CATAPULT
Offshore Renewable Energy

Marine Energy Electrical Architecture

Report 2: Review of SSE Contractor Reports

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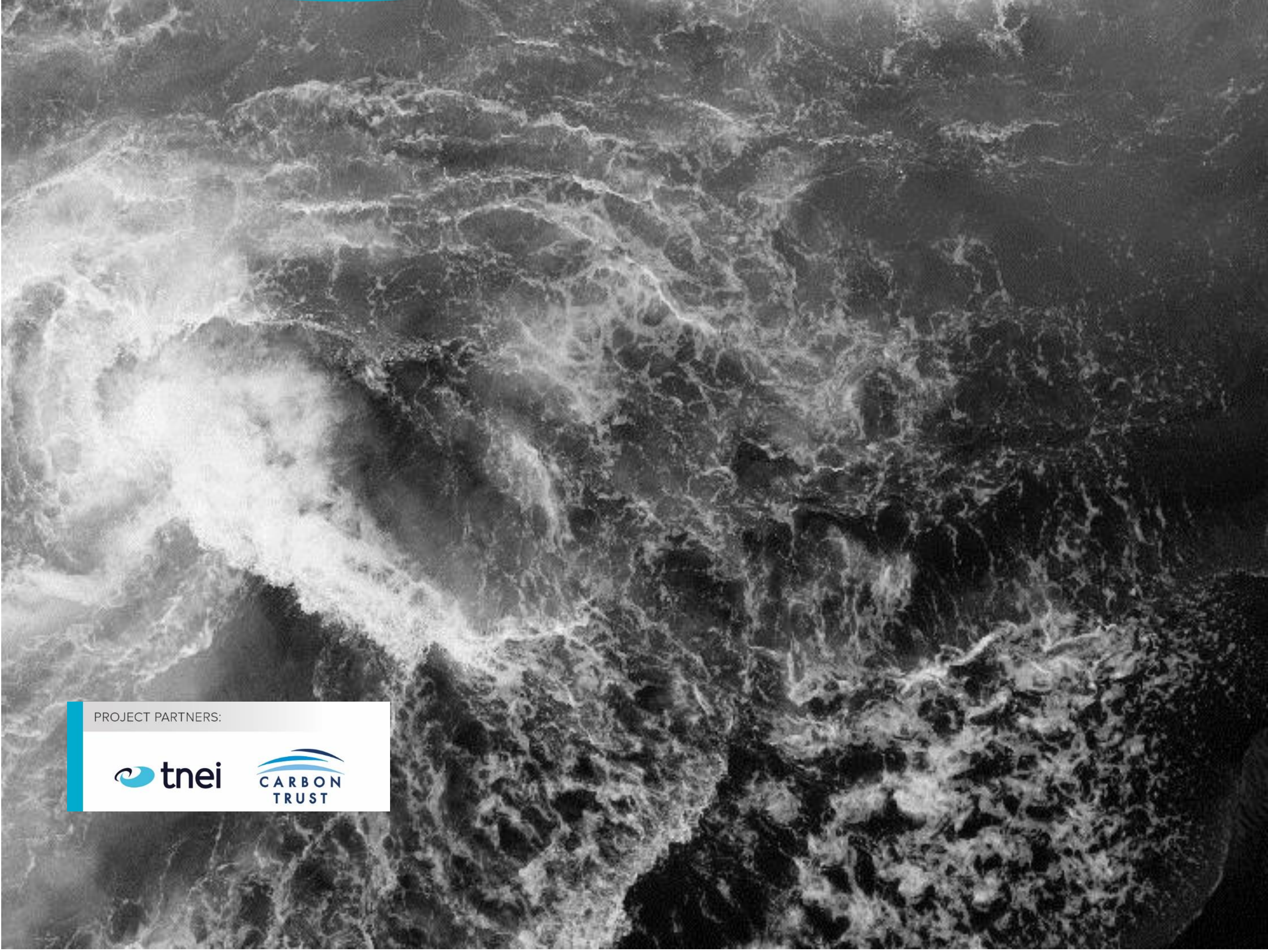

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1 Executive summary

The three SSE contractors' reports [1], [2], [3] provide a useful starting point for a study of array system designs for commercial-scale marine energy projects. In particular, the ABB and Siemens reports both offer a comprehensive discussion of the key component technologies, their electrical capabilities and their suitability for use in a sub-sea application.

The array system designs proposed in the three reports can be classified according to a set of seven 'system concepts'. These concepts are listed in Table 1. The first concept involves the use of a separate connection cable between each MEC and the collector substation; as such, it does not provide any aggregation of power from multiple MECs. The next two concepts are based on a 'daisy chain' topology, and allow for aggregation of up to 10MW on each radial string. The last four concepts are based on a 'hub and spoke' topology, and allow for aggregation of up to ten 1MW devices at each hub.

Aggregation topology	System concept	Coverage in the three SSE contractor reports		
		ABB	GE	Siemens
No aggregation	No conversion at MEC Separate cable for each MEC Conversion at shore or at collector platform	12.1.8	Option A	SURFACE1
Daisy-chain	Conversion to DC at MEC MECs connected in parallel, on MVDC strings or loops	12.1.1		
	Full conversion and step-up at MEC MECs connected in strings or loops at 11kV or 33kV	12.2.2	Option B	SUBSEA2&3
Hub and spoke	Full conversion at MEC Voltage step-up at local hub Hubs on AC rings at 33kV	12.1.4	Option X	SUBSEA1 HYBRID1
	No conversion at MEC Full conversion and step-up at hub Hubs on AC rings at 33kV	12.1.5	Option C	
	No conversion at MEC Conversion to DC at local hub Hubs on MVDC rings		Option D	
	Conversion to DC at MEC No conversion at local hub Hubs on MVDC rings	12.1.2 12.2.1		

The table gives the following information:

A colour code for the concept, based on the contractors' own Levelised Cost of Energy (LCOE) assessment (green = lowest LCOE; orange = mid; and red = high LCOE)

For each 'system concept', the contractor's own designation (or report section) that corresponds to the concept.

Table 1 Summary of 'system concepts' proposed in the SSE contractor reports

Table 1 highlights discrepancies between the LCOE assessments provided in the three contractors' reports. In some cases, the contractors have arrived at different LCOE results for array designs that share the same basic concept. This is likely to be due to a combination of the following factors:

- Important differences in the implementation of the concept, leading to different performance outcomes for the two designs; and
- Use of different methodology or assumptions for LCOE assessment.

There is no clear agreement between the three reports regarding which system concept offers the best LCOE performance. This indicates that there may not be a clear 'winner' and that different concepts may be suited to different application scenarios (e.g. near-shore projects, versus those further from land). Moreover, optimisation and 'value engineering' of a given system concept is likely to yield important improvements in performance.

Many of the array systems in the reports are designed in isolation of the electrical characteristics of the marine energy converter (MEC). As a result, few of the array designs could be developed to work in conjunction with the MECs currently available on the market. In addition, a number of the designs rely on components that have not yet been developed or are at a low technology readiness level. These components would require significant development and testing before they could be considered suitable for installation as part of a commercial array architecture. As the marine energy industry develops and the technology and processes mature, the ideas contained in the reports may begin to gain ground. A good example of this is the split converter topology proposed by General Electric (GE). At present, the Medium Voltage Direct Current technology needed to realise this concept is not mature enough. The coming years will see the advances in this technology that may mean that this method, which will reduce transmission losses, will become viable.

One of the conclusions that has been drawn from this review of the reports is that a common naming system for array concepts would improve clarity, facilitate sharing and learning and identify gaps in array options and sub-component development requirements.

The final conclusion drawn from the review, is that the performance of a given array concept cannot be evaluated in any meaningful way unless the design of the sub-systems that are used in the array (e.g. subsea hubs or converter modules) is elaborated to a reasonable extent. An attempt must be made to quantify the dimensions and weights of these sub-systems, and to consider issues of deployment (including the installation and connection of associated cables), operation and maintenance.

2 Introduction

The marine energy industry has reached the stage where a number of devices have completed pre-commercial, full-scale demonstration. Over the next few years, array-level projects will start to be constructed. One of the challenges facing the marine energy industry is the need to reduce the Levelised Cost of Energy (LCOE) of these projects. The lack of a standard marine electrical architecture means that it is more difficult to identify areas where cost savings can be made.

To address this issue, ORE Catapult, under the umbrella of the Marine Farm Accelerator (MFA), has instigated a project to identify a preferred array electrical architecture. The aim of the project is three fold:

- Review recent and ongoing work on the subject;
- Engage with the industry to develop a preferred array electrical architecture; and
- Look at areas of this architecture that require cost reduction.

A previous study into marine energy electrical architectures was commissioned in 2012. The study was undertaken by SSE Renewables, with additional funding provided by Scottish Enterprise, in partnership with sector stakeholders Scottish Power Renewables, Alstom Hydro France, Tidal Generation Ltd, Andritz Hydro Hammerfest and Voith Hydro Ocean Current Technologies. The project was supported by Scottish Enterprise. For this study, three equipment manufacturers (ABB, GE and Siemens) were approached and asked to investigate optimal connection solutions and identify any potential design standardisation. These were substantial reports and the aim of the current work package (WP2) is to provide a systematic review of these reports and where appropriate, use the findings to inform this project.

This report is divided into four main chapters, starting with a brief overview of the three SSE contractors' reports in chapter 3. Chapter 4 then sets out the key requirements that must be addressed in the design of any array architecture for marine energy projects. Section 4.2 focuses on the 'services' that the array system has to provide to each marine energy device; Section 4.3 addresses requirements relating to installation and maintenance activities in the marine environment; finally Section 4.4 discusses issues relating to array system design and topology. Later in the report, an analysis of the system concepts offered by the three contractors is undertaken.

The remaining sections summarise the information provided by the three contractors and in particular highlight the similarities and differences between their proposed array concepts. Chapter 5 focuses on the information provided in the reports relating to the availability and limitations of key components that are likely to be used in the array system. Finally, chapter 6 categorises and describes the system concepts proposed by the three contractors.

3 SSE Report Structures and Content

3.1 Introduction

The three SSE contractor reports all offer different approaches to the brief that was provided to them. This brief was to develop a marine array architecture for 1MW devices of array sizes of 30MW, 100MW and 200MW. This chapter provides a brief description of the public version of each report. The public versions of the reports do not include the cost calculations that were carried out by each of the contractors.

3.2 ABB Report

The ABB report contains pertinent information relating to the component technologies, array design, installation and technical issues. ABB is an advocate of DC architectures, with rectification taking place at the MEC using passive diode bridges and conversion from DC to grid frequency AC at the main collector substation. This approach is referred to as ‘alternative 1’ in the report, with ‘alternative 2’ used to refer to schemes using active power conversion with converters located either in the MEC itself or elsewhere in the array.

The key part of the report comprises sections 9, 10 and 11, which progressively develop the components, notably ‘hubs’, to facilitate various array concepts, together with the array concepts themselves. A range of different concepts are developed in the report although a lack of classification means that it is difficult to evaluate them.

3.3 GE Report

The GE report is more focused than the ABB report but contains less information with regard to the capabilities of key component technologies, installation issues and other related topics.

The key part of the GE report is section 4, which provides an overview of each of GE’s four main array concepts:

- Option A – Conversion equipment located at collector substation (base case)
- Option B – Conversion equipment located within the turbine unit
- Option C – Conversion equipment located offshore in a separate unit
- Option D – Conversion equipment split between local hub and collector substation

Further development of these concepts is provided in sections 7 through to 11. A split converter topology (option D) is regarded as the preferred architecture and is fully explored in the report.

3.4 Siemens Report

The Siemens report focuses on the design development of the key ‘sub-systems’ for use in marine energy arrays rather than on a number of array options. The sub-systems in question are:

- Section 5: subsea power converter module;
- Section 6: passive collection hub; and
- Section 7: tidal generator interface platform.

The converter module and passive hub are used to implement a range of different array designs based around a ‘hub and spoke’ topology. The tidal generator interface platform implements a completely different approach; here, MVDC converters are used to provide up to 32 radial links from the platform to individual MECs, thereby avoiding the need for any subsea equipment other than the cables themselves.

The designs of these sub-systems are developed in some depth, and the report offers background information relating to converter technologies and connectors. Section 8 reports the results of the LCOE appraisal for the two approaches.

4 Electrical Array Architecture Requirements

4.1 Introduction

This chapter aims to define the array architecture challenges by considering the various requirements and objectives that the system architect/designer is trying to reconcile. These requirements are grouped as follows:

- MEC connections and services;
- Operational requirements; and
- System design and topology.

This definition of the design challenges will provide a useful reference point for discussion of the array concepts offered by the three SSE contractor reports.

4.2 MEC Connections and Services

4.2.1 Introduction

In this section, three key services that the array system provides to each of the MEC devices in the array are considered. These are power take-off, auxiliary power and communications. Attention is often focused on the design of the power take-off system however, the other two functions must also be given due consideration in the development of suitable architectures.

4.2.2 Power Take-Off

The majority of MEC devices are variable-speed machines, reflecting the variability in the intensity of the primary energy input (i.e. wave or tidal energy). Some devices incorporate on-board systems to provide electrical power at grid frequency (50Hz in the UK and Europe). However, many devices do not offer this functionality; the electrical output of these devices varies in frequency depending on the rate of energy conversion.

For devices with AC output synchronised at grid frequency using onboard power conversion, the power take-off function is relatively straightforward. Multiple devices can be connected, in parallel, to a single AC circuit operating at grid frequency. Speed control is implemented on-board the device, allowing each machine to operate at the optimum speed given the availability of energy at its specific location. Various different array topologies are possible, including linear ‘strings’.

For devices with variable-frequency output where no power conversion occurs on the device, the power take-off function presents a more complex set of challenges. This is particularly the case when the aim is to collect power from multiple devices using a common electrical infrastructure. The challenges are:

- At some point, the variable-frequency output of the device has to be converted to grid frequency.
- Parallel connection of devices to a common circuit operating at variable frequency is not possible – each device must be free to control its own speed and output frequency. This means that there has to be a separate machine-side converter for each individual MEC.
- The machine-side converter, which is located off-board the MEC, controls the operating frequency and voltage of the device output. As such, this converter must be incorporated in the speed control loop of the device so that the MEC has control over its own speed. This requirement is discussed further under 'communications' (section 4.2.4).

4.2.3 Auxiliary Power

MEC devices that export electrical power at grid frequency will, in most cases, have an on-board arrangement that allows an auxiliary power supply to be derived from the main medium voltage (MV) connection to the device. This can be achieved using a dedicated auxiliary transformer, or a tertiary winding on the MV/low voltage (LV) transformer associated with the main power train.

For devices with variable-frequency output, the on-board derivation of a LVAC auxiliary supply is less straightforward. In most cases, these devices require auxiliary power to be supplied to the device from an external source. Array architectures for use with this type of machine must incorporate systems to derive LVAC power from the main power train. Moreover, the output cable system from each MEC must incorporate a LVAC circuit in addition to the main MV export circuit.

4.2.4 Communications

All MEC devices need a communications link to allow for control and data acquisition. This is normally implemented using an optical fibre interface, which can be integrated into the main power cable. Data rates for supervisory control and data acquisition (SCADA) systems are low.

Where the MEC device is reliant on an external machine-side converter to provide speed control, the communications link between the device and the converter must be specified in accordance with the requirements of the speed control loop. The data bandwidth required for the speed control is unlikely to be high, but data refresh rates will need to be high in order to ensure that the communications link does not introduce a large time constant into the control loop.

4.3 Operational Requirements

4.3.1 Introduction

In this section, we consider requirements relating to installation and maintenance activities at the site. These operations take place at sea, which is a difficult and hazardous working environment. Operations at site may be constrained to short time windows, either due to bad weather or, in the case of tidal energy sites, because of slack tide times.

4.3.2 Maintenance Intervals

The array system may include elements (i.e. hubs), which contain equipment such as power converters, transformers and switchgear. The array concept may involve installing the hubs on the sea-bed, or they might be tethered, floating structures. Either way, it is likely that inspection and maintenance of the equipment contained in the hub will involve recovery and re-deployment of the hub, so that maintenance can take place at a dockside facility.

Given the disruption and risks involved in this process, the equipment on the hub should be selected and specified so as to extend, as far as possible, the required maintenance interval. Intervals of less than 12 months are unlikely to be acceptable; the aim should be to achieve intervals of 5 years or more.

4.3.3 Deployment and Recovery

Each element of the array system should be designed to allow for rapid deployment at site. Elements requiring maintenance should also be designed to facilitate recovery and re-deployment. In order to address these objectives, consideration should be given to the following approaches:

- For sub-sea hubs or other elements installed on the sea-bed, the hub may be mounted on a base frame which is permanently fixed to the sea-bed. The mechanical interface between the hub and the base frame is designed to allow for quick engagement and release of the hub, while also preventing movement of the hub when it is fully engaged with the frame.
- To facilitate deployment and recovery, all cable links between devices and other elements should incorporate means of coupling and uncoupling each element from the wider cable network. Although it might be possible to use wet-mate connectors in certain cases, this may not always be the most appropriate or cost-effective solution. In the other cases, dry mate connectors may be used which will require the hub to be lifted out of the water to disconnect.
- The network of sub-sea cables will have to be installed piece-wise, in sections of manageable length given the time windows for installation work at the site. Means of coupling and uncoupling these sections, once installed, should be included in the design of the array system.

4.3.4 Electrical Safety

It is apparent that maintenance of the array infrastructure will involve un-mating and re-mating connections in the sub-sea cable network. Given the likelihood that this cable network operates at ‘high voltage’ (defined in the UK as 1000V or higher), it is essential that the design of the system provides suitable facilities to ensure that these operations can be carried out safely and that the electrical hazards are mitigated so far as is practicable.

It is possible that the un-mating and re-mating operations would be carried out without manual intervention, for example using a remotely operated vehicle (ROV) or similar. If this is the case, an appropriate risk assessment would need to be carried out in order to determine the appropriate level of mitigation against the possibility of working on a 'live' connector.

However, if the un-mating and re-mating operations involve manual manipulation of the connectors, the requirements are quite clear:

- The part of the network on which work is to be carried out must be isolated from all sources of energy; this includes the MEC devices as well as the grid.
- The part of the network on which work is to be carried out must be locally 'earthed down'. This serves two functions, it discharges any residual charge on the conductors, and it provides positive assurance that the conductors are no longer being energised from elsewhere in the system.

4.4 System Design and Topology

4.4.1 Introduction

The need to collect power from a large array of MEC devices is likely to influence the design of the array system. Although the selection of suitable electrical parameters (e.g. voltage levels and load currents) is important, these choices must be made in the context of an overall array concept and topology that is both practical and cost-effective. Moreover, the development of the array concept must be carried out with due regard to the availability and capability of suitable components (e.g. cables, connectors, converters)

4.4.2 Aggregating Power from Multiple Devices

The main attraction of using a common collection infrastructure to collect power from multiple MEC devices is the potential for reductions in cable costs and losses. At a conceptual level, this would be achieved by aggregating the power from a group of devices at a location reasonably close to the devices themselves, so that export to shore, or to a central collection point, can be achieved using a single cable for all of the devices in the group.

This approach offers a number of benefits, including:

- Reduction in total cable quantities and associated costs for supply and installation;
- Reduction in congestion at critical 'collection points', e.g. at the shoreline, or the offshore substation platform; and.
- Potential for lower cable losses.

- In practice, aggregation is the key driver for the design of the array system topology. Two alternative topologies are outlined here, for illustration:
- Hub and spoke – In this topology, each MEC device is connected to a local hub via a short cable. The hub contains equipment that enables the output from several devices to be aggregated and exported via a single export cable.
- Daisy-chain – This topology is similar to that used in wind farms. Each MEC device has the facility to connect an incoming cable from another device, as well as an outgoing cable. This means that several devices can be connected together in a ‘chain’ or ‘string’, with the outgoing cable from the last device providing the export connection.

The hub-and-spoke topology offers the potential to work with devices that produce variable-frequency output. However, to achieve this, the hub must incorporate multiple converters; one for each connected device as well as the relevant plant for aggregation and export to the grid connection. The daisy-chain topology involves connecting multiple MEC devices, in parallel, to a single collector circuit. As such, it only works with devices that provide an AC output synchronised at grid frequency.

4.4.3 Voltage Step-up

The output voltage of a MEC device is typically less than 10kV (AC, root mean square phase-to-phase). 6.6kV is a commonly used voltage (Alstom, Scotrenewables, Tidal Energy Ltd), though some developers have opted for higher voltages (Aquamarine Power has opted for 8.0kV; Schottel has gone for 13.8kV to meet the requirements of the local Canadian distribution network operator (DNO)).

The maximum load current in the output cable will be 87.5A with a ‘typical’ MEC rating of 1MW and output at 6.6kV. The current is doubled for a 2MW machine, which are being considered as the standard MEC size for this report, but even at this level (i.e. 175A) the output from a single device can be exported using a reasonably light and flexible cable (e.g. 3x50mm2 or 3x70mm2 copper conductors).

However, if the power produced by several machines is aggregated together for transmission to shore, or to a central collection point, the load current soon becomes an issue at 6.6kV. Total power per circuit is limited to around 6MW (i.e. 525A). This amount of current requires the use of much larger cables (e.g. 3x400mm2 or 3x500mm2 copper conductors). These cables will be expensive, heavy and hard to install. Moreover, cable losses will be significant if the power has to be transmitted over any distance.

This issue can be overcome by using a higher MEC output voltage or, alternatively, by stepping up the voltage externally in the array system. Subsea cables rated for voltages up to 36kV are readily available, with 72kV cables under development and testing for offshore wind farm arrays. At this voltage, it is possible to aggregate power from ten or more 1MW devices without having to use unduly large and stiff cables.

4.4.4 Fault Protection and Isolation

An outage or fault affecting the common collection infrastructure will result in loss of generation from all the devices that are connected to that infrastructure. However, if the faulty part of the infrastructure can be by-passed and isolated, it may be possible to bring some, or all, of the affected devices back into service before the fault repair is made. This requires the provision of switching facilities at suitable locations in the system.

For AC infrastructure, fault protection and circuit breakers are also needed to interrupt fault currents quickly. Without these measures, a short circuit fault will result in wider damage to the array system.

5 Component Availability and Limitations

5.1 Introduction

Given the requirements discussed in the previous chapter, it is apparent that most array system architectures will involve the use of components from the following categories:

- Power converters;
- AC components (transformers; switchgear); and
- Subsea cables and connectors.

The three contractors' reports contain information regarding the availability and capability of these components. The purpose of this chapter, is to provide a brief summary of this information, and to highlight any useful insights provided in the reports.

5.2 Summary Table

Table 1 provides two sets of information for each listed component:

- Page numbers for the relevant sections of the contractors' reports, together with a 'rating' for the coverage provided in each report (+++ = in-depth coverage; + = cursory mention)
- A summary of the information provided, regarding the electrical capability of the component and the recommended maintenance interval (MI)

	Coverage in the three SSE contractor reports			Summary of component capability / limitations		
Array system component	ABB	GE	Siemens	Voltage	Current	MI
Power converters						
LV converters	pp15-21, p34 +++	-	pp21-28 +++	690Vac	1.4MVA	Siemens 5 years
MV converters	pp15-21, p34 +++	-	p23 +	11kVac	20MVA	-
AC system components						
Transformers	pp24-25 ++	p12 +	pp29-30 +	72kV	60MVA	-
MV switchgear	pp23-24 ++	-	-	11kV [1]	630A	-
Cables and connectors						
Subsea AC cables	pp34-37 ++	-	-	33kV	630A	N/A

Array system component	Coverage in the three SSE contractor reports			Summary of component capability / limitations		
	ABB	GE	Siemens	Voltage	Current	MI
Subsea DC cables	pp34-37 ++	-	-	+/-7.5kV [1]	13MW	N/A
Wet-mate connectors	pp40-41 ++	pp32-33 +	pp16-20 +++	13.2kV	300A	N/A
Dry-mate connectors	pp41-42 ++	-	-	33kV	630A	N/A
Note [1]: These values are quoted in the ABB report, but are not maximum values for these components						

Table 2 Summary of component information provided in the SSE contractor reports

5.3 Analyses

5.3.1 ABB Report

Of the three contractors' reports, the ABB report offers the most comprehensive discussion of the component technologies and their capabilities in relation to the overall requirements for the array system. Section 2 of the report provides a discussion of AC/DC converter technologies, transformers and switchgear. Section 5 offers coverage of a similar standard relating to cables and connectors.

One notable feature of the ABB report is their coverage of passive converter technology (thyristor or diode bridge) in addition to active power converters using insulated-gate bipolar transistor (IGBT) or integrated gate-commutated thyristor (IGCT) devices. The report highlights some important advantages of using passive converters for subsea applications, notably their compactness, reliability, lower losses and cooling requirements, as well as low maintenance requirements. It also proposes a system architecture based on the use of passive converters at each MEC; this is discussed further in section 6 of this report.

Despite the caution that it expresses regarding the application of active converters in subsea applications, the ABB report does provide some indication of likely maintenance intervals for these devices (p20). It quotes mean time between failure (MTBF) values of 15 years for LV converters and 12 years for MV converters. These figures are based on regular maintenance of the converter system, which involves replacing auxiliary components (pumps and fans) after 20,000-30,000 hours of operation. In continuous operation, this corresponds to a maintenance interval of two to three years. However, it is possible that this interval could be extended to 5 years or more given that the converter would not be operating continuously at full load, and the possibility of providing dual-redundancy in the cooling system so that each pump or fan unit would only operate 50% of the time.

Finally, the ABB report provides some insights into the specification and design of transformers for subsea applications (pp24-25). ABB suggests using conventional liquid-cooled units with natural circulation for application onshore or on a fixed, surface-piercing platform. Liquid-cooled units are also preferred for application in subsea and floating hubs, but in this case the ABB recommends the use of forced cooling to minimise the size of the transformer. The report also presents the following recommendations:

- Apply marine standards, particularly with regard to vibration and shock;
- Specify an earth screen between windings, to prevent transmission of high-frequency noise and harmonics; and
- Use multiple LV windings in order to provide galvanic isolation of individual grid-side converters.

5.3.2 GE Report

Of the three contractors' reports, the GE report provides the shallowest coverage of the component technologies. The report focuses almost exclusively on array topology options, with only passing reference to individual components and their capabilities.

The report does include a discussion of zero sequence currents, and the electro-chemical effects of these currents in array architectures where the machine-side converter is housed in a hub, some distance away from the MEC (pp10-12). In this case, rapid erosion of exposed metal parts is likely, due to the return of zero sequence currents via the surrounding seawater. It recommends the use of a two-winding transformer, interposed between the generator and the converter, to block the zero sequence path and significantly reduce the galvanic effect.

5.3.3 Siemens Report

The Siemens report provides information and discussion about some components and focuses on the specific requirements of the converter and hub units set out in sections 5 and 6 of the report. The report provides coverage of wet-mate connector capabilities (pp16-17), and converter systems (pp21-28).

The section of the report focusing on converters includes a discussion of the likely maintenance requirements and service intervals for converters in subsea applications (p27). Siemens estimates the MTBF of their proposed power conversion train to be about 16 years. Although the service interval for the converter modules is normally set at 2 years, which is driven by the need to change air filters associated with the forced air cooling system. Given the likelihood that the atmosphere in the subsea converter unit would be largely dust-free, Siemens expect to be able to increase the service interval to 5 years for this application.

6 Proposed System Concepts

6.1 Introduction

Although there are many possible solutions to the array system design challenges, these tend to be based on a relatively small number of common approaches at the 'system concept' level.

The three contractors' reports each set out a number of different ideas for the design of the array system. The purpose of this chapter is to identify the areas of commonality between the designs in the three reports, as well as to note the useful points of difference between them.

6.2 Summary Table

Table 3 lists seven system concepts that feature in the designs proposed in the three contractors' reports. The first concept involves the use of a separate connection cable between each MEC and the collector substation; as such, it does not provide any aggregation of power from multiple MECs. The next two concepts are based on a 'daisy chain' topology and allow for aggregation of up to 10MW on each radial string. The last four concepts are based on a 'hub and spoke' topology and allow for aggregation of up to ten 1MW devices at each hub.

Aggregation topology	**System concept**	**Coverage in the three SSE contractor reports**		
		ABB	GE	Siemens
No aggregation	No conversion at MEC Separate cable for each MEC Conversion at shore or at collector platform	12.1.8 p109 ++	Option A pp13-14 +	SURFACE1 p76 +++
Daisy-chain	Conversion to DC at MEC MECs connected in parallel, on MVDC strings or loops	12.1.1 pp93-95 ++	-	-
	Full conversion and step-up at MEC MECs connected in strings or loops at 11kV or 33kV	12.2.2 pp114-117 ++	Option B pp15-17 ++	SUBSEA2&3 pp75-76 ++
Hub and spoke	Full conversion at MEC Voltage step-up at local hub Hubs on AC rings at 33kV	12.1.4 pp101-104 ++	Option X pp15-17 ++	SUBSEA1 p75, + HYBRID1 p76, +
	No conversion at MEC Full conversion and step-up at hub Hubs on AC rings at 33kV	12.1.5 pp104-105 +	Option C pp18-20 +++	-
	No conversion at MEC Conversion to DC at local hub Hubs on MVDC rings	-	Option D pp20-23 ++	-
	Conversion to DC at MEC No conversion at local hub Hubs on MVDC rings	12.1.2 pp95-99, +++ 12.2.1	-	-

Aggregation topology	System concept	Coverage in the three SSE contractor reports		
		ABB	GE	Siemens
		pp112-114, +++		

For each 'system concept', the table gives the following information:

- The contractor's own designation (or report section) that corresponds to the concept
- Page numbers for the relevant sections of the contractors' report
- A 'star rating' for the concept, based on the contractor's own LCOE assessment (+++ = lowest LCOE; + = high LCOE)

Table 3 Summary of 'system concepts' proposed in the SSE contractor reports

Table 3 reveals some discrepancies between the LCOE assessments provided in the three contractors' reports. In some cases, the contractors have arrived at different LCOE results, for array designs that share the same basic concept. This is likely to be due to a combination of the following factors:

- Important differences in the implementation of the concept, leading to different performance outcomes for the two designs; and
- Use of different methodology or assumptions for LCOE assessment.

There is no clear agreement between the three reports regarding which system concept offers the best LCOE performance. This indicates that there may not be a clear 'winner', and that different concepts may be suited to different application scenarios (e.g. near-shore projects, versus those further from land). Moreover, optimisation and 'value engineering' of a given system concept is likely to yield important improvements in performance.

6.3 Analyses

6.3.1 Concept 1 – No Aggregation

The most comprehensive development of this concept is provided in the Siemens report (sections 7.2 and 7.3, pp56-69). The key features of the Siemens design are:

- Collector substation (fixed, surface-piercing platform) with capacity to connect up to 32 x 1MW MEC devices.
- The collector substation contains eight 'banks' of frequency converters operating at a nominal AC voltage of 3.3kV.
- Each converter bank comprises 4 x 1MW machine-side converters, a common DC bus, and a single 4MW line-side converter.
- The collector substation also contains MV switchgear and two 33/3.3kV transformers, allowing for export to shore via a single 33kV subsea cable.

The Siemens collector substation is a substantial structure, with a jacket foundation to provide enough space for all the incoming cables. The topside structure has three decks: cable deck, main equipment deck and roof deck containing emergency refuge, control room and stand-by generator. The topside dimensions are estimated at 25m x 37m and the estimated topside weight is 750 tonnes.

Concept 1 corresponds to 'option A' in the GE report (section 4.1, pp13-14). In the GE design, the collector substation is located onshore, so total quantity and cost of cables is considerably higher than in the Siemens design. Key features of the GE design are as follows:

- Collector substation located onshore, with capacity to connect up to 36 x 1MW MEC devices.
- The collector substation contains 36 identical power trains (one for each MEC); nominal AC voltage is 6.6kV.
- Each power train comprises a machine-side converter, DC bus, capacitor and chopper, line-side converter, 33/6.6kV transformer and 33kV circuit breaker.
- Grid connection is via one or two 33kV circuits.

Given the costs and losses associated with the use of multiple shore cables, GE rated this design poorly with respect to the alternatives in terms of LCOE.

The ABB report includes an array solution utilising 16-turbine fixed 'hubs' (i.e. collector substations), with export to shore at 33kV (section 12.1.8, p109). The solution is not fully described so it is not possible to establish the extent to which it shares features with the Siemens SURFACE1 design. The ABB hubs only allow for connection of 16 MECs, compared with 32 in the Siemens design, so the cost of the structure is shared across fewer devices. This is likely to be a contributing factor in the ABB design LCOE not being as low as the Siemens design.

6.3.2 Concept 2 – DC Strings

Of the three contractors, ABB is the only one to propose this system concept. The ABB report contains a long section developing the concept of using a passive bridge to rectify the output of the generator at the device and explaining the merits of this approach compared with the use of an active power convertor (section 9.1, pp53-56). Another section (section 9.3, pp58-61) develops the idea of a 'single-turbine hub', which is essentially a sub-sea ring main unit. The hub allows the output cable from a single MEC to be coupled in to a DC ring that collects power from several MECs. This concept is further developed elsewhere in the ABB report (section 12.1.1, pp93-95).

The key features of the ABB design are:

- DC ring main operates at 15kV DC (+/-7.5kV).

- The hub includes motorised switches, allowing for off-load isolation of each MEC, or reconfiguration of the ring in the event of a cable fault.
- The hub also provides LVAC power to the MEC, via a step-down transformer (the ring cable also contains a MVAC circuit for distribution of auxiliary power to MECs and hubs).
- Each DC ring main would collect power from up to 15 x 1MW MEC devices; this indicates a maximum cable load current of 530A.

ABB expects that the hub would be large (3m diameter x 2.75m high), with a displacement of 15 tonnes.

6.3.3 Concept 3 – AC Strings

The clearest development of this concept is provided in the GE report (Option B, section 4.2, pp15-17). The key features of the GE design are:

- Each MEC contains its own back-to-back power converter, step-up transformer and MV circuit breaker.
- MEC output and collection is at 33kV AC.
- Each MEC provides the facility to connect two 33kV cables, so devices can be connected in a ‘daisy-chain’ arrangement.
- A single 33kV collector circuit is used to collect and export power from up to 36 x 1MW devices; this indicates a maximum cable load current of 630A (assuming unity power factor).

The ABB report also proposes two 100MW array solutions that utilise this concept (section 12.2.2, pp114-117). The design is not described in any detail, but the main features are:

- Each MEC contains its own back-to-back power converter, step-up transformer and MV circuit breaker.
- MEC output and collection may be at 11kV or at 33kV.
- A 100MW array requires either 10 x 11kV rings, or 4 x 33kV rings; this indicates a maximum cable load current of 525A in the 11kV case, or 440A in the 33kV case.
- Single, fixed collector substation platform with step-up to 132kV for export to shore.

Finally, the Siemens report proposes two array solutions that combine the daisy-chain and hub-and-spoke concepts. This arrangement is presented initially as a refinement of Siemens simple hub-and-spoke design, in which a single hub can aggregate power from ten 1MW MECs. By adding a second MEC to each of the ‘spokes’, the capacity of the hub can be increased from 10MW to 20MW, thereby making the hub more cost-effective (section 6.2.2, pp50-53). It is also possible to add a third MEC to each spoke, without exceeding the current limits imposed by the use of wet-mate connectors.

The key parameters of the Siemens design are:

- The power converter and step-up transformer are housed in a separate subsea converter module, rather than in the nacelle of the MEC itself.
- Converter output and collection is at 8.6kV (to suit voltage rating of Siemens Spectron 8 wet-mate connectors).
- With three 1MW devices connected in parallel, maximum cable load current is 200A – also within capability of wet-mate connectors.

6.3.4 Concept 4 – Hubs with Conversion at the MEC

In this concept, the hub is a largely passive device. Conversion of the MEC output to line frequency AC occurs either at the MEC itself, or at a nearby ‘converter module’.

The fullest development of this concept is provided in the Siemens report (section 6.1, pp47-50). The key features of the Siemens design are:

- Subsea hub provides facility to connect up to 10 incoming AC circuits from MECs, via wet-mate connectors at the hub.
- MEC circuits operate at 8.6kV; this indicates a maximum cable load current of about 70A for a single 1MW device.
- Hub contains 10 line switches (one for each MEC circuit), 30kV step-up transformer, and 30kV ring main unit (transformer circuit breaker and two line switches).
- Hub has facility to connect two 30kV cables; hubs can be daisy-chained together to form a ring.

The Siemens subsea hub is a large and complex structure, with an estimated weight of 150 tonnes (excluding foundation).

ABB also develops the hub concept (section 9.4, pp61-63). Two options are proposed and developed: a submersible hub (section 11.3, pp75-78) and a floating hub (section 11.6, pp82-89). These modules are used in a variety of array designs, including one with converters at the MEC (section 12.1.4, pp101-104). The key features of the ABB design are:

- Hub (may be subsea or floating) provides facility to connect up to 4 incoming circuits from MECs, via wet-mate connectors.
- MEC circuits operate at either 6.6kV or 11kV; this indicates a maximum cable load current of 90A at 6.6kV, or 55A at 11kV, for a single 1MW device.
- Hub contains line switches for the four MEC inputs, 33kV step-up transformer and 33kV switches.

- Hub has facility to connect two 33kV cables; hubs can be daisy-chained together to form a ring.
- A 30MW array requires 8 hubs connected in a single ring, with two 33kV export cables to shore.

For the submersible hub, ABB proposes to house the electrical equipment in a tubular vessel 8m long by 4m diameter. The floating hub is estimated at 30m long by 4.5m diameter, with a total weight of around 150 tonnes.

Finally, GE also proposes a design based on concept 4 (Option X, section 4.2, p16). The key features of the GE design are:

- Subsea hub provides facility to connect up to 4 incoming circuits from MECs.
- MEC circuits operate at 6.6kV; this indicates a maximum cable load current of 90A for a single 1MW device.
- Hub contains 4 x 6.6/33kV transformers and a 4-panel 33kV switchboard (1 panel for each transformer). There are no line switches for the 33kV ring cables.
- Hub has facility to connect two 33kV cables; hubs can be daisy-chained together to form a ring.
- A 30MW array requires 8 hubs connected in a single ring, with two 33kV export cables to shore.

Thus, there is a lot of commonality between the ABB and GE designs for this concept.

6.3.5 Concept 5 – Hubs with Back-to-Back Converters

In this concept, the function of the hub is extended to include power conversion as well as aggregation and voltage step-up. This means that the power conversion function does not need to be provided at the MEC itself.

The Siemens report does not offer a design for this concept. The ABB report develops the concept to a reasonable level, including embodiment design of the subsea hub (section 11.3, pp75-78) and array development (section 12.1.5, pp104-105). The key features of the ABB design are:

- Subsea hub provides facility to connect up to 4 incoming circuits from MECs, via wet-mate connectors.
- MEC circuits operate at 4.16kV; this indicates a maximum cable load current of 140A for a single 1MW device.
- Hub contains four back-to-back power converters, a single 33kV step-up transformer (with four secondaries for galvanic isolation of the converters) and a 33kV ring main unit.

- Hub has facility to connect two 33kV cables; hubs can be daisy-chained together to form a ring.
- A 30MW array requires 8 hubs connected in a single ring, with two 33kV export cables to shore.

In order to accommodate this equipment, ABB warns that the subsea hub will be a large and unwieldy structure (see figure 26, p76). The displacement would be around 200 tonnes, with dimensions of 20m x 10m x 5m high.

The GE report does not provide any real design development for the array, or any embodiment design for the hub. The key features of the GE design (Option C, section 4.3, pp18-20) are:

- Hub (may be subsea or floating) provides facility to connect up to 10 incoming circuits from MECs.
- MEC circuits operate at 6.6kV; this indicates a maximum cable load current of 90A for a single 1MW device.
- Hub contains ten machine-side converters coupled to a common DC bus, a single 10MW line-side converter, 33kV step-up transformer and 33kV circuit breaker.
- Hubs can be daisy-chained together to form a ring.
- A 36MW array can be implemented with 4 hubs connected in a string, with a single 33kV export cable to shore.

Given the amount of equipment required, the GE hub is likely to be a substantial structure. Without proper embodiment design, the ‘good’ LCOE rating awarded by GE for this concept may be optimistic.

6.3.6 Concept 6 – Hubs with Split Converters

In this concept, the hub contains only machine-side converters, and export from hub to shore (or to collector platform) is by MVDC rather than MVAC. Power conversion at the MEC is not required.

Of the three contractors, GE is the only one to propose this concept (Option D, section 4.4, pp20-23). The design is well-developed, including embodiment design for the subsea hub and array development (section 7.3, pp28-30). The key features of the design are:

- Subsea hub provides facility to connect up to 9 incoming circuits from MECs.
- MEC circuits operate at 6.6kV; this indicates a maximum cable load current of 90A for a single 1MW device.
- Hub contains nine machine-side converters coupled to a common DC bus, plus an additional converter for auxiliary supplies to the MECs devices.

- Each hub is connected to the collector substation (onshore or offshore) via its own radial DC cable circuit. These circuits operate at 10kV DC (+/-5kV), and carry a DC current of 900A.
- A 36MW array can be implemented with 4 hubs, and 4 MVDC export cables.
- Conversion from DC to AC takes place at the collector substation onshore.

The proposed design for the subsea hub is a simple tubular vessel with displacement of around 115 tonnes (see figure 16, p29). Although the dimensions of the vessel are not given in the report, this displacement would be consistent with a length of 15m and diameter of 3m. Given that the hub can aggregate up to 9MW of power, this appears to be an efficient and practicable solution. Interestingly, the design includes an integral support structure with external pontoons rather than a separate base-frame or foundation.

6.3.7 Concept 7 – MVDC Hubs

In this concept, the MECs provide rectified DC power to the hub. The hub itself is a purely passive device, possibly incorporating line switches to allow for isolation and reconfiguration. Export from hub to shore (or to collector platform) is by MVDC rather than MVAC.

Of the three contractors, ABB is the only one to propose this concept. The design is well-developed, including embodiment design for the subsea hub (section 9.3, pp58-61) and array development (section 12.1.2, pp95-99 and section 12.2.1, pp112-114). The key features of the design are:

- Hub (may be subsea or floating) provides facility to connect up to 4 incoming circuits from MECs, via wet-mate connectors.
- MEC circuits operate at 15kV DC (+/-7.5kV); this indicates a maximum cable load current of 70A for a single 1MW device.
- Hub contains six line switches: four for the MEC circuits, and two for the main ring cables.
- The hub also provides LVAC power to the MEC, via a step-down transformer (the ring cable also contains a MVAC circuit for distribution of auxiliary power to MECs and hubs).
- Hub has facility to connect two DC ring cables; hubs can be daisy-chained together to form a ring.
- A 30MW array requires 8 hubs connected in two rings, with four DC export cables to shore; this indicates a maximum export cable load current of around 500A.
- Conversion from DC to AC takes place at the collector substation.

The embodiment designs for the DC hub are similar to those that ABB proposes for concept 4. For the submersible hub, ABB proposes to house the electrical equipment in a tubular vessel displacing 25 tonnes. The floating hub is estimated at 30m long by 4.5m diameter, with a total weight of around 150 tonnes.

7 Conclusions

In the context of this project, the three SSE contractors' reports provide a useful starting point. Although all three contractors were given the same brief they produced different conceptual designs. While ABB, and to a lesser extent GE, attempted to offer a comprehensive set of alternative system concepts for elaboration and review, Siemens starts with some design solutions at the sub-system level and offers a limited number of array designs utilising these solutions.

Although it is possible to identify some conceptual commonality between array designs proposed by the different contractors, the differences between these designs are nonetheless significant. The LCOE results given in the three reports do not provide a consistent picture of which concepts are likely to offer the most cost-effective solutions for commercial-scale arrays.

A second observation emerging from the review is that the design of the array system cannot be addressed in isolation from the electrical design of the MEC device itself. Moreover, the assumptions regarding the MEC electrical design should be based on the characteristics of actual devices, rather than on postulated designs. At present, there are no device designs that produce rectified DC output, or any that produce grid-frequency AC at 33kV. Variable-frequency AC is the norm, at voltage levels from 6.6kV up to 13.2kV.

A third observation emerging from the review process is the need for a taxonomy for categorising and naming different array system concepts and variations on these concepts. The development of such a taxonomy would offer some obvious benefits for the further elaboration and study of alternative array designs, namely:

- A common naming system would improve clarity and remove the need for long descriptions of each concept or design, as seen in the ABB report.
- Use of a common naming system would facilitate the sharing and cross-fertilisation of ideas between different system designers and OEMs.
- The use of a systematic taxonomy could reveal the existence of 'gaps' – parts of the conceptual family tree which are under-populated. Development of new array concepts to fill these gaps could result in advances in array performance.

The final conclusion drawn from the review is that the performance of a given array concept cannot be evaluated in any meaningful way unless the design of the sub-systems that are used in the array (e.g. subsea hubs or converter modules) is elaborated to a reasonable extent. As a minimum, an attempt should be made to quantify the dimensions and weights of these sub-systems, and to consider issues of deployment (including the installation and connection of associated cables), operation and maintenance.

8 References

[1] ABB stage 2 report "Proposal for a commercial scale tidal array concept study", version PD1, November 2013

[2] GE report "Electrical infrastructure required for commercial scale tidal power arrays – selection of turbine collection topology", revision 04, September 2013

[3] Siemens phase 2 report "Electrical infrastructure of commercial scale tidal power array", revision 01, not dated

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