SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549 / https://doi.org/10.14445/23488549/IJECE-V9I11P101

Volume 9 Issue 11, 1-10, November 2022

Original Article

SACP Design Calculation for Monopile Wind Turbine

Bahat Taskiran

Department of Shipbuilding and Ocean Engineering, ITU, Istanbul, Turkey

Received: 07 October 2022 Revised: 14 November 2022 Accepted: 16 November 2022 Published: 30 November 2022

Abstract *- Cathodic Protection is the most typical method of preventing corrosion from steel surfaces of offshore structures. In addition to Cathodic Protection, the coating might be applied to provide more efficient protection. Especially for the system that Sacrificial Anode Cathodic Protection (SACP) is applied since SACP produces its anode without any generator. Hence coating has a strong combination with Cathodic Protection. On the other hand, coating types change based on thickness and layer. According to DNV (Det Nortske Veritas) guide, there are four coating types categorized in terms of Coating Breakdown Factor (f_c) and each type has different constant values of coating properties, which will be used for anode calculations. Using these parameters, anode requirements can be calculated using the DNV guide and differences among coating types can be observed. This paper aims to determine the differences between coated and uncoated structures in terms of anode type, anode size, environmental conditions and other factors by means of the DNVGL-RP-B401 guide. In order to observe these differences, a hypothetical wind turbine to be designed as SACP and located on the Canary Islands is considered in this study.*

Keywords *- Sacrificial Anode Cathodic Protection, Corrosion control, Design of cathodic protection, Anode calculation, Monopile wind turbines.*

1. Introduction

In order to generate sustainable electricity, offshore wind turbines are designed to capture the more robust, more consistent winds that blow over the oceans. These structures are supported by various foundation types depending on the seabed type and depth of the water. Due to their simplicity in construction and reduced cost when compared to other varieties, monopoile foundations are the most popular foundation type [1]. Although most offshore wind turbines are anchored to the seafloor up to 50 meters deep (with the exception of floating wind turbines, which are connected to the sea bed with mooring lines), monopile foundations perform better at depths of 40 meters and lower in terms of technical advantages. As a result, a monopile foundation is chosen for the wind farm foundation in question, and the structure is constructed 30 meters offshore of Canary Island. The Spanish Wind Energy Association, Asociación Empresarial Eólica (AEE), chose the Canary Islands as their preferred location because it plans to build at least 3 GW of offshore wind turbines in Spain by 2030. Based on the DNV RP B401 recommendations that were used in the preceding sections, these calculations will be evaluated. Figure 1 shows the order in which the design calculations proceed.

Corrosion can have an impact on both the monopile construction's internal and external sections. Regarding the exterior, the splash and atmospheric zones should be coated, whilst the submerged zone of the wind turbine should be coated with CP, as it was indicated in earlier sections. Hence, a coating is compulsory for all primary steel areas at the external part from 1 m below the mean seawater level [18]. Corrosion also affects the internal component of the system; therefore, corrosion control is quite important. However, these devices cannot prevent the complete volume of air; thus, CP or a coating system may offer a superior method for prevention. To prevent this, corrosion control can be achieved if the internal portion is confined from the air entrance. Experience has shown that using SACP for internal protection raises the acidity of the water in question.

Additionally, the internal component of SACP does not result in a significant change in hydrogen levels other than an increase in hydrogen sulfide levels [3]. Daily replacement of 5% water from J-Tube components is required for maintenance [4]. A coating might not be used since internal cathodic protection would be expensive and difficult to monitor because of the small interior surface area. Internal components have been left uncoated for this experiment.

It has been observed that many anodes required for protection interact with one another for the external part, resulting in protection for the submerged part because anodes are stacked. Therefore, when the current requirement decreases, a coating is a substitute for employing a large amount of anode to give protection. Standoff anodes can be used to choose an anode type. Based on the DNV B401 recommendation for coating quality, Category 3 coating for standoff anode aluminum anode mass can achieve up to 80% insulation [5]. The flash-mounted anode will also be used to categorize the differences between the standoff anode and the flash-mounted anode. Both anode shapes will be regarded as weighing 100 kg because common criteria will be followed [6].

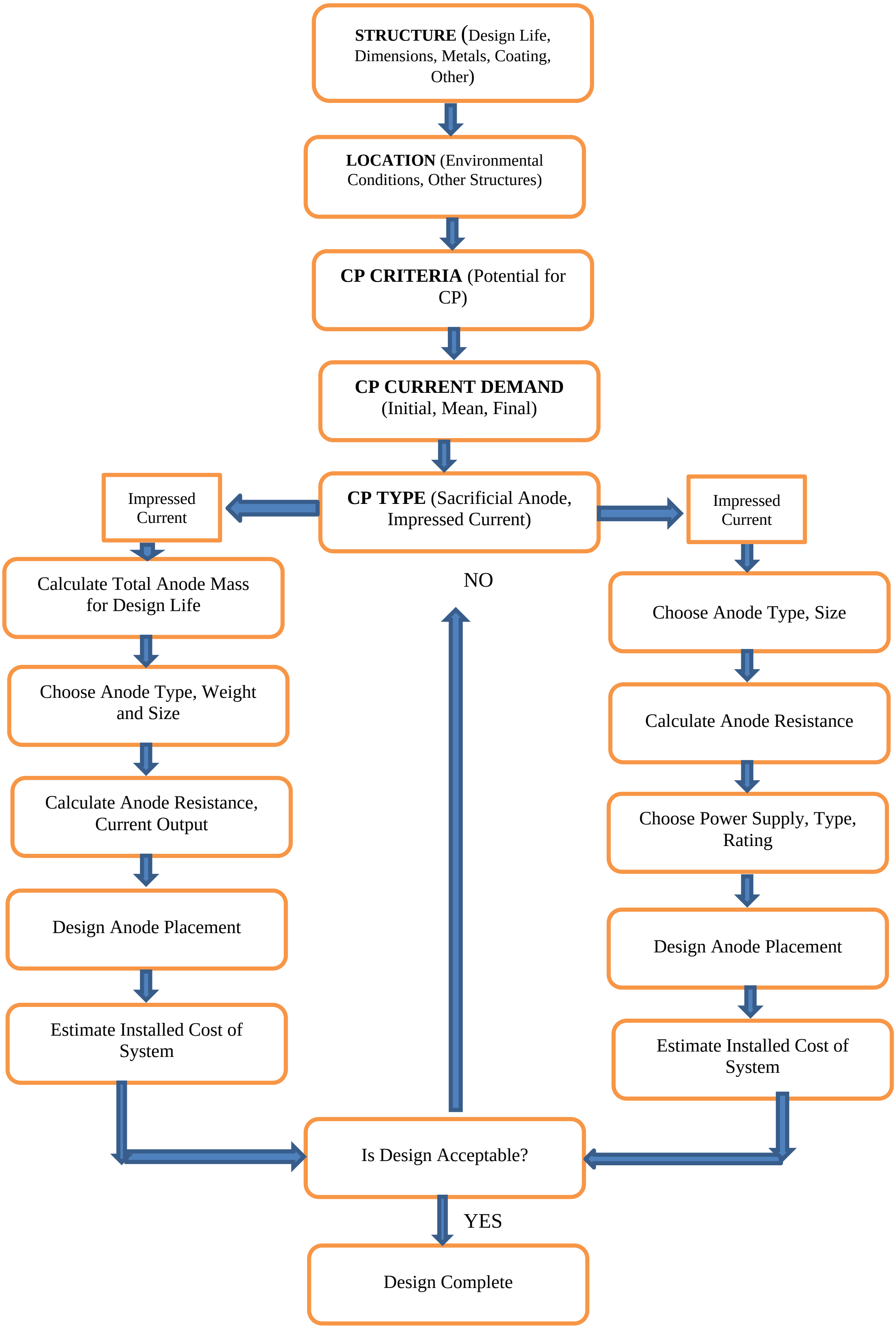

Fig. 1 The flow of design calculation (Swain, Conceptual Sacrificial Anode Cathodic Protection Design for offshore wind monopiles , 2021)

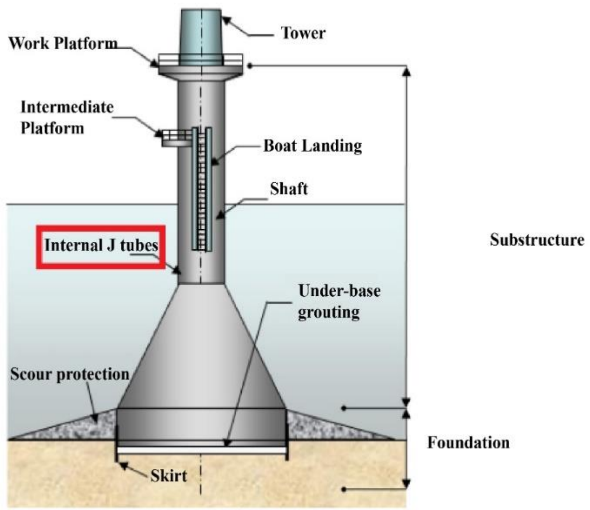

Fig. 2 Internal J Tubes for daily seawater changing (Swain, Conceptual Sacrificial Anode Cathodic Protection Design for offshore wind monopiles , 2021)

2. Calculation Procedure of DNV B401

Surface area, environmental factors, current demand, anode mass, steel type, total current output, and anode resistance should be gathered to follow the Sacrificial Anode calculations flow (Figure 1).

3. Structural and Environmental Parameters

Related parameters for the monopiles are;
Outer diameter: 8 m
Wall thickness: 120 mm
Total length: 90.5 m (50 m buried zone, 40 m column of seawater, 0.5 m mean water line (MWL))

The upper part and the monopile part are joined by a transition piece (TP) [19]. As seen in Figure 3, this piece begins below sea level and extends across the intertidal and splash zone. This area can be ignored while performing design calculations.

The building will be 20 kilometers from the coast of the island of Gran Canaria in the southeast. The lowest portion of the water's temperature is between 15 and 25 degrees, according to Puertos del Estado, a port agency of the Spanish government.

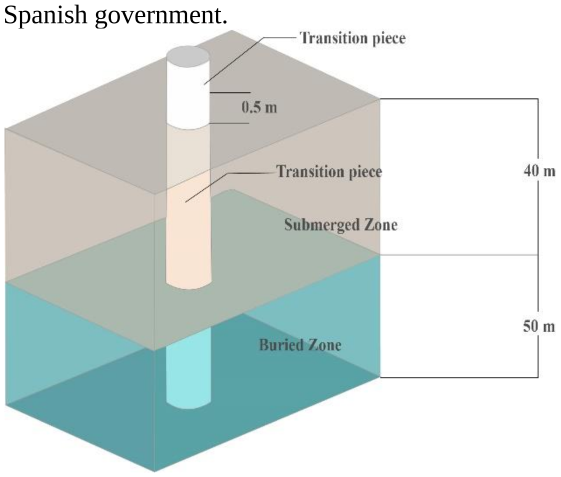

Fig. 3 Zones of Monopile Foundation

Salinity and dissolved oxygen levels of roughly 34,32 and 5,63 mg/L are the other saltwater parameters [8]. Southeast of Canary Island has a 30–40 cm s^{-1} Sedimental current [7]. Moreover, lastly, the wave height ranges from 1.25 to 2.7 meters [8].

A modern wind turbine of sufficient quality should normally last 20 years, although depending on the environment and good maintenance techniques, its lifespan could reach 25 years or even longer. However, maintenance costs will increase as the buildings get older. Severe corrosion rates develop during this lifespan when tidal and splash zones are exposed to the transition piece's cover due to sporadically dry and wet circumstances and oxygen concentration. Due to the lack of subsurface seawater in this zone, cathodic protection would be ineffective if applied; as a result, the coating is used in this area. Barrier coating will be developed for this area, and with a 20-year lifespan, it also meets the structure's design life.

4. Calculations and Results

4.1. Calculations of Surface Area

First, the surface area of the exterior section, which consists of splash zones, buried zones, and submerged zones, was measured. The steel surface area that needed to be protected was multiplied by the initial, mean, and current densities required to complete the polarization and maintain a potential more negative than -0.800 V based on the silver/silver chloride electrode to derive the CP current demand. Current demand is reduced because the coating breakdown factor considers covered locations. Additionally, since the calcareous deposits formed during the initial phase decrease the current demand, the initial current density must be higher than the mean current density [26]. Mean current density calculates the anode mass required for the entire design lifespan. However, the initial current density encourages rapid calcareous deposit formation, reducing the system's overall current demand over its expected lifespan.

Furthermore, finally, when the calcareous component and associated fouling are partially eliminated through waves or other circumstances, the final current density is used. In conclusion, all densities are necessary to satisfy CP's current demand [2]. Subtropical conditions of current densities for saltwater-exposed bare metal surfaces are employed when the temperature ranges between 15 and 25 degrees (Table 1).

Table 1. Current densities based on Canary Island conditions[26]

Sub Tropical (12^o-20^oC)			
Depth (m)	Initial	Mean	Final
0-30 m	0.170	0.080	0.110
30-100 m	0.140	0.070	0.090

Table 2. Calculations of surface area to be protected

Zone	**Length (m)**	**Surface Area (m^2)**
Mean Water Line	0.5	113.098
Submerged	40	1105.84
Burried	50	1357.17

4.2. Calculation of Current Demand

In order to obtain current demand, the formula is used as follows;

$$I_c = A_c * i_c * f_c \quad (1)$$

Where;
A_c : Surface Area
i_c : Current Density
f_c : Coating Breakdown Factor

Figure 2 in Table 2 shows surface areas. Table 1 also includes the recommended current density for the subtropical environment. The current design densities for each zone will be determined independently because they depend on the depth and temperature of the area. For the buried region, the current density is 0.020 A/m2 [9].

The application of coating reduces the current consumption. The estimate will adhere to DNV-RP-401 guidance and rely on the coating category. According to DNV, the categories are;

Category 1: Primer coat which is 50 μm nominal DFT (dry film thickness).
Category 2: Primer coat and one layer of coating for top, 150–250 μm nominal DFT.
Category 3: Primer coat and two layers of coating for top, 300 μm nominal DFT.
Category 4: Primer coat and three layers of coating for top, 450 μm nominal DFT.

The coating breakdown factor is taken to be 1 for the uncoated portions. For coated regions, the beginning, mean, and final parts are each calculated independently using the k_1 and k_2 values from Table 3. And finally, values are calculated by the formulas below;

$$f_c\,(initial) = k_1 + k_2 * \text{t}$$
$$f_c\,(mean) = k_1 + k_2 * \text{t}/2$$
$$f_c\,(final) = k_1 + k_2 * \text{t} \quad (2)$$

Table 3. Calculations of constants of Coating Breakdown Factor

Coating Category				
	I	**II**	**III**	**IV**
	k_1=0.1	k_1=0.05	k_1=0.02	k_1=0.02
Water Depth (m)	k_2	k_2	k_2	k_2
0-30m	0.1	0.03	0.015	0.012
30+m	0.05	0.02	0.012	0.012

Table 4 displays the outcomes for each category for a 25-year design lifespan. The values greater than 1 were displayed as 1 since the coating breakdown factor cannot be greater than 1. As shown in Table 5, current demand is achieved after each coating breakdown factor, and the result for each zone can be added to determine the total current demand for CP (Table 6).

Table 4. Results of each Coating Breakdown Factor categorized

Depth(m)	Coating Breakdowns	Uncoated	Cat I	Cat II	Cat III
0-30m	Initial	1	1	0.8	0.395
	Mean	1	1	0.425	0.2075
	Final	1	1	0.8	0.395
30+m	Initial	1	1	0.55	0.32
	Mean	1	0.725	0.3	0.17
	Final	1	1	0.55	0.32

Compared to Category II and Category III, Category I has the lowest reduction, according to Table 4. It should be highlighted that, given the existing demand, Category II and III offer greater convenience. Calculations for the submerged zone are divided into two calculations because the inputs used for calculations will differ at depths of 30 meters and above.

As stated before, anode mass is calculated by the formula below;

$$M_a = \frac{I_{cm}.t_f.8760}{\text{u}.\epsilon} \quad (3)$$

Where;
I_{cm} : Current demand with mean current density
t_f : Design life
u: Anode utilization factor
ϵ: Electrochemical capacity of design

Design lifespan characteristics and current demand, including mean current demand, are already known. The total number of hours in a year is 8760. Final and initial current demands do not have a constant value, which is why mean current demand is used in the anode mass formula.

Table 5. Current Demand results for each zone

Depth (m)	Zone		Unco.	CAT I	CAT II	CAT III
0-0,5	MWL	Initial	19.22	19.22	15.38	7.59
		Mean	90.47	90.47	38.45	18.57
		Final	12.44	12.44	9.95	4.91
0,5-30	Submerged	Initial	145.27	145.27	116.21	57.38
		Mean	683.60	683.60	290.53	141.85
		Final	94.00	94.00	75.20	37.12
30-40,5	Submerged	Initial	49.14	49.14	27.09	15.76
		Mean	24.62	18.85	7.38	4.18
		Final	31.66	31.66	17.41	10.13
40,5-90,5	Burried	Initial	190.00	190.00	104.50	60.80
		Mean	95.00	68.87	28.50	16.15
		Final	122.14	122.14	67.18	39.08

Table 6. Total Current Demands

Totals	Uncoated	Coating I	Coating II	Coating III
Initial	403.63	403.63	268.18	141.53
Mean	893.69	861.79	364.86	180.95
Final	260.24	260.24	169.74	91.24

Regarding anode type, zinc anodes are often preferable for SACP [20], but aluminum was chosen since it is more cost-effective electrochemically and requires less weight than zinc or magnesium. However, choosing an anode should not be based just on these aspects. A standoff aluminum anode, for instance, might offer a good condition in terms of weight or electrochemical efficiency. Still, these characteristics might also adversely affect the structure's wave loading throughout the duration of its design life. According to the DNV recommendations, the utilization factors of standoff and flush-mounted anodes are 0.90 and 0.85, respectively. The electrochemical capacity of the design (ϵ), the recommended value depends on the zone to be computed, and these values are preferable up to 30° average yearly degrees, according to the DNV recommendation in Annex A. The electrochemical capacity of aluminum based on this guideline is 1500 Ah/kg for the sediment zone and 2000 Ah/kg for seawater [11].

The result of the calculations for anode mass is shown in Table 7 below;

Table 7. Anode mass calculations

	Uncoated	CAT I	CAT II	CAT III
Standoff	108732.2	104851.1	44391.3	22015.5
Flush Mounted	115128.2	111018.8	47002.5	23310.6

4.3. Number of Anode Calculations

The anode number needs to meet the requirements listed below;

$$C_{a\,tot} = N.\, C_a \geq I_{cm}.\, t_f.8760$$

$$I_{a\,tot\,i} = N.\, I_{ai} \geq I_{ci}$$

$$I_{a\,tot\,f} = N.\, I_{af} \geq I_{cf} \quad (4)$$

Where;
I_{cm} : Current needed for the design life
$I_{tot\,i}$: Total initial current demand
$I_{tot\,f}$: Final initial current demand
C_a : Current capacity for each zone
$C_{a\,tot}$: Total current capacity
I_{ai}, I_{af} : Individually initial and final current outputs

Hence, the current capacity should be first known to calculate the anode number. In order to obtain current capacity for both coated and uncoated design, the value of anode mass along with electrochemical capacity and utilization factor are used in the formula as follows;

$$C_a = m * \epsilon * u$$

Where;
m = anode mass (kg)
ϵ = Electrochemical capacity (Ah/kg)
u = Utilization factor (Ohm)

The anode dimensions must be planned so that the required number of anodes can satisfy initial and final polarization output requirements and current demand during the design lifespan.

4.4. Anode Current Output

The anode current output must satisfy both initial and final current needs. Ohm's Law is used, as previously stated, to calculate the current output.

$$I_c = N.\, I_a = \frac{N.(E_c{}^o - E_a{}^o)}{R_a} = \frac{N.\Delta E^o}{R_a} \quad (5)$$

Where;
$\in_a$: Circuit design potential of anode selected (V)
R_a : Resistance of anode (Ohm)

I_a : Individual current output (are to be calculated for initial and final current separately)
$\in_c$: Potential of protective design

Individual results can also be found by removing N in the formula. $\Delta E°$ is the difference between steel potential and closed-circuit anode potential; hence, -1.05 V – 0.8V in silver/silver chloride reference. Additionally, using the following equations, anode resistance, or R_a, should be determined separately for Stand-off and Flush mounted anode geometries. When calculating the final anode resistance for both anode geometries, the final length can be considered 10% shorter than the initial length [21].

For standoff:

$$R_a = \frac{\rho}{2.\pi.L}\left(ln\frac{4.L}{r} - 1\right) \quad (6)$$

For Flush mounted:

$$R_a = \frac{\rho}{2.S} \quad (7)$$

In terms of standoff geometry, they typically acquire more trapezoidal dimensions due to being pressed into molds. The square root of the cross-sectional area should be divided by pi to determine the standoff radius. A formula for estimating anode resistance is developed using this radius value, anode length, and seawater resistance.

Regarding Flush mounted geometry, the arithmetic average of the anode's width and length should be used. The factors of salinity and temperature are used to generate the following seawater resistance. The chosen location's minimum temperature and salinity are 15 and 34,32 mg/L, respectively. Therefore, the resistance of seawater is 0.26 Ω·m.

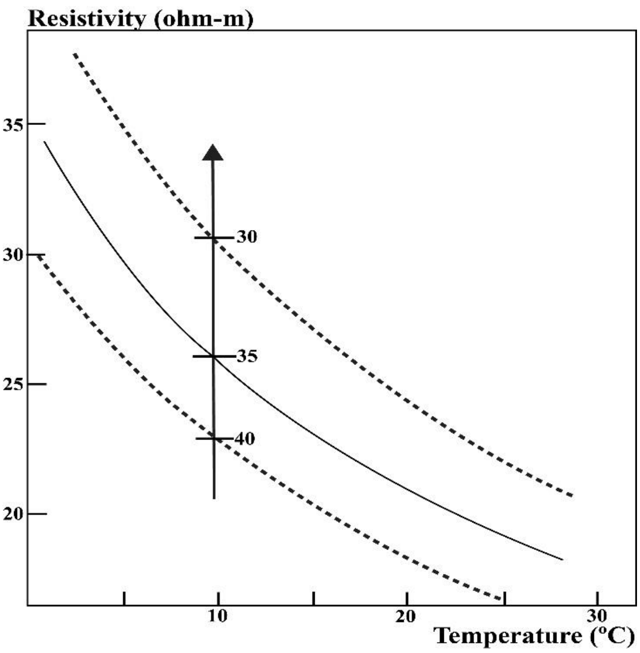

Fig. 4 Seawater resistivity by using temperature and salinity (DNV, 2010)

The formula below was used to determine the mass of anodes left over after using the usage factor to determine anode resistance for both initial and final;

$$m_{af} = m_{ai}.(1 - u) \quad (8)$$

Where;
m_{af} : Final anode mass
m_{af} : Initial anode mass
U : Utilisation factor

The final volume formula uses this final mass value coupled with the anode density.

$$V_f = \frac{m_{af}}{I_a} \quad (9)$$

The final shape of standoff and Flush mounted anodes can be expected to be cylindrical because the geometric shape will be altered later.

5. Discussion

The design and use of cathodic protection systems determine the long-term condition of offshore constructions. According to DNV - RP-401, calculations of anode properties for the outside surface of a hypothetical structure put in 30 meters of water off the Canary Islands are obtained for both coated and uncoated structures. The SACP system uses standoff and flush-mounted anode forms to protect its 25-year design life, and the total currents that must be calculated must be more significant than or equal to the mass required for the design lifespan. The mass of the anode required for a standoff-shaped, uncoated CP system is 108732.2 kg; however, using a CAT I, CAT II, or CAT III coating might reduce this mass to 104851.1, 44391.3, or 22015.5 kg. These results for anode mass make it clear that coating significantly impacts how much anode mass is used compared to an uncoated structure. The uncoated mass for Flush mounted is 115128.3 kg, but it can be reduced to 111018.8, 47002.5, or 23310.6 kg by using CAT I, CAT II, or CAT III coating according to the DNV guidance. The standoff anode design has a modest benefit over the Flush mounted anode shape despite the anode mass not differing significantly between the two. As a result, standoff shapes will be chosen for the design, and Table 8 provides calculations for coating categories. Current capacity, mean current demand, year of design life, and total annual hours are all used to determine the number of anodes. Based on these standoff shape characteristics from Table 9 and the assumed uncoated structural design life of 25 years, 490 anodes are needed. If the coating is used, category III coating, it could be dropped to 170.

Due to system area variability, particularly in complex systems, some components may be inadequately insulated while others may be overprotected. On the other hand, the amount of anode, location and dimension is quite significant to deliver the maximum protection to current demand [25]. Therefore, anode distribution is important if the system is to be completely protected. In essence, because of installation concerns, getting complete security is challenging. Additionally, using fewer coating layers in poorly protected areas is preferable to avoid worsening the anode distribution. In terms of anode distribution, the transition piece is one of the problematic locations.

Table 8. Anode Calculations for Uncoated Structure

Shape of Anode			
DIMENSIONS			
Width A	0.24	0.17	m
Width B	0.285	-	m
Length	2	1.42	m
Density	2700	2700	kg/m^2
Thickness	0.2	0.153	m
Initial Mass	221.52	97.565	kg
Final Mass	22.152	14.634	kg
Final Volume	0.08	0.05	m^2
Electrochemical Capacity	2000	2000	Ah/kg
Closed Circuit Potential	-1.05	-1.05	V
Seawater Resistance	0.26	0.26	$\varphi.m$
Utilization Factor	0.9	0.85	Ohm
Anode Resistance($Initial$)	0.135	0.163	Ohm
Anode Resistance($Final$)	0.141	0.179	Ohm
Anode Current($Initial$)	1.85	1.53	Amphere
Anode Current($Final$)	1.77	1.39	Amphere
ρ: $seawater\ resistance\ (ohm.m)$ L(m): anode length r: radius S(m): arithmetic mean of anode length and width			

Table 9. Calculations based on Long Slender Stand-off anode

Dimensions	Uncoated	Coating I	Coating II	Coating III	
Length	2	1.6	1.188	1.55	m
Width	0.26	0.198	0.175	0.187	m
Thickness	0.2	0.166	0.151	0.153	m
Initial Mass	221.52	147.56	96.236	129.875	kg
Final Mass	22.152	14.756	9.623	12.987	kg
Final Volume	0.08	0.05	0.03	0.05	m^3
Anode Resistance($Initial$)	0.027	0.031	0.036	0.031	Ohm
Anode Resistance($Final$)	0.029	0.032	0.038	0.033	Ohm
Anode Current($Initial$)	9.26	8.06	6.94	8.06	Amp
Anode Current($Final$)	8.62	7.81	6.57	7.57	Amp
Number of Anodes	490	710	461	170	
Mass of Anodes	108732.32	1048551.1	44391.3	22015.5	kg

The high anode number exposes the surface area to more layers if the uncoated design is considered. However, if CAT III coating is used, 170 anodes will be used rather than 490. As a result, fewer layers will be utilized, and the layer effect will less impact the anode distribution.

In order to protect steel, electricity moves from the anode into the seawater, creating a potential difference due to insufficient polarization for a specific distance when too far from the anode in terms of corrosion prevention; this condition could be problematic. To prevent inadequate anode distribution and current weakness, design calculations must be carefully provided, and calculations findings must be followed. Regarding ICCP and SACP designs, it is simpler to produce practical design estimates for ICCP systems because, unlike SACP systems, it is not necessary to identify the adequate anode mass to generate electricity over the design lifespan. Additionally, ICCP's utilization of dielectric isolation between the cathode and anode and its high voltage output from the DC power source produces an efficient distribution solution. Mohamed A. El-Reedy (2012) highlighted the significance of anode shapes for SACP systems by using the contrast between a flush-mounted and standoff anode as an example. Based on this illustration, standoff anodes produce greater current output and, consequently, better current distribution even if the anode mass applied is the same for both anode shapes [6]. A standoff anode's advantage is also that it has a higher usage value (For standoff: 0.90, for Flush mounted 0.85).

A useful way to choose anode locations for CP systems to obtain better potential distribution is to study optimization approaches using Boundry Elements Technology (BEM), a numerical modeling tool [10]. A boundary element analysis system (BEASY) can be integrated into the CP process prior to installation. Useful results for the effectiveness of anodes to be installed in the system can be evaluated as it was done in the experiment described in Z Shamsu's (2011) experiment, SIMULATION OF GALVANIC CORROSION USING BOUNDARY ELEMENT METHOD [22]. On the other hand, Pei Y. Hang and Robert A. Adey revealed an approach using global optimization of the ship's ICCP with a global optimization method called 'Simulated Annealing'. Anodes were sent element to element to the related area. Due to the numerous function evaluations involved in the computation process, they discovered that the SA technique is quite expensive and that the potential distribution on the ship hull must be anticipated using the BEM model at each step [23].

The results show that, except for a slight variation in mean current demand, there is no difference between uncoated and Category I in terms of outcomes for current demand. In contrast, an obvious benefit can be obtained using the current demand for Category II or Category III coating. The cathodic breakdown factor's value is the key element in why current demand performs worse in Cat II and Cat III. When "good coating" is used, according to DNV RP 401, the coating breakdown factor can lower current demands by almost 80% [11]. Additionally, according to anode mass results, Cat I is experiencing only a slight reduction, whereas Cat II and Cat III are experiencing significant reductions.

Following the recommendation of DNV RP B401, current densities are shown in Table 1. According to DNV, the current densities in this table are determined by the water's depth and climatic zones. The corresponding zone's current densities are 0.150, 0.070, and 0.090 for beginning, mean, and final density, respectively, according to the current densities displayed in Table 6.1 in Singh's 2014 book Corrosion Control for Offshore Structures [11]. DNV recommendations are higher than these values, which results in higher current demands and better protection in this experiment. This method enables the use of ISO standards for additional offshore structures (such as pipelines, which employ ISO/DIS 23221).

The material should be chosen based on time. It should meet an effective tolerance against fatigue damage because the system's design lifespan is estimated to be 25 years, making long-term corrosion loss visible. S355 steel is used to build most wind turbine monopile systems. Understanding the corrosion-fatigue characteristics of extra-large wind turbines in-depth and choosing the suitable steel with care can help with design optimization and cost-effectiveness [12]. Testing can be used to provide the best understanding of fatigue during the course of a design [13]. In order to prevent failure, maintenance should be carried out on a regular routine based on the data obtained from testing. The other corrosion-fatigue problems may happen due to environmental conditions, such as marine growth, which may result in microbially induced corrosion.

Due to the system's designated place in a subtropical region, increased temperatures and humidity will be observed during the design process. Therefore, it is crucial to check on offshore wind farms regularly. A daily note containing all the information gathered from monitoring systems should be kept.

The system's anode type might be either magnesium or zinc. However, the aluminum anode was chosen because of its greater electrochemical capacity, lighter weight, and financial advantage. Compared to zinc or magnesium, aluminum will become passive sooner, reducing the current output. As a solution, aluminum can be alloyed with mercury, gallium, or indium to prevent passivation [14]. Additionally, the coating will reduce the amount of anode, which is essential from an environmental standpoint.

Coated design selection is also preferable in terms of environmental factors. Cathodic protection causes the anode to dissolve over time, which causes marine sediments and water pollution. According to (C. Rousseau) 's study, providing information about the mobility of zinc anode in marine sediments, a high amount of zinc anode concentration was observed in the seawater and surface sediments due to anode dissolution. Additionally, as seawater can remobilize zinc anodes, existing sediments also lead to secondary contamination [15]. Whereas, the case study of (C. Gabelle a), providing information about the dissolution of Aluminum anodes, shows that while anodic dissolution did not significantly raise the concentration of Aluminum in the seawater, sediments tested near the sacrificial anodes revealed both enrichment and increase in Aluminum mobility[16]. Aluminum would therefore be a better choice in terms of less pollution than the zinc anode, in addition to being a good choice due to its electrochemical capability and low weight. While the average aluminum concentration in coastal waters is 0.5-0.68 g/L, the average zinc concentration is 4 g/L or higher.
According to Martin Mederos et al. (2011), González et al. (2017), Schallenberg-Rodrguez and Garca Montesdeoca (2018), and Martin Mederos et al. (2018), the area between Tenerife Island and the west-northwest coast side, as well as the south and southeast parts of the island, are the best locations to exploit the offshore wind source in Canary Island [24]. Regarding authorization, Asociación Empresarial Eólica (AEE) supports the construction of offshore wind farms, and this experiment may consider a CP design for 4 assembled wind structures. According to

DNV calculations, if an uncoated structure with 108 tonnes of anode mass is proposed for each structure, the total amount of aluminum used in the system will be 532 tonnes for each building. By using Coating III, it could be reduced to 88 tonnes.

6. Conclusion

DNV recommendations are used to obtain the sacrifice cathodic protection design calculations for the hypothetical offshore wind farm in the Canary Islands. Initial parameters that are relevant (such as seawater parameters, initial mass, length, and thickness) have been collected from relevant offshore online sources and earlier studies on CP design calculations. On this basis, it is obvious that cathodic protection design for an offshore system requires using initial parameters to provide a reliable result.

These calculations are meant to identify the variations between coated and uncoated construction in terms of anode and mass requirements. The findings make it clear that using Coating II or Coating III would significantly positively impact the lowering of current demand, the need for anodes, and the overall mass of anodes. This beneficial impact will reduce anode costs, consumption, and aluminum emissions, resulting in a better anode distribution so that Cathodic Protection can be used across a wider area due to a smaller IR drop.

Therefore, utilizing coating in combination with cathodic protection can reduce the risk of corrosion, and design calculations support this approach. Despite the coating's relative effectiveness, other considerations still need to be made. For example, the standoff anode has a better result in design calculation, but considerations may be given to provide better resistance. Materials that reduce environmental dangers by using corrosion inhibitors, altering chemical reactions, avoiding sea pollution, adjusting temperature or velocity, etc., can also be included when discussing environmental factors. Finally, one of the essential factors is anode distribution. Therefore, providing a better distribution and combining the different zones to reach every place is the central point of cathodic protection design.

References

[1] C Lavanya, and Nandyala Darga Kumar, "Foundation Types for Land and Offshore Sustainable Wind Energy Turbine Towers," *2nd International Conference on Design and Manufacturing Aspects for Sustainable Energy ICMED*, vol. 184, 2020. *Crossref*, https://doi.org/10.1051/e3sconf/202018401094

[2] Caglar Erdogan, and Geoffrey Swain, "Conceptual Sacrificial Anode Cathodic Protection Design for Offshore Wind Monopiles," *Ocean Engineering,* vol. 235, pp. 1-5, 2021. *Crossref,* https://doi.org/10.1016/j.oceaneng.2021.109339

[3] Alex Delwiche, Patrick Lydon, and Isaac Tavares, "Concerns over Utilizing Aluminium Alloy Anodes in Sealed Environments," *NACE - International Corrosion Conference Series,* 2017.

[4] Alex Delwiche, and Isaac Tavares, "Retrofit Strategy using Aluminium Anodes for the İnternal Sections of Windturbine Monopiles," *NACE - International Corrosion Conference Series*, 2017.

[5] Ali Sarhadi, Asger Bech Abrahamsen, and Mathias Stolpe, "Optimal Design of Galvanic Corrosion Protection Systems for Offshore Wind Turbine Support Structures," *Corrosıon Engıneerıng Sectıon*, vol. 74, no. 7, pp. 829-841, 2018. *Crossref,* https://doi.org/10.5006/2688

[6] M. El-Reedy, "*Offshore Structures: Design, Construction and Maintenance*," 2nd Edition, pp. 373-395, 2012.

[7] Antonio Martinez, Esther Perez, and Miguel Bruno, "Variation of the Tidal Properties Around Gran Canaria," *Oceanologıca Acta*, vol. 22, no. 1, pp. 19-30, 1999.

[8] Ministry of Transport Mobility and Urban Agenda. [Online]. Available: https://www.puertos.es/en-us/oceanografia/Pages/portus.aspx

[9] Veritas, Det Norske, "*Cathodic Protection Design*," Recommended Practice DNV-RP-B401, pp. 12-19, 2010.

[10] E. Santana Diaz, and R. Adey, "Optimizing the Location of Anodes in Cathodic Protection Systems to Smooth Potential Distribution," *Advances in Engineering Software,* vol. 36, no. 9, pp. 591-598, 2005. *Crossref,* https://doi.org/10.1016/j.advengsoft.2005.03.003

[11] Ramesh Singh, "*Corrosion Control for Offshore Structures: Cathodic Protection and High-Efficiency Coating*," Gulf Professional Publishing, pp. 71-77, 2014. *Crossref*, https://doi.org/10.1016/C2012-0-01231-8

[12] Victor Igwemezie, Ali Mehmanparast, and Athanasios Kolios, "Materials Selection for XL Wind Turbine Support Structures: a Corrosion-Fatigue Perspective," *Marine Structures*, vol. 61, pp. 381-397, 2018. *Crossref,* https://doi.org/10.1016/j.marstruc.2018.06.008

[13] Feargal Brennan, and Issac Tavares, "Fatigue Design of Offshore Steel Monopile Wind Substructures," *Proceedings of the Institution of Civil Engineers – Energy,* vol. 167, no. 4, pp. 196-202, 2014. *Crossref,* https://doi.org/10.1680/ener.14.00005

[14] Branko N. Popov, and Swaminatha P. Kumaraguru, "*Handbook of Environmental Degradation of Materials*," Second Edition, 2012.

[15] C. Rousseau et al., "Cathodic Protection By Zinc Sacrificial Anodes: Impact on Marine Sedimentmetallic Contamination," *Journal of Hazardous Materials*, vol. 167, no. 1-5, pp. 954-957, 2009. *Crossref,* https://doi.org/10.1016/j.jhazmat.2009.01.083

[16] C. Gabelle et al., "The Impact of Aluminium Sacrificial Anodes on the Marine Environment: A Case Study," *Applied Geochemistry*, vol. 27, no. 10, pp.2088-2095, 2012. *Crossref*, https://doi.org/10.1016/j.apgeochem.2012.07.001

[17] T.N.Guma, and James A.Abu, "A Field Study of Outdoor Atmospheric Corrosion Rates of Mild Steel around Kaduna Metropolis," *SSRG International Journal of Mechanical Engineering,* vol. 5, no. 11, pp. 7-21, 2018. *Crossref,* https://doi.org/10.14445/23488360/IJME-V5I11P102
[18] Jutta Stutzmann, "*Cathodic Corrosion Protection in the Context of Lifetime Extension of Monopile-based Offshore Wind Turbines,*" Master's Thesis in Master Programme Sustainable Energy Systems, 2017.
[19] Kingsley Sunday, and Feargal Brennan, "A Review of Offshore Wind Monopiles Structural Design Achievements and Challenges," *Ocean Engineering,* vol. 235, 2021. *Crossref,* https://doi.org/10.1016/j.oceaneng.2021.109409
[20] C. Rousseaue et al., "Cathodic Protection by Zinc Sacrificial Anodes: Impact on Marine Sedimentmetallic Contamination," *Journal of Hazardous Materials,* vol. 167, no. 1-3, pp. 953-958, 2009. *Crossref,* https://doi.org/10.1016/j.jhazmat.2009.01.083
[21] Mohamed Abdallah El-Reedy, "*Offshore Structures*," Second Edition, 2020.
[22] Zaifol Samsu, "Simulation of Galvanic Corrosion Using Boundary Element Method," *Journal of Nuclear and Related Technologies,* vol. 8, no. 2, pp. 78-83, 2011.
[23] Hang Pei Yuan, and Adey Robert A, In: Brebbia CA, Power H, Editors, Boundary Elements XXI, pp. 195-206, 1999.
[24] Giovanni Barone et al., "Supporting the Sustainable Energy Transition in the Canary Islands: Simulation and Optimization of Multiple Energy System Layouts and Economic Scenarios," *Frontiers in Sustainable Cities,* 2021. *Crossref,* https://doi.org/10.3389/frsc.2021.685525
[25] ABS, Guidance Notes on Cathodic Protection of Offshore Structures, 2018.
[26] Yong Bai, and Qiang Bai, "*Subsea Engineering Handbook*," Second Edition, pp. 472-473, 2019.