Comparing the electrical transmission systems for Archimedes Wave Swing parks

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Abstract

One way to satisfy the increasing need of clean and renewable energy is to convert the energy of the sea waves into electricity. In this paper Archimedes Wave Swing converters are used to extract energy from the sea and to create various wave parks with an average power of 45 MW. The converters are connected via electrical components in the most suitable way for power transmission to the grid resulting in different topologies. The aim of this paper is to analyze and compare these topologies according to annual energy yield, yearly losses, price and levelised production cost. The results show that economically the most attractive solution is if the Archimedes Wave Swing devices are equipped with back-to-back converters.

Keywords: Archimedes Wave Swing, Wave Energy Conversion, Wave Energy Converter Park.

Nomenclature

y = vertical floater position
M_f = floater mass
M_{ad} = mass representing the water above the floater
β_{wb} = hydrodynamic damping coefficient of AWS
β_{gen} = damping coefficient provided by generator
k_{aws} = the spring constant of the AWS
F_w = wave force vertical direction
E_w = energy of the waves
T_w = period of the waves
t = time
LPC = levelised production cost
TC = present value of all costs, discounted to year t=0
ANE_t = annual energy yield in kWh in year t

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1 Introduction

The utilization of renewable energy sources is a vital aspect for sustainable development. An as of yet unexploited energy source is ocean waves. According to [1], wave energy's estimated potential contribution in the world electricity market could be in the order of 2,000TWh/year. That is 10% of total world consumption of electrical energy. When comparing renewable energy sources, the main advantage of waves with respect to wind is that they represent a more constant and predictable energy source. Furthermore, unlike solar power, wave power has quite high density.

Over the last 20 years extensive research has been done to develop Wave Energy Converters (WECs). There have been several government-sponsored programs, particularly in the UK, Portugal, Ireland and Denmark [2]-[4]. Many WEC concepts have been proposed and explored, but only a few could reach a sufficient level of development to meet commercial demands in the near future. Some highly developed technologies include: Pelamis, a floating attenuating device with a hydraulic conversion system [5], Limpet, an oscillating water column converter located in the UK [6], the Danish Wave Dragon, which includes traditional hydropower technologies [7] and Archimedes Wave Swing [8]. It is not currently obvious which technologies will prevail. Moreover, as a WEC is chosen according to wave conditions in the sea where it will be deployed, more than one solution can remain attractive for the market.

However, it is not possible to produce sufficient energy using only one device, which means that converters need to be connected to form parks. This can be done using similar concepts and technologies as in wind parks [9], [10]. One of the latest proposals for connecting wind parks to the electrical transmission system is the North Sea electrical grid. It would establish connection between offshore renewable energy projects, primarily 100 wind farms, and the national grids of seven North Sea countries: Britain, Belgium, Denmark, France, Germany, the Netherlands and Norway [11]. It is not enough to achieve a sufficient production of energy for grid transmission, at the same time is needs to be economically viable.

Since the focus of current research is mainly on the operation of WECs, there has not been much research done on how to connect them into wave parks. A few concepts, though, for connecting WECs in arrays were proposed in [12]. Occasional references are made to wind farms because their widespread application and similar farm concept make them convenient for comparison.

A test facility in England, called the Wave Hub, offers an exceptional solution for linking WECs. It provides an offshore electrical connection to the national grid for arrays of wave energy generators and demonstrates and observes the operation of the devices in the actual sea conditions [13], [14].

In this paper, Archimedes Wave Swing (AWS) devices are used to set up parks with average power output of 45 MW. The authors present a method for modeling such a park could compare the results obtained by simulations of different wave-park topologies according to annual energy yield, yearly losses, price and levelised production cost.

The paper structure is the following: in Section 2 a brief overview about the AWS device is given. In Section 3 general layouts of wave parks are discussed and in Section 4 different topologies for wave farms are presented. Section 5 describes the simulation method while the simulation results are shown in Section 6. Finally, conclusions are given in Section 7.

Figure 1: The prototype of the AWS [15].

2 Archimedes Wave Swing

The AWS converter was developed by a Dutch company Teamwork Technology in 1993 [15]. AWS is an offshore point-absorber originally equipped with a linear generator as a power take-off system. It is submerged near the shore in approximately 50 meter deep water. Basically, AWS is an air-filled cylindrical steel chamber whose lid, the floater, is a vertically moving body, while the bottom part, the silo, is fixed. In Figure 1, the prototype of the AWS can be seen, which was submerged and tested in 2004 at the northern coast of Portugal [17].

The force is generated by the variations in wave pressure above the converter exciting the system and lifting and lowering the floater [16], [17]. When a wave crest is above the AWS, the volume of the chamber is reduced. The opposite occurs when a wave trough is above the converter. In this case, the pressure exerted by the water will be lower than the pressure inside the chamber, causing the lid of the chamber to rise (see Figure 2) [16].

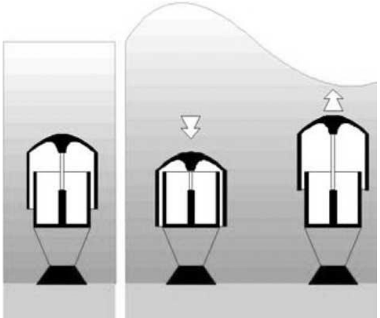

Figure 2: Operating principle of the AWS [16].

A direct-drive, permanent magnet linear synchronous generator is used for energy conversion. The considerations which determined the design of the generator are presented in [8], [17], [18].

The air within the chamber behaves like a spring whose stiffness can be adjusted by pumping water in or out of the chamber. In case the height of the waves exceeds the limit for the device, water brakes are activated in order to decrease the wave force acting on the system. These actions of the water brakes together with the generator provide damping. A simplified physical model describing this motion consists of a parallel connection of a spring and a damper which are attached together to mass of the floater. Equation (1) defines the vertical floater position.

$$\left(M_f - M_{ad}\right)\frac{d^2y}{dt^2} + \left(\beta_{gen} - \beta_{wb}\right)\frac{dy}{dt} + k_{AWS}dy = F_w \quad (1)$$

The maximum energy can be extracted if the device is tuned in resonance with the waves. This can be achieved by setting the two above mentioned damping coefficients to equal values while the stiffness can be adjusted by controlling the volume of the chamber. From (1) the maximum energy can be calculated as follows:

$$E_w = \int_0^{T_w} P_w dt = \int_0^{T_w} \beta_h \left(\frac{dy}{dt}\right)^2 = \int_0^{T_w} \frac{F_w^2}{4\beta_h} dt = T_w \frac{F_{w,\max}^2}{8\beta_h} \quad (2)$$

When the system is in resonance, the wave force acting on the floater, the floater position and speed are all sinusoidal functions of time with the period same as the period of the waves. Because the generator has to provide damping, the generator force is also a sinusoidal function of time [8].

However, applying the above mentioned principle to all waves would lead to floater strokes much longer and velocities much higher than the AWS is capable of converting. If this is the case, the damping is increased to reduce the stroke and the velocity to operating ratings within the AWS limits.

3 Park layout

The aim of the paper is to present the design of 45 MW AWS parks. The AWS which is used for simulations in this paper is a more powerful version of the prototype, with a maximum peak power of 3MW, which is assumed as an approximate magnitude of future commercial devices. The average power of one device is close to 1.5 MW. To reach the desired overall performance, 30 WECs need to be connected.

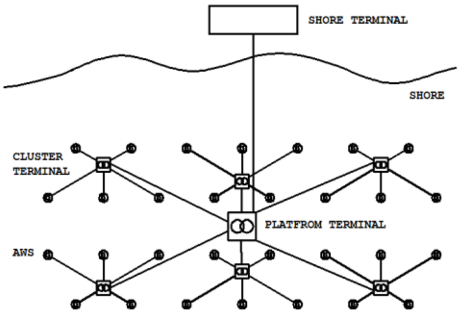

Figure 3: An example for star layout of an AWS park.

Two types of layouts are used when creating the parks: star (Figure 3) and string (Figure 4). Each layout consist six clusters, which are small groups of WECs (or any other type of generator) connected to a high voltage transformer or converter station if needed. These stations are placed on terminals in the water, called platforms. In the case of the presented AWS parks the WECs are divided into six clusters, each containing five devices.

Each layout can be divided into three parts according to voltage levels: low voltage (LV), middle voltage (MV) and high voltage (HV) regions. In the LV region, six converters are connected in series or in parallel depending on the configuration (in the case of AWS parks only parallel connection were choosen), further connected to cluster nodal platforms when necessary. In the MV region, the six clusters are connected to the main nodal point. In the HV region, the whole park is connected to land over a long Dc or Ac cable with a sufficient power rating to carry the full load of the AWS park.

Both string and star layouts have their own advantages and disadvantages. An advantage in the string layout is that the cable lengths are shorter than at the star layout, which equates to lower cable prices and cable losses. The greatest disadvantage of the string layout affects the reliability of the system: all the generators upward the place of a failure in a string have to be switched off and cannot be reconnected to the grid until the failed module has been repaired. Also, the number of WECs which can be connected to a string is limited by the power carrying capacity of the used cables. In case of failure in the star cluster, only the single failed device needs to be switched off, all the remaining WECs connected to the platform can stay in operation. However, the more frequent use of platforms in the star layouts will increase their price.

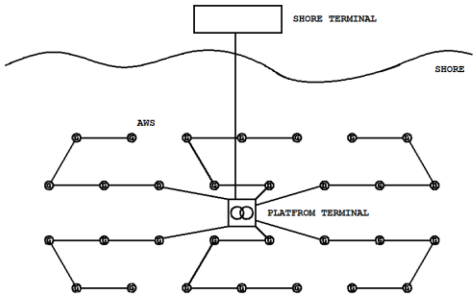

Figure 4: An example for string (octopus) layout of an AWS park.

It is important to emphasize in this paper that it has been assumed that all AWS units are identical and hydrodynamically independent from each other. These assumptions have two consequences. Firstly, the actual placement of AWS units within the park was not important. However, the assumption is, if a 200 m distance kept between two generators, they do not interfere with each other. Secondly, it is sufficient to assume the same working parameters for all 30 devices.

4 Inventory of topologies

The function of this electrical system is to convert the AWS fluctuating power into controlled electric power and to collect electric power from the individual AWS devices and transmit it to the shore with appropriate voltage and frequency. The system consists of amongst others: cables (Ac and Dc), back-to-back converters, rectifiers, inverters, transformers and step up converters. These elements were selected from a confidential database from several manufacturers, where all their parameters were listed. Unfortunately the electrical standards (voltage, power) set by manufacturers don’t exactly match the electrical properties of the AWS generator, resulting in mismatches during component selection (for example: the average power for an AWS is 1.5 MW while a back-to-back converter can convert 6 MW, which is an obvious over-dimensioning, raising the price unnecessarily). The components were selected with the aim with minimizing the error between the nominal power of the item and the actual power at the nod.

Depending on the ratio between the individual WEC power and the wave park power it is necessary to collect the power at least at one or possible more levels, each of them having different voltage level. The number of collection levels is a trade off between investment costs and losses. The minimum voltage level is limited by the current carrying capabilities of cables. Choosing a low voltage level will cause high losses and bring the necessity of parallel cables. On the other hand, the use of high voltage equipment is more expensive but losses will decrease [19].

Wave parks are operated as power plants, just like wind farms. They have to contribute to voltage control by controlling reactive power generation and do frequency control by controlling active power generation. With the use of voltage source converters the reactive power flow can be controlled. In systems without an energy buffer, this is difficult, because they depend on the incoming power from the waves. However this simulation takes place in steady state condition, simplifying this problem [15]. Moreover, it is assumed that at each AWS generator the sea state is exactly the same, but in reality there are phase shifts between the waves and in the whole power conversion. To take into account the real behavior of the generator used in the AWS, which produces pulsating power. At the same time its output voltage frequency and amplitude oscillates as well, meaning each generator needs its own converter and that all topologies become variable speed systems.

The topologies which are introduced here are similar to offshore wind farms presented in [19]. Eight topologies are presented in three groups: topologies with back-to-back converters, topologies with HVAC transmission and topologies with HVDC transmission.

A. Topologies with Back-to-Back converters (BB)

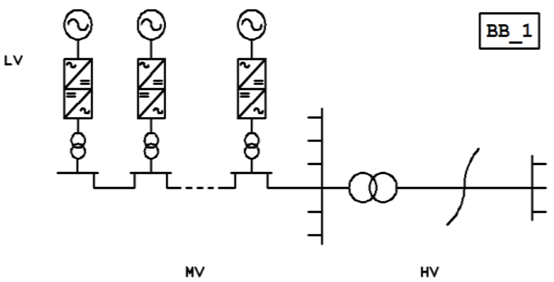

Figure 5: String layout of an AWS park with Back-to-Back converter topology.

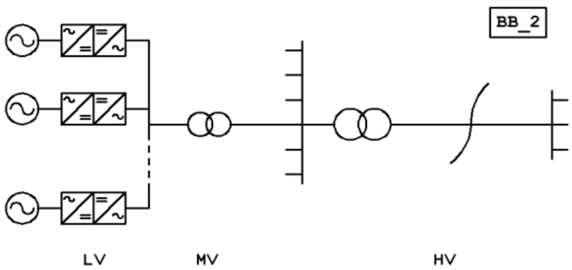

Figure 6: Star layout of an AWS park with Back-to-Back converter topology

Figure 5 and 6 show the two types of back-to-back converter topologies. In these two cases it is common that they both use back-to-back converter, but the difference between them is not only the layout, but also the number of transformers that are used. With the help of star topology, the generator transformers can be left out, but cluster platform transformers needs to be included. This leads to differences in losses and prices. In these types of topologies the back-to-back converters (in case of BB_1, also the transformers) are placed in the AWS. This makes maintenance harder, but the whole topology is cheaper. (In Table I. and II. the detailed characteristics are shown for these topologies.)

BB_1 string 45MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Back-to-back converter	4.16/5	6,25	30
Converter Transformer	5/33	6,25	30
LV Ac Cable	32	33	5 km
MV Ac Cable	32	33	1.5 km
Transformer	33/150	125	1
HV Ac Cable	150	190	5 km

Table I: BB_1 characteristics

BB_2 star 45MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Back-to-back converter	4.16/5	6,25	30
LV Ac Cable	32	6,25	5 km
Cluster Transformer	5/33	31.25	6
MV Ac Cable	32	33	3 km
Transformer	33/150	125	1
HV Ac Cable	150	190	5 km

Table II: BB_2 characteristics

B. Topologies with HVAC transmission (AC)

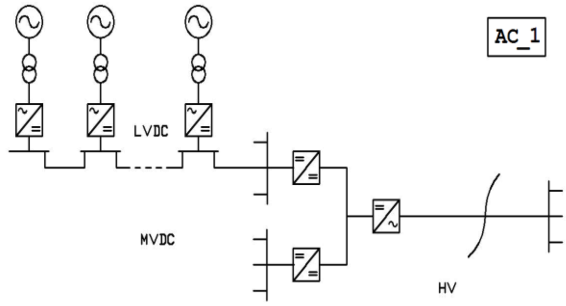

Figure 7: String layout of an AWS park with HVAC transmission topology and equipped with cluster terminals

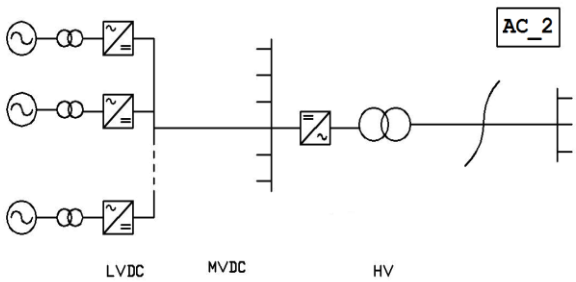

Figure 8: Star layout of an AWS park with HVAC transmission topology

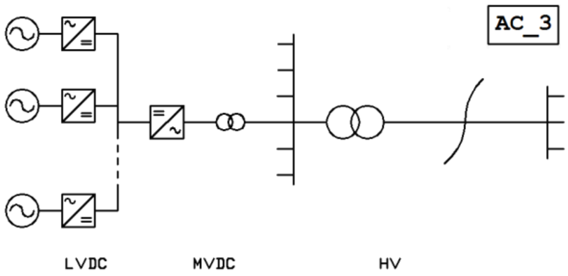

Figure 9: Star layout of an AWS park with HVAC transmission topology equipped with DC-DC converters and cluster platforms

The converter transformers used in the AC (and also in DC) topologies are over-dimensioned on purpose, to be able to withstand the varying frequencies produced by the generator.

If the AWS converters are equipped with various terminals (see in Figure 7-9), the back-to-back converters can be split into Ac\Dc converters and Dc\Ac converters. In this way more Dc transmission exists and also the number of converters used also decreases. AC_1 is outfitted with Dc-Dc converters, but unfortunately they can only transfer up to 50 MW power, which means two of them are needed to be put in parallel in order to keep the park capacity at the maximum rated level. At present the prices are very expensive for these devices, which make this type of topology extremely expensive. In AC_3 several transformers were eliminated by a common platform transformer, which also led to a price decrease. (In Table III., IV. and V. the detailed characteristics are shown for these topologies.)

AC_1 string 45MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Converter Transformer	4.16/33	31,250	30
Rectifier	33/70	6,250	30
LV Dc Cable	70	5	5 km
MV Dc Cable	70	33	1.5km
Dc-Dc converter	70/290	50	2
Inverter	290/150	125	1
HV Ac Cable	150	190	5 km

Table III: AC_1 characteristics

AC_2 star 45MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Converter Transformer	4.16/33	31,25	30
Rectifier	33/70	6,25	30
LV Dc Cable	70	5	5 km
MV Dc Cable	70	33	3 km
Inverter	70/33	125	1
Transformer	33/150	125	1
HV Ac Cable	150	190	5 km

Table IV: AC_2 characteristics

AC_3 star 45MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Rectifier	4.16/10	6,25	30
LV Dc Cable	10	5	5 km
Inverter	10/5	31.25	6
Cluster Transformer	33/150	125	6
MV Ac Cable	33	33	3 km
Transformer	33/150	125	1
HV Ac Cable	150	190	5 km

Table V: AC_3 characteristics

C. Topologies with HVDC transmission (DC)

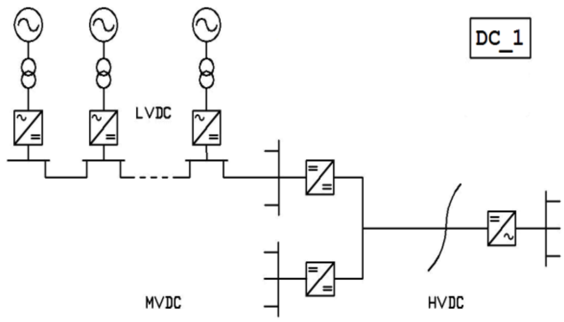

Figure 10: String layout of an AWS park with HVDC transmission topology equipped with cluster terminal

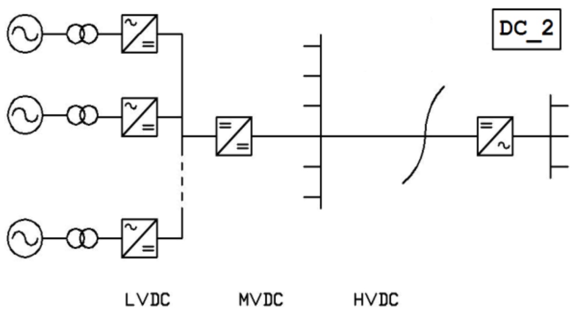

Figure 11: Star layout of an AWS park with HVDC transmission topology equipped with cluster terminal

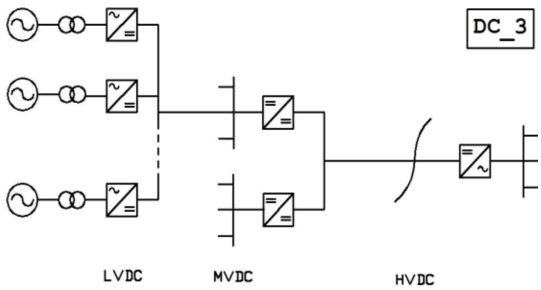

Figure 12: Star layout of an AWS park with HVDC transmission topology equipped with DC-DC converters

The biggest difference between the AC and DC topologies (see in Figures 11-12) is that HVDC level transmission is used to transmit power to the shore in the DC topologies instead of HVAC.

At DC_1 and DC_3 Dc-Dc converters are used, the same way as in AC_1, two of them are needed to be put in parallel to make it possible to reach the maximum rated power. This has the same effect, which is mentioned under 4.B. (In Table VI., VII. and VIII. the detailed characteristics of these topologies are presented.)

DC_1 string 90MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Converter Transformer	4.16/33	31,250	30
Rectifier	33/70	6,250	30
LV Dc Cable	70	5	5 km
MV Dc Cable	70	33	1.5km
Dc-Dc converter	70/290	50	2
HV Dc Cable	280	500	5km
Inverter	290/150	125	1

Table VI: DC_1 characteristics

DC_2 star 90MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Converter Transformer	4.16/33	31,25	30
Rectifier	33/70	6,25	30
LV Dc Cable	70	5	5 km
Dc-Dc converter	70/290	50	6
MV Dc Cable	282	100	3 km
HV Dc Cable	280	500	5km
Inverter	290/150	125	1

Table VII: DC_2 characteristics

DC_3 star 90MW	*Nominal Voltage* [kV]	*Nominal Power* [MW]	Nr. /length
Converter Transformer	4.16/33	31,25	30
Rectifier	33/70	6,25	30
LV Dc Cable	70	5	5 km
MV Dc Cable	70	33	3 km
Dc-Dc converter	70/290	50	6
HV Dc Cable	280	500	5km
Inverter	290/150	125	1

Table VIII: DC_3 characteristics

5 Simulation

Straightforward power flow calculations were carried out during simulation using Matlab to obtain results. The calculations start with voltage, current and power produced by the generator of the AWS. These calculations are based on a two main factors: Firstly on the wave spectrum (see in Figure 13) of the WEC, which tells the amplitude and period of the waves with a given probability (the given energy which can be transformed). Secondly on the parameters of the generator (how effectively this energy can be transformed to electricity).

All the models of the components (except the generator) have input and output parameters which are the following: voltage level, current - both in phasor form in case of complex case for three phase systems or real numbers for Dc transmission- and frequency which are the basis for apparent, reactive and real power. The input parameters depend on the components place in the park, they equal the previous components output values. At each component the input power is calculated based on the input current, input voltage and frequency. According to the input parameters a suitable component is chosen, whose input parameters match the circumstances where it will be placed. The output voltage at the given point in the topology usually can be selected according to the apparent power. Next, according to the power balance the output current of the component is calculated, which is obtained by defining the output power and the losses. If these values are known, the output power (voltage and current) can be determined. The real, apparent and reactive power can be calculated respectively if the voltage and current parameters are known. The output frequency is determined depending on the converter type and its control method. After the power is determined at each nodal point, it is transformed to energy taking the given time period and probability of each sea state into account.

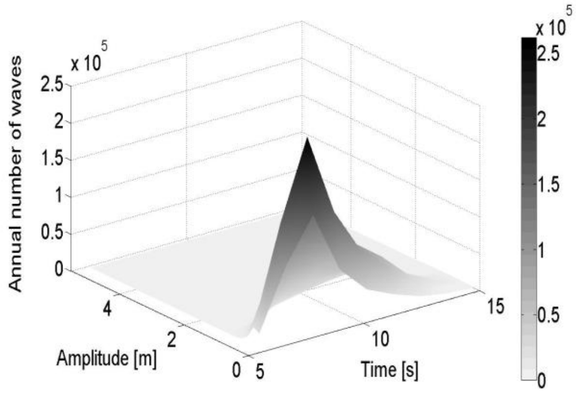

Figure 13: Annual number of waves at the test site [8].

The models used in this simulation have been developed according to this method. The elements for power transmission which were modeled in these simulations are: cable (Ac and Dc), back-to-back converters, rectifiers, inverters, transformers and step up converters.

To prevent the current from exceeding the maximum allowable value, its value was checked for each component individually [20].

6 Results

A. Annual Energy Yield and Yearly Losses

For each topology the input is the energy generated by the AWS and after subtracting the losses for each element in the transmission system, the Annual Energy Yield (AEY) is obtained. The generator losses are not included, because the price of the AWS is not know presently and in order to make fair comparison both of them should be included, or left out, which is the case in this paper. It can be seen that the AEY is approximately the same volume for each topology. The reason is that for every park the same wave spectrum was used as input and the converters are hydrodynamically independent from each other. Therefore at the levelised production costs the prices of the topologies will be the most important factor.

5km to shore	*Config. name*	*Config. type*	*AEY* [GWh/y]	*Yearly Losses* [GWh/y]
45 MW 5x6	BB_1	string	124,19	4,90
45 MW 5x6	BB_2	star	125,17	3,92
45 MW 5x3x2	AC_1	string	124,72	4,37
45 MW 5x6	AC_2	star	124,50	4,49
45 MW 5x6	AC_3	star	124,92	4,17
45 MW 5x3x2	DC_1	string	124,57	4,52
45 MW 5x6	DC_2	star	125,06	4,03
45 MW 5x3x2	DC_3	star	125,05	4,04

Table IX: The AEY and Yearly losses for the AWS Parks

The more components are used in the topologies the higher the losses will be. From Table IX. it can be seen that the BB_2 topology has the highest AEY and the BB_1 topology the lowest, although the difference is small. The yearly losses are evaluated the same way and they correspond to AEY. BB_1 has the highest losses and BB_2 the lowest.

B. Price and Levelised Production Cost

The final goal of the paper is to evaluate the economic parameters of the electrical infrastructure. The different topologies are compared to each other through price and levelised production cost (LPC) in Table X. It must be mentioned here that the price of the AWS and prices of the platforms for the power electronic devices are unknown and therefore left out, which means only the electrical infrastructure price is included in the calculations. The prices of the elements were obtained by contacting and collecting data from different manufacturers, but unfortunately they are not allowed to be published. LPC is the cost of production per unit of energy, expressed in actualized nominal money. This means that the LPC expresses the production cost in terms of current purchasing power, allowing comparison with other current costs of energy. The LPC is calculated the following way:

$$LPC = \frac{TC}{\sum_{i=1}^{n} ANE_t} \qquad (3)$$

5km to shore	*Config. name*	*Config. type*	*Price* [MEuro]	*LPC* [Euro/kWh]
45 MW 5x6	BB_1	string	21,09	0,030
45 MW 5x6	BB_2	star	19,06	0,027
45 MW 5x3x2	AC_1	string	95,78	0,138
45 MW 5x6	AC_2	star	67,41	0,097
45 MW 5x6	AC_3	star	68,82	0,099
45 MW 5x3x2	DC_1	string	85,27	0,123
45 MW 5x6	DC_2	star	150,85	0,217
45 MW 5x3x2	DC_3	star	94,58	0,136

Table X: The Prices and LPC of the topologies for the AWS Parks

As it was mentioned under 5.A the AEY and the Yearly Losses of the different topologies are not very different, which leads to the price of the configurations being in the most important factor of LPC. The LPC is in the range from 0,027 Euro/ KWh up to 0,217 Euro/KWh, which is comparable to LPCs of wind farms [21].

The results from the AEY and Yearly losses calculations showed that the BB_1 configuration had the highest losses while BB_2 the lowest. These two topologies are the configurations that are the cheapest. AC_1 and DC topologies are more expensive, because of the Dc-Dc step up converters.

7 Conclusion

The paper introduces several topologies for AWS parks with the power of 45 MW. Parameters of the individual park components are selected, modeled for power flow and economic calculations are derived. Eight different park topologies are defined and compared from the point of view of annual energy yield, yearly losses, price and levelised production cost. The calculations show that the annual energy yield and yearly losses has a similar value in each case, giving the price of the network the most important factor for developing parks. Back-to-back converter topologies appear to be the most economically attractive solution. At present HVDC transmission seems unsuitable for AWS parks, because Dc-Dc converter costs are particularly high. The levelised production cost compared to the wind parks is still slightly higher, but remains in a similar price range.

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