Material Selection for Vertical Axis Tidal Current Turbine using Multiple Attribute Decision Making (MADM)

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Abstract. Marine renewable energy technology has attracted many stakeholders to develop due to its enormous resources and future potential advantages. One of them is the vertical axis tidal current turbine technology, which converts the kinetic energy of flowing seawater to electrical energy. To operate the vertical axis tidal current turbine, especially its metallic components of the supporting structure, it is required to endure the aggressive and corrosive marine environment. Thus, deciding the good and suitable material for this application is very important in order to reduce the risk and hazards from the sea environment. The purpose of this paper is to decide the best metal material for the support structure of the vertical axis tidal current turbine. Therefore, the material candidate and their properties were firstly reviewed and discussed. Then, the material selection was processed through Multiple Attribute Decision Making (MADM) and formulated via the method of a Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). The result of material selection was carbon steel AISI 1045 as the selected material instead of other candidates such as carbon steel AISI 1018, stainless steel, and nickel aluminium bronze. Thus, it is expected to perform well to be used for the support structure and endure the marine hazards during the vertical axis tidal current turbine application.

1. Introduction

Ocean energy has the potential to have an important role in the world’s future energy system [1]. Of all ocean energy technologies, tidal current energy is an eco-friendly and abundant energy source by converting it to electricity [2,3]. Tidal current energy also has distinct advantages of high predictability and regularity, which makes the exploitation of tidal current energy more attractive [4,5]. One of tidal current energy technology types is Enermar’s Kobold Turbine that is a full-scale prototype of vertical axis tidal current turbine deployed in Messina Strait, Italy [6]. The main component of vertical axis tidal current turbine consists of a blade, shaft, and connecting arm. While the vertical axis tidal current turbine technologies operate in the sea environment, there are challenges that are common to all. The nature of marine renewable energy technologies means that the greatest challenge is the operation in the marine environment itself [7]. Marine renewable energy devices are exposed to highly dynamic, harsh marine environments, and complex stresses, i.e.: corrosive stresses, mechanical stresses, and biological stresses [8]. Therefore, it is important to provide materials that can meet the vertical turbine design criteria, withstand those challenges, and ensure the survivability of the devices.

Several material selections have been done to choose suitable material for ocean energy technology. Thakker et al. [9] studied a new approach for material selection strategy of wave energy extraction.
turbine blade material. It resulted that the GFRP was the optimum material and followed by titanium alloys in the second-ranking. Shiekh-Elsouk et al. [10] also reviewed the material selection for tidal turbine blades and discussed the parameters that affect the performance of the tidal turbine. They considered several materials such as carbon steel, stainless steel, aluminum, titanium, and composite and concluded that the composite was the most suitable material for a tidal current turbine blade. The composite material is usually used for the prime mover or the moving parts (turbine blade) of ocean energy [11], thus it can affect the performance efficiency of the turbine blades. Besides, several investigations of composites have been done to obtain the optimum design of tidal turbine blades such as Grogan et al. [12], Davies et al. [13], and Wang et al. [14]. In the other side, the supporting structure of the ocean energy device requires more materials in great quantities compared to the turbine blade [15]. Moreover, the information on the material selection for the support structure of the vertical axis tidal current turbine is still limited.

Therefore, this paper aims to choose the suitable metal material that will be used in the vertical axis tidal current turbine, especially the supporting structure. First, the material candidate and their properties will be reviewed and discussed. Followed by the process of material selection and it will be performed using multiple attribute decision making (MADM). Lastly, the material selection of the vertical axis tidal current turbine will be concluded.

2. Methods

The decision making is performed using Multiple Criteria Decision Making (MCDM) and one of its types is Multiple Attribute Decision Making (MADM). The MADM is the selection of an alternative from a set of options which is based on prioritized attributes of the options [16]. Several types of methods are formulated based on MADM, and one of them is the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) to find the best alternative.

With using the TOPSIS method, the chosen alternative will be near to the ideal solution and it will be far from the negative-ideal solution. There are several steps to conduct the TOPSIS method [17]:

1. Build the decision matrix of the alternatives after reviewing several material candidates, and construct the normalized decision matrix. The criteria are divided by total outcomes vector (the Euclidean length of a vector). So that the elements $r_{ij}$ of the normalized decision matrix $R$ are:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n}x_{ij}^2}}$$

(1)

2. Construct the weighted normalized decision matrix by setting the value weight $W = (w_1, w_2, ..., w_n)$, so the weighted normalized matrix $V$:

$$V = W \times r_{ij} = \begin{bmatrix} w_1r_{11} & \cdots & w_nr_{1n} \\ \vdots & \ddots & \vdots \\ w_1r_{m1} & \cdots & w_nr_{mn} \end{bmatrix}$$

(2)

3. Determine the value of the ideal solution and negative-ideal solution. The ideal solution $V^+$ and negative-ideal solutions $V^-:

$$V^+ = \{(\max V_{ij}| j \in J_1), (\min V_{ij}| j \in J_2), i = 1,2,3, ..., m\} = \{v_1^+, v_2^+, ..., v_n^+\}$$

(3)

$$V^- = \{(\min V_{ij}| j \in J_1), (\max V_{ij}| j \in J_2), i = 1,2,3, ..., m\} = \{v_1^-, v_2^-, ..., v_n^-\}$$

(4)

Where:

$J_1 = \{j = 1,2,3, ..., n\}$ and $j$ is related with benefit criteria

$J_2 = \{j = 1,2,3, ..., n\}$ and $j$ is related with cost criteria

4. Estimate the separation measure. Then the separation distance of each alternative from the ideal solution and negative-ideal solutions can be attained by the n-dimensional Euclidean distance method. The distance (in a Euclidean sense) $S_i^+$ of each alternative from the ideal solution is defined:

$$S_i^+ = \left[\sum_{j=1}^{n}(V_{ij} - V_{ij}^+)^2\right]^{0.5}$$

(5)

And the distance from the negative-ideal solution is defined:
3. Results and Discussion

3.1. The Candidate of Material Selection and Their Properties

There are several important factors that should be considered in material selection for the ocean structure: (1) the physical and chemical properties of materials, (2) cost and availability, (3) fabrication facility, and (4) maintenance costs [18]. During the material selection, the physical characteristics of the material are very important to consider. Especially, the yield strength value of material as the first factor that needs to be taken into consideration, and then followed by the value of Young’s modulus and ductility. Hence, those factors were used to screen alternative metal materials.

Some metals with the marine grade that is usually applied in marine environment are carbon steel and steel alloy, aluminum, stainless steel, copper, bronze, and brass. Among those metals, carbon steel, stainless steel, and nickel aluminum bronze (NAB) offer good corrosion resistance, hence they are selected to be material candidates used on this research. Carbon steel consists of three types, that is low, medium, and high. For offshore structures, the low or medium carbon steel is usually used, for example, AISI 1018 and AISI 1045. Carbon steel AISI 1018 is mild/low and it is widely used for engineering materials and in ocean applications [19]. AISI 1018 has good strength and ductility, its cost is affordable, and it is easy to cut and to be welded. Carbon steel AISI 1045 is a medium type. It is easy to weld and set up through the machine and can receive heat treatment.

Stainless steel is well known for its general corrosion resistance due to its passive characteristics (oxide film) [20]. It has the composition of chromium, nickel, molybdenum, etc. and its example is SS304, SS316, and SS316L. SS316 and SS316L have better corrosion resistance compared to SS304. The difference between SS316 and SS316L is located on the carbon composition. SS316L has a maximum carbon content of 0.03% compared to SS316 that has a maximum carbon content of 0.08%. “L” represents the abbreviation of “low.” Thus, SS316L is easier to weld than SS316. Because of its higher carbon content, SS316 will be more prone to weld decay or welding damage. In other words, the SS316L is more resistant to intergranular corrosion, and their costs also do not differ greatly. SS316L can provide high strength and ductility properties close to carbon steels (S355) [21], which is the main steel grade used in offshore structures. However, SS316L is susceptible to pitting corrosion and crevice corrosion [22,23]. This localized corrosion (pitting and crevice corrosion) emerge because the passive film breaks down influenced by high chloride ion concentration, low dissolved oxygen, and acidity [24].

For NAB, it is one of the copper-based alloys and it has good strength and corrosion resistance that is commonly used in marine applications, especially ship propeller [25,26]. Oldfield and Masters [27] stated that NAB has good pitting corrosion resistance, reasonable erosion-corrosion resistance, comparable resistance to cavitation and fatigue, and immune to stress corrosion cracking (SCC). Its corrosion resistance is originated from a protective oxide film with thickness for about several hundred nanometers [28]. The average erosion-corrosion rate of NAB in fresh unfiltered seawater with velocity over the range of 7.6-30 m/s [29]. For the tidal stream velocity, the peak tidal current velocity ranges about 2-3 m/s which is lower compared to the ship propeller applications [30]. However, the turbine rotating conditions are in quite dynamic and turbulent conditions and so there is a chance that the protective layers are unable to repassivate and local attacks can occur. Therefore, carbon steel AISI 1018 and AISI 1045, stainless steel 316L and nickel aluminum bronze (NAB) C95800 are selected to be candidates used on this material selection.

3.2. Material Selection for Vertical Axis Tidal Current Turbine

The material selection for the vertical axis tidal current turbine was conducted using the TOPSIS method [16,17]. There are four selected material candidates, i.e.: AISI 1018, AISI 1045, NAB C95800, and
SS316L. Table 1 presents the decision matrix of four types of alternative with their properties. For the availability attribute, it was determined by considering the easiness to get the material and the readiness of the vendor to provide materials at any time. The availability value is shown in Table 2. Furthermore, the four material candidate properties related to the application of vertical axis tidal current turbine were evaluated.

Table 1. The decision matrix with four types of alternative from the metallic materials and its properties [19,27,31-33]

| Material      | Yield strength, MPa | Young Modulus, GPa | Tensile strength, MPa | Density, g cm⁻³ | Cost, IDR kg⁻¹ | Corrosion rate, mm year⁻¹ | Availability |
|---------------|---------------------|--------------------|-----------------------|-----------------|----------------|--------------------------|---------------|
| AISI 1018     | 370                 | 205                | 440                   | 7.87            | 10400          | 0.026                    | 4             |
| AISI 1045     | 450                 | 200                | 585                   | 7.87            | 25850          | 0.02                     | 4             |
| SS 316 L      | 205                 | 193                | 485                   | 8               | 67550          | 0.5                      | 4             |
| NAB           | 240                 | 130                | 620                   | 7.5             | 486000         | 0.05                     | 2             |

Table 2. The values of the material availability

| Value | Availability       |
|-------|--------------------|
| 1     | Not Available      |
| 2     | Less Available     |
| 3     | Quite Available    |
| 4     | Available          |
| 5     | Very Available     |

To apply the TOPSIS method, the decision matrix was normalized using equation (1). The normalization was in order to change the data value on the numeric column into data with the same scale, without disturbing the difference in the value range. It is only necessary if its properties have a different range. The results of the normalized decision value are shown in Table 3. Then, the normalized decision matrix was weighted using equation (2) to demonstrate the importance of material potentialities. The values of weight are: W={5,4,4,2,4,4,5}. The values of weight were based on Jadidi et al. [34] and its results of the weighted normalized decision matrix are shown in Table 4.

Table 3. The normalized decision of the material selection

| Material      | Yield strength, MPa | Young Modulus, GPa | Tensile strength, MPa | Density, g cm⁻³ | Cost, IDR kg⁻¹ | Corrosion rate, mm year⁻¹ | Availability |
|---------------|---------------------|--------------------|-----------------------|-----------------|----------------|--------------------------|---------------|
| AISI 1018     | 0.5584              | 0.5555             | 0.4093                | 0.5037          | 0.0212         | 0.0516                    | 0.5547        |
| AISI 1045     | 0.6792              | 0.5420             | 0.5442                | 0.5037          | 0.0526         | 0.0397                    | 0.5547        |
| SS 316 L      | 0.3094              | 0.5230             | 0.4512                | 0.5120          | 0.1374         | 0.9929                    | 0.5547        |
| NAB           | 0.3622              | 0.3523             | 0.5768                | 0.4800          | 0.9889         | 0.0993                    | 0.2774        |
The material selection for vertical axis tidal current turbine. Therefore, choosing a suitable material is crucial, especially for the supporting structure that still needs metal as the main material.

Carbon steel was chosen as the best material for the vertical axis tidal current turbine, especially for the supporting structure that still needs metal as the main material. Carbon steel AISI 1045 possesses good strength and corrosion resistance, affordable price and it is easy to provide. Therefore, carbon steel AISI 1045 as the chosen material can be expected to be able to meet the material design requirement for the vertical axis tidal current turbine.

Table 4. The weighted normalized decision matrix of the material selection

| Material | Yield strength, MPa | Young Modulus, GPa | Tensile strength, MPa | Density, g cm⁻³ | Cost, IDR kg⁻¹ | Corrosion rate, mm year⁻¹ | Availability |
|----------|---------------------|-------------------|----------------------|-----------------|-----------------|--------------------------|--------------|
| AISI 1018 | 2.7921              | 2.2221            | 1.6373               | 1.0074          | 0.0846          | 0.2065                   | 2.7735       |
| AISI 1045 | 3.3958              | 2.1679            | 2.1769               | 1.0074          | 0.2104          | 0.1589                   | 2.7735       |
| SS 316 L  | 1.5470              | 2.0920            | 1.8048               | 1.0240          | 0.5498          | 3.9717                   | 2.7735       |
| NAB       | 1.8111              | 1.4091            | 2.3072               | 0.9600          | 3.9555          | 0.3972                   | 1.3868       |

Table 5. The matrix of ideal solution $V^+$ and negative-ideal solution $V^-$ of the material selection

| Material | Yield strength, MPa | Young Modulus, GPa | Tensile strength, MPa | Density, g cm⁻³ | Cost, IDR kg⁻¹ | Corrosion rate, mm year⁻¹ | Availability |
|----------|---------------------|-------------------|----------------------|-----------------|-----------------|--------------------------|--------------|
| $V^+$     | 3.3958              | 2.2221            | 2.3072               | 1.0240          | 0.0846          | 0.1589                   | 2.7735       |
| $V^-$  | 1.5470              | 1.4091            | 1.6373               | 0.9600          | 3.9555          | 3.9717                   | 1.3868       |

Table 6. The value of separation measure (Si+ and Si−), the value of relative closeness (Pi) to the ideal solution, and the rankings of the best selected material

| Material | Si+     | Si−     | Pi       | Ranking |
|----------|---------|---------|----------|---------|
| AISI 1018| 0.9031  | 5.7703  | 0.8647   | 2       |
| AISI 1045| 0.1897  | 5.8970  | 0.9688   | 1       |
| SS 316 L | 4.2943  | 3.7444  | 0.4658   | 3       |
| NAB      | 4.4878  | 3.6463  | 0.4483   | 4       |

Subsequently, the value of the ideal solution matrix $V^+$ and negative-ideal solution matrix $V^-$ (Table 5) were determined and calculated using equations (3) and (4). Then, the distance value (Si+ and Si−) between the separation measure of each alternative with the ideal solution and negative-ideal solution were estimated using equations (5) and (6), and are shown in Table 6. Afterwards, the value of preferences (Pi) or relative closeness to the ideal solution for each alternative were also determined by the equation (7), and the results were also given in Table 6. Finally, the ranking of alternative in this material selection was sorted based on Pi values, and the results can also be obtained in Table 6. The best-selected material is AISI 1045 and this is in agreement with [15] that steel material is selected as the most suitable material for the support structure of tidal current energy devices. Therefore, this material can be expected and able to accommodate the nature of the sea environment and meet the material design requirement for the vertical axis tidal current turbine.

4. Conclusion

The material selection for vertical axis tidal current turbine using the MADM-TOPSIS method has been conducted in this paper. There are several factors to consider in order to select the suitable material: the physical and chemical properties of materials, cost and availability, fabrication facility, and maintenance costs. From the analysis, carbon steel AISI 1045 was chosen as the best material for the vertical axis tidal current turbine, especially for the supporting structure that still needs metal as the main material. Carbon steel AISI 1045 possesses good strength and corrosion resistance, affordable price and it is easy to provide. Therefore, carbon steel AISI 1045 as the chosen material can be expected to be able to meet
the design requirement, withstand the marine hazards and avoid catastrophic failure during the operation of vertical axis tidal current turbine.

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