Conceptual Design of Co-Axial Floating Multiple-Rotors Water Current Turbine (FMRCT)

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Abstract – *Depletion and the current instability in the price of fossil fuel have led world interest in wind and water turbines as the two main categories of renewable energy. With the efficiency improvement as the major concern, these two types of turbine currently emphasize on the blade design, where the challenge is on the structural strength on the blade itself as well as the tower, while some other research concentrates on co-planar (parallel) rotor's arrangement. This paper interest is to describe the novel concept of a floating multiple-rotor water current turbine (FMRCT) arranged in co-axial (series) with the focus on the influence of distance between two rotors over diameter ratio (S/D) towards power increment. Furthermore, the contribution of each rotor toward the FMRCT power output increment also will be investigated. The FMRCT model was tested in an open stream at Lata Ulu Licin (Lecin). Results show that the increment of the output voltage is very significant as S/D increased up to S/D = 1.48. Furthermore, extra rotor on FMRCT also proportionately increased the power output, ranging almost similarly from 6.28% to 8.91% of power.*

Keywords*: co-axial multiple rotors, distance between rotor, renewable energy, water current turbine*

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I. Introduction

World scenario currently focuses on the development of renewable energy due to the price hike of global petroleum oil, as well as the reduction of the resources. Hydrokinetic energy conversion is one of the traditional methods of harvesting water current energy. However, this concept is still being researched especially on the ocean current energy which related to hydrokinetic turbines. There were few companies which are currently undergoing pilot marine current turbine farms between the years of 2016 to 2019 [1].

Additional of extra rotor either co-axially (in series along the turbine axis) or co-planar (in parallel between every rotor) with appropriate distance between each other on a current turbine system would able to increase the power generated [2]. A theoretical study shows how dual rotor wind turbine able to increase the power coefficient (C_P) and further been verified with computational analysis and wind tunnel test [3]. Therefore, by increasing the number of rotors with consideration of drag force generated by each rotor, the power output can be increased. This theory further supported by a group of researchers where they managed to add a smaller rotor in co-axial, in front of a bigger rotor wind turbine used to capture the wind speed around the hub section [4]. There were also patented inventions of a novel multi-rotor wind turbine which further increase the power generated and already available in the market [5].

However, wind turbines array in co-axial will experience a reduction in power generated since they are affected by the wake generated from the upwind turbine [6]-[7] as compared to the arrangement in co-planar. For a relatively very large stream over the rotor's diameter (Fig. 1), upstream current velocity, V_0 can be assumed as constant in average. After passed through the first rotor, the wake will be generated, whereas the speed will reduce. In other words, some amount of current kinetic energy already been absorbed by the first rotor [8]. Further, the surrounding upstream current, V_0 will mix together with the wake which moved downstream and thus regains its speed which can be considered as almost similar to the upstream, V_D. Therefore, it is necessary to ensure the upcoming turbines to be arrayed in co-axial are placed outside this wake region, where the wake will gradually reduce further downstream [9]. This can be clearly seen in Fig. 2 which shows the reduction of wake effect as moved towards downstream at 1D, 3D and 5D distance of turbine diameter.

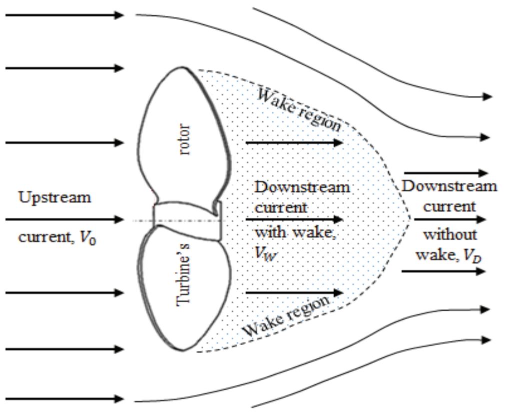

Fig. 1. Diagram showing the relationship between upstream current, wake and downstream current

Latest reported full-scale horizontal axis wind turbine (HAWT) number of rotors arranged in co-planar fitted on a single structure is up to four units [10], which is on HAWT. This concept has many parts involved as compared to the vertical axis wind turbine (VAWT) [11]. For example, HAWT require an extra motor-gearing system in order to ensure the turbine able to yaw according to wind direction. In addition, the construction and maintenance cost relatively higher since most of the part located in nacelle higher above the tower. Latest patent by Selsam [5] of a wind turbine with multi-rotor arranged in co-axial with flexible shaft able to fit more number of the rotors with a much simpler gearing system. This innovation was designed to span across a valley where the two shaft ends were mounted on two opposite cliffs. A comprehensive assessment on the practicality of multi-rotor co-axial wind turbine was reported in [2] had supported the implementation of this concept over the co-planar array and counter-rotating rotors.

The major concern in wind or water current turbines is on efficiency improvement. Swept area is one of the major factors which determines the power output performance and literally come from the diameter size. Currently, the longest blade of horizontal wind turbine reported was up to 88.4 m long [12]. The biggest drawbacks on this would be the structural strength on the blade itself, as well as the tower. As for the water current turbine, a conceptual design of inclined floating water current turbine had been developed for sea and inland water use to increase the swept area. These concepts also able to reduce the hydrodynamic load on the strut and support structure of a vertical axis current turbine, as well as for easier maintenance [13].

II. Methodology

Many existing water current turbine research focuses on the blade design and configuration, either horizontal type or vertical type relative to water level. Not only restricted to the types of current turbines, they also compare the placement method for each type, as well as few channels or duct design used to increase the current speed [14]-[15].

A. Conceptual Design of Co-Axial Floating Multiple-Rotor Water Current Design (FMRCT)

The concept of co-axial floating multiple-rotors water current turbine (FMRCT) used the application of multiple rotors in co-axial to fully utilize the water current kinetic energy. The excess kinetic energy of the water current absorbed by the first or upstream rotor will be absorbed by the next rotors. Each rotor connected using a flexible shaft used to permit the water current to orient the turbine axis substantially parallel to the direction of flow so that the force of the water on the blades is optimized. The shaft is designed to be flexibly orient itself in response to small changes in current direction relative to the base, due to movement of the current or even reversals of flow, or due to instability or settling of the support base, in order to maximize force incident on the blades of the turbine from the water.

The conceptual drawing of the FMRCT design was developed using Autodesk Inventor 2016 software. The system consists of four main components namely, direct current dynamo, flexible shaft, 5 rotors (Fig. 3) and a

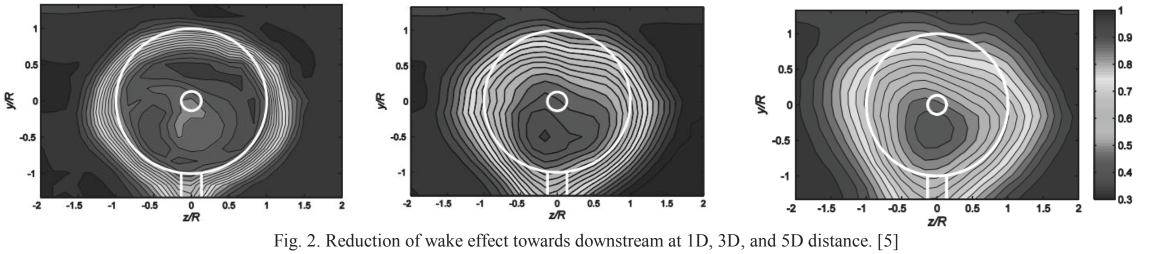

Fig. 2. Reduction of wake effect towards downstream at 1D, 3D, and 5D distance. [5]

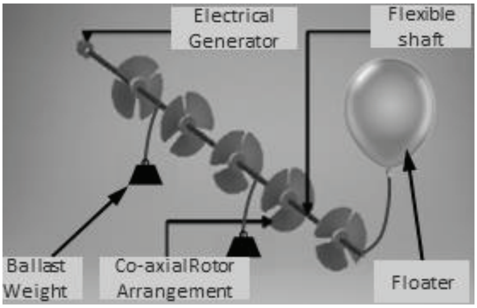

Fig. 3. Conceptual Design of FMRCT

B. Model Assembly

The model of FMRCT is made of a few items which can be bought on the shelf. Table I shows the item used to construct the turbine and their function.

It is decided to connect rotors in co-axial using a flexible shaft in order to increase the flexibility of the FMRCT to change course according to the current flow. This will allow each rotor to receive current at low yaw angle thus maximize the energy captured.

TABLE I
FMRCT PARTS LIST

Parts	Item used	Function in FMRCT
Energy converter	DC 6 volts, 3 watts bicycle generator/ dynamo	Converting kinetic energy (rotation) to electrical energy.
Flexible shaft	Spring (size: 5 mm in diameter) covered by shaft tube.	Connecting rotors.
Rotors	3-bladed of 12 inches (304.8 mm) diameter fan blade made of plastic.	Capture water current and turn into rotational kinetic energy.
Floater and ballast	Rubber ball and ballast weight.	To ensure each rotor afloat at the required water level.

Ballast weights were attached to the flexible shaft between each rotor, while one floater was used at one end which is in water. Fig. 4 shows the final arrangement of FMRCT on site. This arrangement was selected to ensure that the rotors were fully submerged, but not too deep. One end of the flexible shaft is connected to an energy converter. It is a direct current (DC) type which able to produce 6 volts and 3 watts power output.

The output voltage reading was measured using a digital multi-meter (model Fluke 179 True RMS) that provides a digital readout. Detail specification of the multimeter used is stated in Table II.

Fig. 4. The arrangement of the FMRCT on site

TABLE II
FLUKE 179 MULTIMETER SPECIFICATIONS

Specifications		
Voltage DC	Accuracy	± (0.09%+2)
	Max. Resolution	0.1 mV
	Maximum	1000 V
Current DC	Accuracy	± (1.0%+3)
	Max. Resolution	0.01 mA
	Maximum	10 A
Frequency	Accuracy	± (0.1%+1)
	Max. Resolution	0.01 Hz
	Maximum	100 kHz

C. Experimental Site and Condition

The experiment was carried out at Ulu Licin (Lecin) Waterfall (N4 31.50 E100 47.00) located in Beruas, Perak, as shown in Fig. 5. It took a half day process from 10 am to 4 pm on a clear sunny day. The day before was rainy which results in increasing to water level as well as current speed.

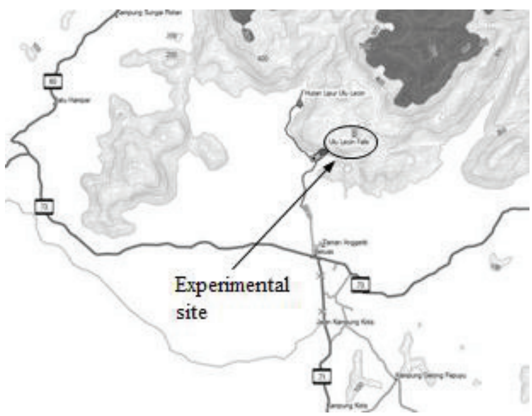

Fig. 5. Ulu Licin (Lecin) Waterfall where the experiments were carried out

D. Experimental Details

The research was divided into two main sections which are mainly to determine the required location for the second rotor when arranged in co-axial which will give the highest possible voltage output. At first, FMRCT with two rotors were used by varying the distance between these two, *S*, (refer to Fig. 6) as depicted in Table III. The distance was set to be non-dimensional, *S/D*, which is the ratio of the distance between rotors over the rotor's diameter. The diameter size will determine the swept area, which plays a major role in the turbine performance, and further will affect the size of the wake area. The distance is measured from the face boss of rotor no. 1 to the face boss of rotor no. 2. The distance was varied until there were no more significant changes in voltage output measured. Total of five configurations was recorded with the increment of 100 mm each.

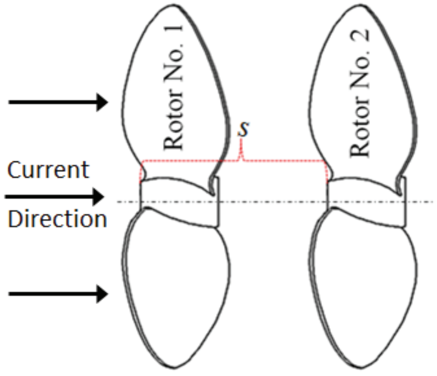

Fig. 6. The setting of distance between two rotors, *S*

TABLE III
VARIATION OF DISTANCE (S) BETWEEN THE TWO ROTORS AND THE EQUIVALENT S/D RATIO

Expt. No.	Distance, *S* (mm)	S/D
1	150	0.49
2	250	0.82
3	350	1.15
4	450	1.48
5	550	1.80

The second part of this research continues with investigating the effect of voltage output with the increasing number of rotor started with single rotor up to five number of rotors. Each rotor was assembled at a fixed distance as determined in the first experiment. The distance between each rotor was set to be 350 mm (S/D = 1.15) since beyond this distance, the increment of voltage output became less significant (refer to Fig. 7).

E. Data Recording and Analysis

The output voltages were measured manually using a digital multimeter and were recorded using a smartphone in MP4 format for a total period of 30 seconds. Each measurement was repeated three times giving a total of 90 second recording period. For post analysis, the three sets of 30 seconds recorded videos were disaggregated to every five seconds thus giving a total of 18 data (six data per recorded multiple by three measurements). Finally, the average output voltage reading was calculated. The results for the distance between rotors were compared with the voltage output of a single rotor current turbine in the percentage of voltage output increment.

III. Results and Discussion

Table IV shows the percentage of dual rotors output voltage increment over the single rotor at different S/D ratios. The percentage increases significantly as the distance between rotors increases up to S/D = 1.15 distance before became almost constant (refer Fig. 7).

TABLE IV
PERCENTAGE OF DUAL ROTORS OUTPUT VOLTAGE INCREMENT OVER SINGLE ROTOR AT VARIOUS S/D RATIO

	S/D	Average output voltage (mV)	Increment (mV)	%
Single rotor	-	412.63	-	-
Dual rotors	0.49	425.28	12.65	3.07
	0.82	450.76	38.13	9.24
	1.15	467.18	54.55	13.22
	1.48	470.60	57.97	14.05
	1.80	471.84	59.21	14.35

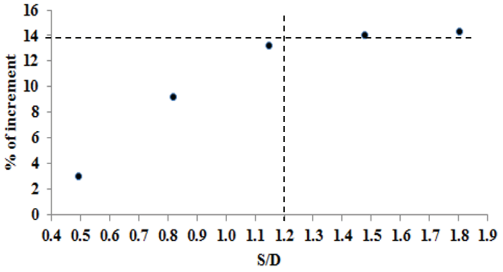

Fig. 7. Percentage of dual rotors output voltage increment over the single rotor at various S/D ratio.

The literature had mentioned that a wake will be generated behind each rotor thus will reduce the power output of every downstream rotor. However, when current moved towards downstream after passed through the first rotor, the wake effect will decrease, hence increased the power output. This can be seen at S/D = 1.2 and onwards where the percentage of increment became less significant (almost constant) due to the reduction of wake effect, whereas the current speed became almost constant towards downstream. Experimental research conducted in [16,17] on a horizontal water current turbine model shows a similar characteristic where the wake effect nearly no effect towards downstream. For that reason, the farther the distance between rotors would increase the power output of FMRCT. However, it is not practical to put the next rotor at the farthest distance since this will increase the difficulties on how to manage its motion.

Table V and Fig. 8 show the percentage of FMRCT output voltage increment after an addition extra rotors. Started with single rotors, the output voltage keeps increasing until a total of five rotors. A series of experiments on a model of dual rotors wind turbine with two different configurations namely counter rotating and co-counter rotating gave a similar result in terms of efficiency improvement. The efficiency was calculated based on the net power output by the two rotors. However, the improvement only becomes significant at higher speed [18].

TABLE V
PERCENTAGE OF MULTIPLE ROTOR CURRENT TURBINE OUTPUT VOLTAGE INCREMENT OVER SINGLE ROTOR CURRENT TURBINE

	Number of rotors (mm)	Average output voltage (mV)	Increment (mV)	%
Single rotor	1	412.63	-	-
Multiple rotors	2	438.41	25.78	6.25
	3	472.91	60.28	14.61
	4	514.88	102.25	24.78
	5	560.74	148.11	35.89

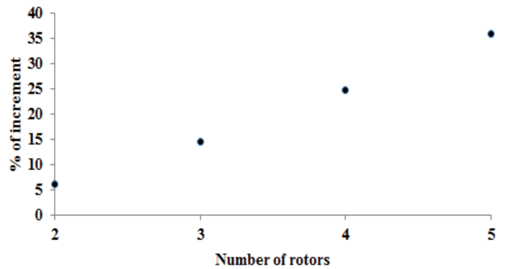

Fig. 8. Percentage of multiple rotor current turbine output voltage increment over the single rotor current turbine.

It is believed that the voltage output will keep on increasing until the current speed reduced such that no more enough energy to rotate the rotors. It is known that energy cannot be created nor destroyed based on the Law of Conservation of Energy. Therefore, the first rotor will convert a certain amount of current speed into electrical energy, while the remaining current speed at smaller magnitude will be converted by the next rotors and so on.

Table VI and Fig. 9 show the percentage of output voltage contributed by every rotor to the multiple rotors current turbine. Kinetic energy in terms of current speed was converted to electrical energy and supposed the percentage of contribution by each rotor will be reduced. However, the results show that the percentage of contribution almost the same which is between 6 ~ 9%. Since the experiments were conducted in an open stream, it is certain that the downstream current of every rotor was already blended together with the surrounding current. As for that, the current speed which enters every rotor almost the same.

TABLE VI
PERCENTAGE OF OUTPUT VOLTAGE CONTRIBUTED BY EVERY ROTOR TOWARD THE FMRCT

Set of rotor	Increment over remaining rotors (mV)	Percentage of increment (%)
#2	25.78	6.25
#3	34.50	7.87
#4	41.97	8.88
#5	45.86	8.91

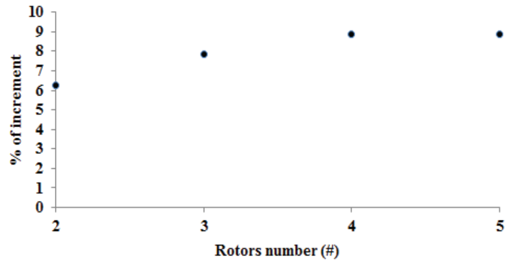

Fig. 9. Percentage of output voltage contributed by every rotor toward the FMRCT

Further, the additional number of rotors not only able to increase the power output (lift force) but will also increase the drag force. As for that, it is expected that the increment of every additional rotor not able to achieve the single rotor voltage output. In addition, the system needs also to consider the mechanical losses (for example the connection between rotors and flexible shaft).

IV. Conclusion

The conceptual design of FMRCT has been described clearly with the support from previous conceptual design of the inclined stream turbine and multiple-rotor co-axis with a flexible shaft wind turbine. The focus was given towards rotors arrangement in co-axial which majority research consider as less efficient. The (S/D) ratios play a major role in determining the efficiency of FMRCT. For this study, the suggested S/D ratio is at 1.2D onwards in order to ensure the downstream rotor been placed outside the wake area. However, there still a few parameters which govern the wake development such as tip-speed ratio and depth of submerged below water level [19].

With the positioning of the downstream rotors outside the wake region, each rotor will contribute almost a similar percentage of power output towards total turbine power generated. Lastly, the findings also show that the power generated keep increasing towards the fifth rotor. This, therefore, contribute to a hypothesis where an addition of the rotor will further able to increase power generated.

Finally, further investigation of the flow pattern between each rotor using computational fluid dynamic (CFD) will be very useful to determine the optimum distance between rotors.

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