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TSR-BASED OPTIMIZATION USING AUXILIARY MOTOR IN TIDAL ENERGY CONVERSION SYSTEM: AN EXPERIMENTAL STUDY

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ABSTRACT

The fluctuating nature of renewable energy is one of the factors that reduces its ability to compete with traditional forms of power generation. In the context of ocean current energy, tidal oscillations are the primary reason for the average power generation being significantly lower than the designed value. Increasing energy production through optimization is necessary for ocean current energy to compete successfully in the market. This experimental study is intended to increase electrical power production through electromechanical engineering with tip speed ratio (TSR) control using auxiliary motors, and adapts the Motor Generator Pair (MGP) approach, where the generator and motor are connected in series. A physical model of a Tidal Energy Conversion System (TECS) was developed. The system consists of a turbine simulator in the form of an AC motor with separate torque and speed controls, torque sensors, a hydraulic transmission system, and auxiliary motors. With this system, a typical tidal turbine profile was built and simulated TSR-based optimization control. The results of this optimization control show that power production can be increased through optimal tip-speed ratio control.

Keywords: tidal energy conversion system (TECS), tip speed ratio, maximum power point tracking, motor generator pair (MGP).

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1. INTRODUCTION

The demand, for energy options has risen in nations because of various factors. The most significant among these is the mounting apprehension regarding the consequences associated with non-renewable energy sources, like fossil fuels, which contribute to air pollution, greenhouse gas emissions, and climate change [1]. On the side, renewable energy sources have an impact, on the environment and can assist in mitigating these challenges [1]. Moreover, the depletion of fossil fuel reserves is a pressing concern that needs to be tackled. Given the decline in fossil fuel reserves, it is crucial to transition, towards renewable energy sources to ensure a reliable and steady energy provision [2]. Renewable energy sources have an impact, on both the environment and the economy. They not only create job opportunities but also contribute to economic growth while reducing our dependence on imported energy [3]. By diversifying our energy sources and decreasing reliance on imports renewable energy can enhance energy security [2]. It is crucial to note that consumer attitudes play a role, in the adoption of energy. Research suggests that consumers understanding of the benefits associated with energy influences their decision to embrace it [3]. Therefore investing in initiatives that increase consumer awareness and knowledge about the advantages of energy becomes imperative [3].

Tidal stream energy has considerable promise for renewable energy applications since it includes capturing the kinetic energy of tidal currents to generate power. This type of renewable energy generation offers a number of features that make it a promising choice for meeting the world's energy demands.

To begin with, tidal stream energy is a dependable and consistent source of power. Tidal currents, unlike other renewable energy sources such as solar or wind, are very predictable and follow a continuous pattern. This predictability allows for accurate scheduling and effective utilization of tidal energy resources[4][5]. The existence of this predictable nature makes tidal currents able to provide a constant and reliable power source making tidal current energy a viable option to meet the growing need for renewable energy sources [5].

The second advantage, tidal flow energy has a high energy density. Since tidal currents are denser than air or wind, a smaller volume of water can produce large amounts of energy. Due to its high energy density, tidal current energy is a highly efficient and powerful renewable energy source [6]. Harnessing tidal energy could enable the construction of large-scale facilities that generate electricity on a large scale[6]. It is proven that tidal turbines do not emit greenhouse gases during operation, making them a clean and sustainable energy source[7].

The next advantage is that tidal turbines have a relatively small environmental impact so they can be installed without significantly disturbing the marine ecosystem [8]. However, to ensure responsible development, a more thorough study of the potential consequences of tidal energy devices on marine biodiversity is needed [9].

Tidal stream energy conversion systems harness the energy from the motion of ocean waters to produce electricity [10]. Electricity can be supplied to communities with limited access to the electricity distribution network, thereby reducing poverty and greenhouse gas emissions

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caused by the combustion of fossil fuels [11]. Blades, a turbine generator, an inverter, and a grid connection are the fundamental components of a tidal energy system [12]. Tidal energy conversion systems, which harness the ebb and flow of seawater to generate electricity, offer the promise of sustainable power generation by harnessing the ocean's abundant energy resources. [12].

Renewable energy's intermittent nature, caused by its energy source's character, hinders its competitiveness [13]. To increase the energy power output of ocean currents, then optimization becomes very important. By optimizing control, operation, and trade-off strategies for intermittent renewable energy resources, power generated from ocean currents can be maximized, allowing it to better compete in the electrical energy market [13][14].

One of the optimization concepts in tidal energy conversion, as well as in wind energy conversion, is setting the tip speed ratio (TSR). The tip-speed ratio is defined as the ratio of the rotational speed of the blade tip to the speed of the fluid current passing through the turbine blade. This can be mathematically expressed as follows: $\omega R/v_{tide}$, where ω is the rotational speed of the turbine (rad/sec), R as the turbine radius and v_{tide} is the velocity of fluid flow (seawater) [15]. This TSR parameter is important in relation to turbine efficiency, which is expressed by the power coefficient (Cp).

The power coefficient (Cp) of the turbine is proportional to the tip speed ratio. Cp is the efficiency of the turbine in converting the kinetic energy from tidal currents into electrical energy. This Cp value is affected by the TSR and pitch angle of the turbine blades. This CP value is limited by the maximum limit defined by Betz's law, which is 59.3 percent for horizontal axis type turbines. The TSR value must be optimal to achieve the maximum Cp value. For each current speed value, there is an optimal turbine rotational speed [16]. Tidal energy conversion systems use a strategy called Maximum Power Point Tracking (MPPT) to increase their power output [17]. The system efficiency and power production can be optimized by adjusting the turbine tip speed ratio. Maximum power extraction from tidal currents is achieved by continuously monitoring tidal velocities and changing TSR [17]. This is because of the ever-changing conditions of tidal flow, so the optimal tip velocity ratio (TSR) may not always be at its optimal value [18].

TSR-based optimization control has been widely researched and has produced several techniques and algorithms, including Power Signal Feedback (PSF), Pertube and Observe (P&O), Incremental Current, Optimal Torque Control (OTC) [19]. Numerical simulations have also developed more complex methods, such as particle swarm optimization (PSO), Neural Network (NN), and adaptive fuzzy inference system (ANFIS) algorithms [19]. TSR-based methods have the simple principle of maintaining an ideal tip velocity ratio by adjusting the generator speed based on the current tidal flow conditions. While the theory behind this approach is simple, in practice, it requires monitoring of tidal flow and rotor dynamics [20].

Although research on TSR-based control for the optimization of tidal current and wind power energy generation has been widely conducted, direct torque-delivery approaches have never been studied. A common approach is electronic load regulation, which is performed through electronic power converters. This arrangement is performed by regulating the current and voltage to affect the loads of the generator and turbine. An approach called the Motor Generator Pair (MGP) has been researched in several studies with the aim of stability and quality of power output. In this study, an approach was carried out with MGP adaptation, but aimed at power optimization with TSR settings. The purpose of this study is to build an experimental model to test whether TSR-based optimization can be performed. This model can be a platform for developing appropriate control optimization algorithms such as optimal and real-time control. However, in this study, because the goal is more on how to test physical models, a simple algorithm is used, namely, the table lookup algorithm.

This paper is organized as follows. The first chapter discusses the research background related to tidal energy resources, their potential, characteristics, problems and optimization efforts. In Chapter 2, we will learn the basic principles of TSR-based optimization, and introduce a new concept, Motor Generator Pair (MGP). The experimental method of the research will be presented in Chapter 3, followed by a discussion of the findings in Chapter 4. And Chapter 5 discusses the conclusions.

2. TSR-BASED OPTIMIZATION AND MOTOR GENERATOR PAIR

2.1 Tips Speed Ratio

Similar to wind power, the mechanical power of tidal currents depends on the density of seawater (ρ in kg/m^3), square of the turbine radius (r in meters), and cube of the seawater flow velocity (v in m/s). This flow potential can be expressed as

$$P_{tidal} = 0.5\ \rho\pi R^2 v^3 \tag{1}$$

By the turbine, the flow of seawater is converted into mechanical energy of the $P_{turbine}$, which is expressed as

$$P_{turbin} = C_p(\lambda,\beta)P_{tidal} \tag{2}$$

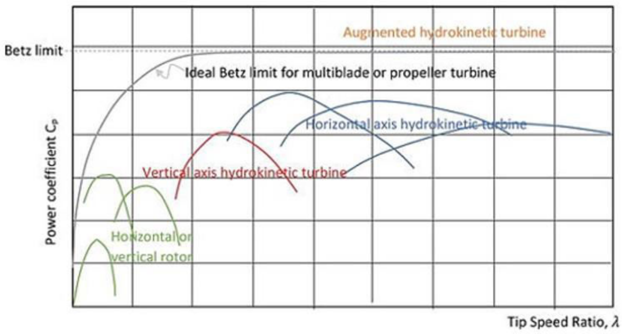
Where $Cp(\lambda,\beta)$ is the turbine power coefficient, which is a function of the tip-speed ratio and pitch angle. *We* typically assume that the pitch angle is 0 °. The tip speed ratio (TSR) is expressed as

$$\lambda = \frac{R\omega_{turbin}}{v} \tag{3}$$

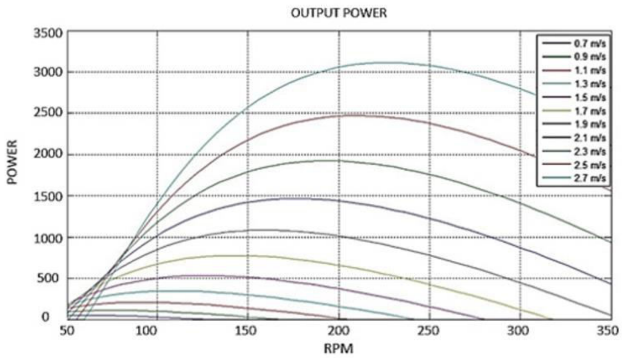
Where $\omega_{turbine}$ is the angular speed of rotation in rad/s

From Equation (2), it appears that the value of Cp also indicates the efficiency value of a tidal turbine. Then how significant is the efficiency that can be generated from a control strategy is equal to ΔCp. The optimization effort is to dynamically maintain the TSR value such that it is close to the optimal value.

The Cp value was obtained from the turbine manufacturer or test results. Different types of turbines have different typical values, depending on the shaft type, blade type, size, and material. Figure-2(a) shows the typical values for various types of turbines [18].



(a)



(b)

Figure-1. (a) Cp values for various turbine types [21] (b) Typical Example of Power vs RPM Curves for Different Tidal Current Speeds [22].

From Equation (3), it can be seen that the TSR value depends on the rotational speed of the turbine shaft or generator shaft. So it can be said that the generator output power is a function of the rotational speed of the shaft. Therefore, for various ocean currents, the power as a function of the rotational speed for a typical turbine can be described as shown in Figure-1(b).

In this study, the table look-up method is used, where it is assumed that the system already has turbine specification data, a power coefficient curve, and a turbine operational mode.

2.2 Motor Generator Pair (MGP)

The Motor Generator Pair (MGP) system is a new approach to on-grid renewable energy systems that utilizes a combination of motors and generators to improve the stability and performance of renewable energy systems [23]. MGP systems are designed to overcome the shortcomings of electronic converter-based renewable energy systems, especially when there is a disruption in the grid [23].

The MGP system consists of a motor and generator connected in series (in one shaft), with the motor connected to the renewable energy source and the generator connected to the grid. MGP systems have been extensively studied and analyzed through simulations and experiments, with promising results for grid-connected renewable energy that overcome the challenges and limitations of converter-based systems [23] [24]. Figure-2 illustrates the concept of MGP.

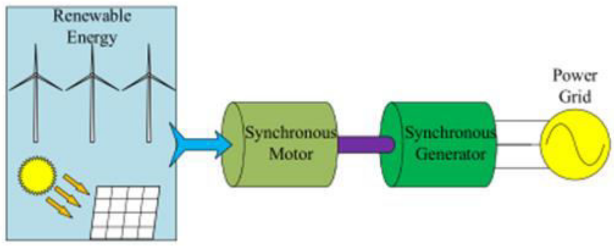


Figure-2. Motor generator pair concept [24].

This study adapts this system, in the sense that it uses an electric motor as a means to adjust the TSR to obtain the maximum power coefficient.

3. METHOD

3.1 Overview of the Tidal Energy Conversion Model

Several components make up the ocean-current power generation system model, as shown in the following diagram.

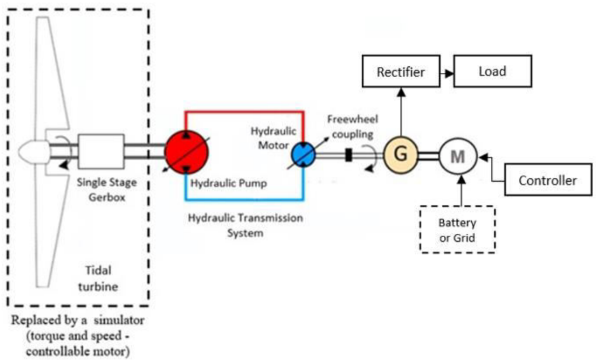


Figure-3. The components of TECS component used in this study.

In this experiment, an electric motor took the place of a turbine or geared turbine (a turbine with an additional gearbox). The driving motor needs to be able to mimic the torque and rotational speed of a turbine. Variable-speed drives (VSDs) were utilized in this experiment to allow for independent speed and torque regulation of 3-phase AC electric motors producing 2 horsepower each.

Ocean current turbines generally rotate at a low speed of 10-30 rpm. To satisfy the speed required by generators in general, up to three-stage gearboxes are required for utility-scale wind turbines [25]. In this study, it is assumed that the system uses a gearbox (geared turbine) such that the rotation is the speed of the turbine unit. In this research, a motor and inverter are used to obtain the actual rotation of the turbine, which can produce rotation and the desired torque. The torque and rotational speed of each current speed were calculated based on the turbine specifications and the existing characteristic curves.

In these investigations, Hydrostatic Transmission (HST) was used. Here, the rotation of the turbine is transferred to the generator. A hydraulic pump and motor are included in this system, as well as relief valves and check valves. The speed of the turbine shaft or hydraulic pump is designed to be three times faster than the rotation of a hydraulic motor.

This model employs a permanent magnet synchronous generator (PMSG) with the parameters detailed in Table-2. An electric motor was placed on one shaft with a generator. The motor helps the generator rotate when required. A freewheel coupling is installed between the generator and hydraulic motor to prevent direct interference with the fluid cycle in the hydraulic transmission system. Thus, the rotation of the auxiliary motor only affects the rotation of the main drive shaft by reducing the mechanical load on the generator. The controller regulates when and how fast the motor rotates. The controller regulated the rotation of the motor based on the readings of the sensors installed in the system. Figure 4 shows the model of the tidal current generation system.

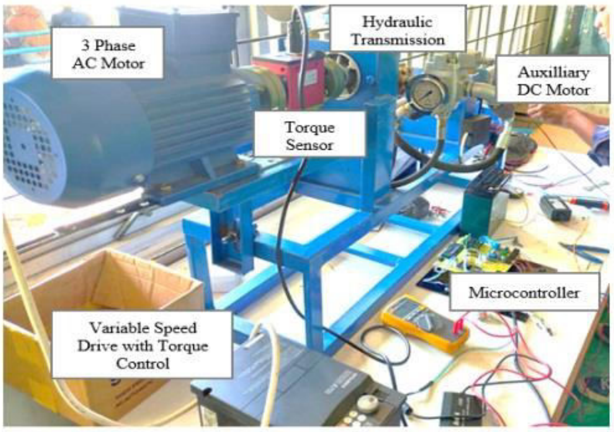


Figure-4. The Tidal Energy Conversion System Model.

3.2 Experiment Setup

The following section describes the tidal turbine profile in this study. The most important part of this system is the turbine simulator. This simulator must be able to simulate the movement of the turbine owing to the flow of ocean currents, which produce a certain torque and rotational speed. The manufacturer's power curves and turbine specification data, as well as turbine testing, can both provide information on a turbine's power characteristics. The power curve can be in the form of a power-to-current curve or power-coefficient curve. This experiment made several assumptions related to the turbine data and the parameters used in the turbine simulator.

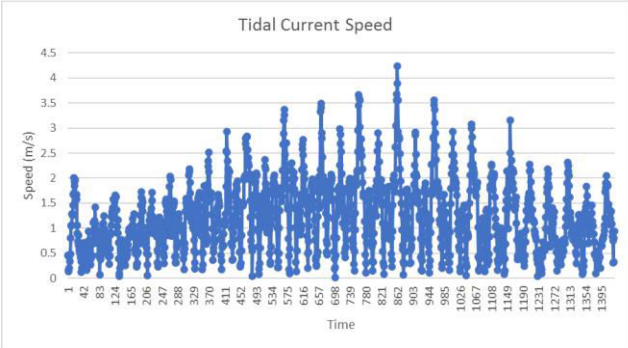


Figure-5. Tidal current measurement result.

This experiment used typical data on the current velocity in Indonesia. Figure-5 shows one of the results of a direct measurement of the current velocity in one of the straits in Indonesia. However, in this experiment, only a few values were used to represent the turbine simulator's data distribution and motor capacity range. The sample current velocity values used in the testing and measurement are listed in Table-1.

Table-1. Sample of tidal current used in the test.

Test No.	Name	Current Velocity (m/s)
1	v_1	0.87
2	v_2	1.28
3	v_3	1.52
4	v_4	1.75
5	v_5	1.91
6	v_6	2.05
7	v_7	2.19
8	v_8	2.45

In this experimental study, it was assumed that the system had technical specification data, as listed in Table-2. The turbine radius was extremely small because the rated power adjustment was only 180 W. The rated current velocity is the current speed that generates power based on the maximum capacity of the generator. A tidal current velocity that is more than the rated current velocity produces a maximum power equal to the rated power. The cut-in speed is the minimum speed of the tidal current required to generate power. Cp max denotes the maximum turbine efficiency. Graphically, these specification values are displayed in the turbine operating mode chart, as shown in Figure-6b.

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Table-2. Specifications of ocean current turbines.

Parameter	Size
Turbine radius	14 cm
Rated Current Velocity	2.2 m/s
Rated rotation Speed	20 rad/s
Rated Power	180 W
Cp max	0.4
Cut-in Speed	0.87 m/s

The next step was to construct the power-coefficient curve of a typical tidal turbine. Based on the data and specifications above, a power coefficient curve was generated, as shown in Figure-6a.

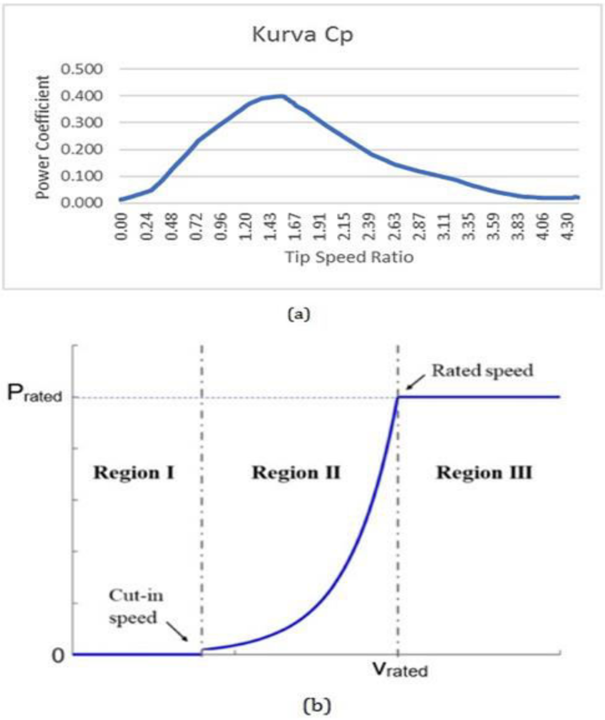

Figure-6. (a) Simulated Turbine Cp Curve (b) Turbine power operating mode curve.

From the curves above, the derivative curve can be derived, which will be used as a reference in this experiment. The first is the power curve as a function of rotational speed for each tidal current velocity. This curve can be created by plotting the values ω for each value of the current velocity such that each value of the TSR is obtained. And from the Cp curve in Figure 6a, it can be plotted the magnitude of the power value for each rotational speed. The power curve can be obtained from this calculation, as shown in Figure-7.

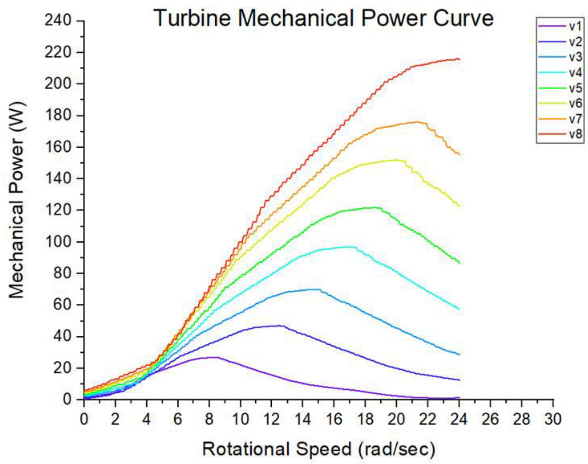

Figure-7. Power curve as a function of turbine shaft rotational speed for each current speed.

By deriving the power curves in Figures 6 and 7, the power curve can be derived as a function of the rotational speed of the turbine shaft. The last is the torque curve as a function of current velocity, which can be obtained from the equation that power is the product of the torque and rotational speed.

3.3 Experimental Steps

The experiment was conducted in two modes. The first is that the system is run in the conditions as is. And the second system is again burdened with the same load assuming that the system is experiencing non-optimal conditions, which are characterized by TSR values below their optimal values. These values are contained in the program library on the Arduino Mega 2560-based controller built to manage auxiliary motors.

This experiment was carried out according to the following steps:

- The values in the curve were converted into tables for use as input and reference values in this experiment. Therefore, a table lookup method was used in this study.
- For each value of the ocean currents in this experiment, the turbine simulator produced a certain torque and rotational speed.
- The torque sensor captures the value of torque rpm, which occurs (down due to load), and the power generated by the rotation of the turbine.
- Next, the controller checks if the generated power is optimal. Otherwise, the controller drives an auxiliary motor to help rotate the generator shaft at a certain speed, which directly affects the turbine rotation.
- Increasing the turbine rotation increases the power generated by the turbine according to the curve in Figure-7, which means that it also increases the value of Cp.
- The addition of this power pushes the turbine shaft to rotate faster, which affects the power required by the assist motor.

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RESULT AND DISCUSSIONS

This section displays the results of experiments that have been conducted. The results are shown in the tables below.

Table-3. Tests result without optimization control.

V_{tide} (m/s)	Mechanical Power			Electrical Power
	Power (W)	Rotational Speed (rpm)	Torque (Nm)	(W)
0.87	27	80	3.2	1.4
1.28	47	117	3.9	3.3
1.52	70	139	4.8	7.2
1.75	97	160	5.9	11.4
1.91	122	175	6.7	16.8
2.05	152	188	7.3	23.5
2.19	176	201	8.4	31.2
2.45	216	225	9.6	40.1

Table-4. Test results with optimization control.

Varus (m/s)	Mechanical Power			Electrical Power Generated
	Power (W)	Rotational Speed (rpm)	Torque (Nm)	(W)
0.87	31	93	3.2	1.7
1.28	55	137	3.9	3.8
1.52	85	165	4.8	8.5
1.75	116	190	5.9	14.2
1.91	147	206	6.7	20.1
2.05	184	223	7.3	28
2.19	180	239	8.4	34
2.45	180	265	9.6	34

These results indicate that there is an increase in power in the generation system with the rotation of the auxiliary motor, which directs the speed of the turbine shaft close to the optimal rotational speed to obtain the maximum Cp value, with reference to the parameter tables that have been made in the previous turbine profile.

Table-5. Electric power generated.

Tidal Current Speed (m/s)	Before Optimized (W)	After Optimized (W)	Change (%)
0.87	1.4	1.7	21.43
1.28	3.3	3.8	15.15
1.52	7.2	8.5	18.06
1.75	11.4	14.2	24.56
1.91	16.8	20.1	19.64
2.05	23.5	28	19.15
2.19	32	34	6.25
2.45	32	34	6.25

When measured against the amount of mechanical power that the turbine is capable of producing, the value of the electricity created appears to be quite low. The reason for this is the generator's poor efficiency. This can be calculated from the generator specifications in Table-2, where the rated torque was 32 Nm for a rated power of only 600 Watts. Another probable explanation is the effectiveness of the hydraulic transmission system, which necessitates a significant amount of rotation in order to generate an adequate amount of pressure in order to cause a significant amount of torque on the hydraulic motor. The table above shows the results after optimization control was performed using an auxiliary motor.

Despite these problems, the findings indicate that the use of auxiliary motors can be effective in maintaining optimal TSR values in wind turbines, even under varying wind conditions. This research presents empirical evidence of the potential for improving the efficiency of wind power generation systems through a TSR control approach with an auxiliary motor.

The findings of this study are expected to have implications for the development of tidal stream power generation systems. The experimental model can be used as a platform for the development of real time optimization control algorithms either TSR-based or based on other strategies by utilizing the existence of torque, power and speed simulators and sensors in an integrated model.

However, this study has limitations and requires improvement, including special studies related to the transmission system, the selection of more efficient generators and also the selection of motors for control.

5. CONCLUSIONS

Experimental results and analysis show that applying the concept of optimal TSR control with auxiliary motors to wind turbines can provide significant benefits in improving energy conversion efficiency. This study successfully fills the research gap in the literature related to the use of auxiliary motors in controlling TSR in wind turbines.

This discovery has important implications in the development of tidal stream power generation systems. The use of an auxiliary motor as an external controller can allow the wind turbine to keep operating at the optimal TSR point, which in turn can significantly increase electrical energy production.

Thus, this study has significant novelty in the context of controlling TSR in wind turbines and demonstrates the potential of using auxiliary motors as a new approach in improving the efficiency of tidal stream power generation. These findings provide an important foundation for further research in the development of more efficient and sustainable tidal stream power generation systems.

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Conflicts of interest

The authors declare that they have no conflicts of interest, financial or otherwise, regarding the publication of this paper

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