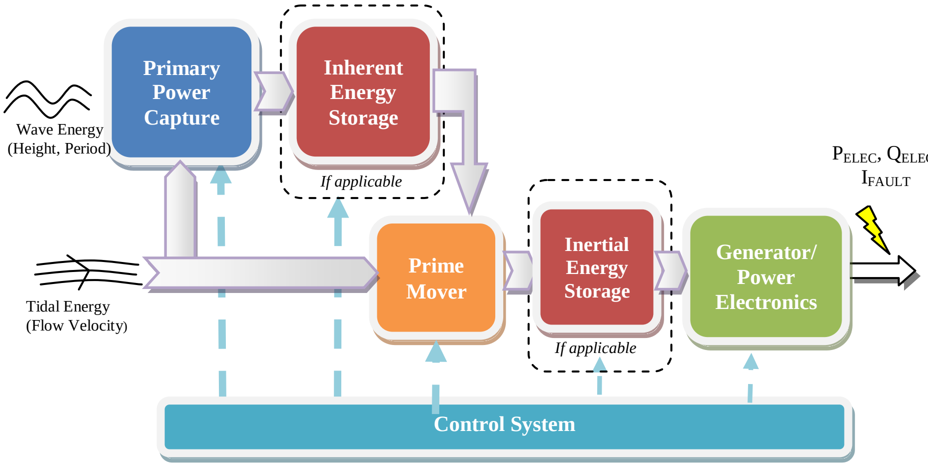

Figure 2: Colour Coded Model Reference

- Primary Power Capture – conversion of ocean power to some primary power, typically either pneumatic or hydraulic power. Note, this stage may not be applicable to tidal turbine devices or directly driven wave devices.
- Inherent Energy Storage – an energy storage mechanism inherent in the device. e.g. reservoir, hydraulic accumulator
- Prime Mover – converts primary power to mechanical power; typically through either a turbine or hydraulic motor. In direct drive wave devices, the prime mover is typically some form of linear translator driven by the motion of the waves.
- Inertial Energy Storage – energy stored in rotating components in the device
- Generator / Power Electronics – converts mechanical power to an acceptable form of electrical power.

Each stage of the conversion process can interact with a control system, which can either optimise the system performance or provide protection in the case of faults or excessive ocean power.

6. Model Development Methodology

The model should be open enough to incorporate the majority of wave and tidal devices in development, but should be specific and clear enough to allow the model parameters to be determined in a relatively straightforward manner.

The main detail of the model should be implementable from a combination of:

- Sea trial or Wave Basin/ Tank Tests
- Laboratory tests of power take-off equipment
- Manufacturer data (in the case of equipment)

The type of data available from developers will depend on the types of testing performed, the testing capabilities of a developer, and the type of device in operation. This will obviously vary with each developer. However, it is envisaged that most developers will be able to provide some common data and parameters that can be used to characterise a device.

7. Developer Survey

A survey of wave and tidal energy device developers was carried out as part of Annex III of the IEA-OES Implementing Agreements [19]. The survey was conducted in an attempt to gather information about the main elements of power take-off in devices currently in development, and also to determine the type of data developers have the ability to provide. In total, 17 developers responded to the survey (14 wave, 3 tidal). The main results from the survey are summarised in this section.

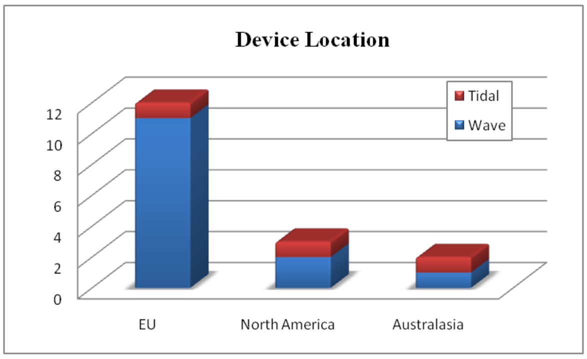

Figure 3: Location of survey respondents

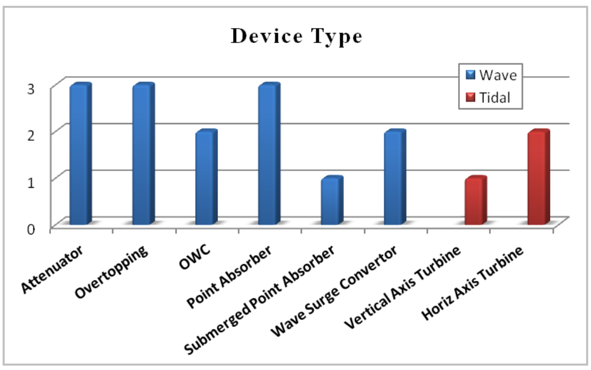

Figure 4: Device Category

Directional Sensitivity - The majority of devices either align themselves to the mean wave or tidal direction or are not affected by it if they do not align. This is an important result from a dynamic modelling point of view as it implies that directional sensitivity is not a major concern. However, the fact remains that a small number of devices are affected by wave or tide direction, so the model will still need to have a basic provision for taking resource direction into account in these devices.

Primary Power Capture - Primary power capture time series data is widely used by developers in characterising their device performance, and this data is available for different tuned states. This is important as it will enable some flexibility in developing the model for this conversion stage. In the case of very non-linear devices and/or devices that are tuned wave to wave, a more complex model may be necessary.

The availability of data for different tuned states is important in developing a table of transfer functions which can be discretely selected as the system tuning or damping changes as a result of control action.

Storage - The majority of energy storage is short term (<30s), so there will be at least some absorption and release of energy during a typical dynamic model simulation run, thus it is important to model the dynamics of this power conversion stage. Inertial (rotating mass) energy storage is present in nearly all devices. The two most common forms of inherent storage are accumulator and reservoir storage; one respondent utilises electrical storage.

Most developers have the ability to provide details on inherent storage capacity, either in terms of seconds of rated power or as a percentage of rated power. However, fewer developers can provide data on charge/discharge rates (either average or maximum). Further work will be required in this area, as these parameters will be important from a modelling point of view.

Prime Mover – In the devices surveyed, the majority actively control a variable speed prime mover. Furthermore, most devices utilise multiple prime movers, which operate simultaneously and independently of each other. In several of these devices, power is unevenly distributed between each of the prime movers. These characteristics indicate that a more detailed understanding of the individual control strategies with respect to multiple prime mover operations will be required.

Most developers stated that a significant knowledge of mean efficiency data is available for a range of prime mover speed and input conditions. It is proposed to use this info to characterise the prime mover, rather that the specific technology based performance curves of each prime mover type.

Generator - The majority of devices surveyed, due to their variable speed nature, will utilise power electronics coupled permanent magnet or squirrel cage induction generators. There are a significant number of generators that are gearbox-coupled to the prime mover and this will need to be taken in to account in the mechanical model of the prime mover block.

The efficiency characteristic of the generator can also be included in the final calculation of power output to the grid connection point. The grid connection and disconnection conditions, reactive power control and low voltage operation must also be included in the model

8. Proposed Model Structure

The finalized conceptual structure of the dynamic model is illustrated in Fig. 5. A resource input block and grid connect block have been added at either end of the generic structure shown previously. The general modelling approach of each block is shown in the centre of the block. The data used to characterise the block model is located in the upper portion of the block. External parameters (which may pass between blocks) or control inputs are depicted as auxiliary inputs to the blocks.

The grid connect block, generator block and the mechanical system portion of the prime mover/mechanical system block will be broadly similar to those utilised in existing wind turbine dynamic models, with the notable exception of linear generator type converters, in which the generator model will be somewhat different in terms of how the current and flux are controlled, and also in the motion aspects of the system.

The remaining blocks are those which tend to be very device specific. The particular model structure and characterisation approach represents a generic approach to these dynamic model blocks, which should be independent of technology.

The exact formulation of each of these dynamic model blocks and their integration to appropriate case studies is the subject of ongoing research activity in the Hydraulics & Maritime Research Centre.

9. Conclusion

In order to facilitate the integration of wave and tidal devices into electrical networks, dynamic models must be prepared in advance of a full scale device launch. In this respect, it is clear that generic dynamic models would be beneficial to both device developers and TSOs alike. Generic models would allow for a reduced computational effort within both parties.

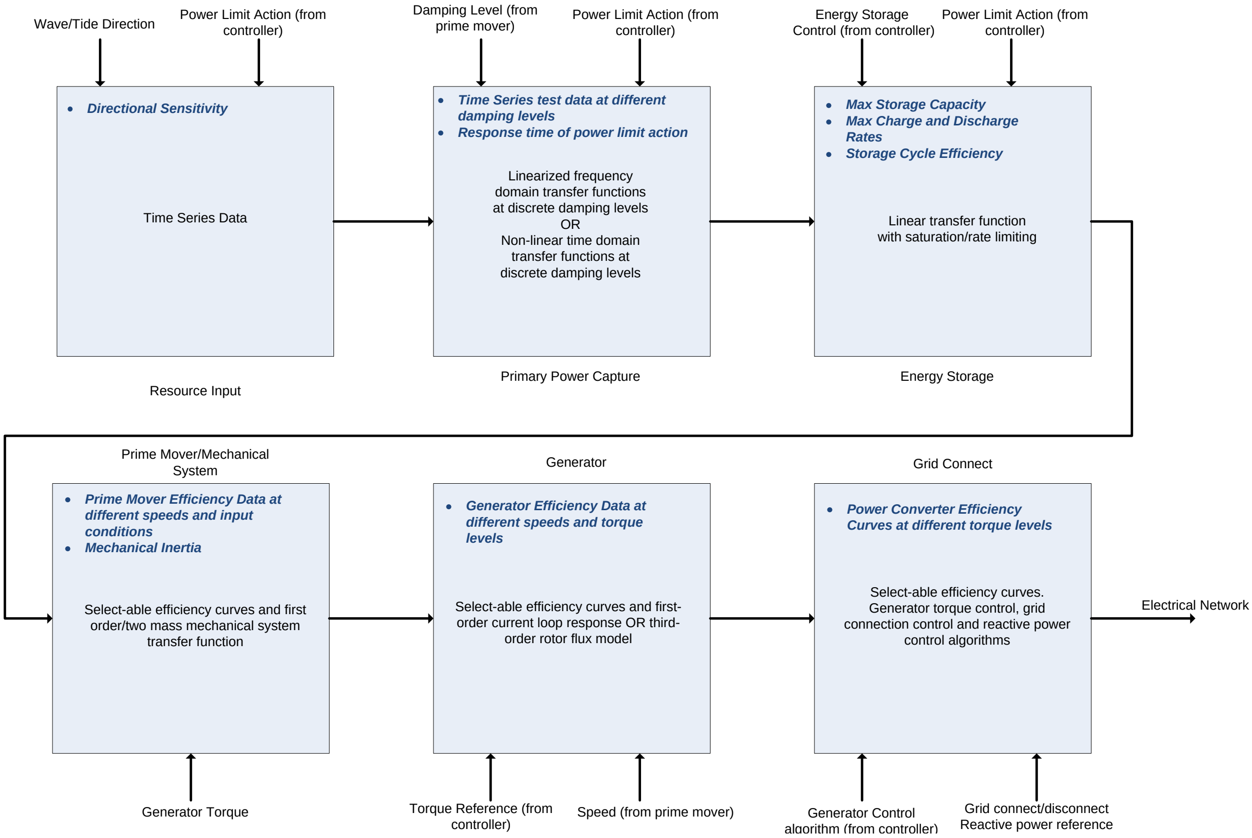

Figure 5: Proposed Model Structure

The main challenge for generic modelling is creating a model that can characterise the main dynamics of all devices using only a minimum amount of generic parameters.

The proposed model structure presented in this paper outlines a possible approach for overcoming these difficulties. The next stage is to develop each of the model blocks and work with developers to find the most effective method for implementing control strategies within a generic model.

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