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Ocean Wave Energy Harvesting via Scotch Yoke-based Rotational Generation

Md. Zahir Hossain, and Hazlee Azil Illias, *Member, IEEE*

***Abstract* — Harvesting energy from ocean waves has been a promising renewable energy source due to its high efficiency, carbon-free, not affected by the depletion of fossil fuels, and replenished nature. Numerous studies have been conducted on wave energy to explore an efficient way to harness energy from wave energy. Among them, linear generators and slider crank mechanism based rotational generations have become common topics in research, which have some limitations due to lower efficiency and technologically challenging. Thus, in this work, wave energy harvesting technique using rotational generator based on scotch yoke mechanism is proposed. A typical slider cranks to convert linear motion into rotational motion is replaced by scotch yoke mechanism to yield higher efficiency since scotch yoke is less in terms of weight, length and space. A comparison of the performance of wave energy system between employing slider crank and scotch yoke is made to evaluate the superiority of the proposed mechanism. From the results obtained in this work, it is found that the output power almost 3.8 W of a rotational generator employing scotch yoke mechanism is higher compared to the output power, which is approximately 2 W of rotational generator employing slider crank for the same input power. Thus, rotational generator by employing scotch yoke mechanism can be one of the alternative methods for ocean wave energy harvesting.**

***Index Terms* — Ocean wave energy harvesting; rotational generator; renewable energy technologies; scotch yoke mechanism**

I. INTRODUCTION

A continuous rise in demand of electrical power is occurring from day to day due to the growth of industries, housing sectors and others [1]. Alternative sources have been actively explored to fulfill the current and future demand of electricity due to the rise in fossil fuel price and greenhouse effects [2], [3], [4]. With the development of technology, renewable energy has become an alternative source of energy [5] [6]. From these growing environmental concerns, the world leaders have reached to a target, known as Paris agreement 2016. According to it, a proposal of carbon neutrality signed by 120 countries can be achieved by the minimum use in fossil fuel whereas a growth in the use of renewable energy can be the mitigation of this environmental concerns [7]. However, the production cost of electricity generation from renewable energy is still the main challenge. Installation cost, enhancement of energy extraction from small areas and the improvement of system efficiency are active research areas of renewable energy. In order to limit these challenges, some actions have been taken by some countries in renewable energy research, which aid them to fulfil the Paris agreement. In renewable energy, solar and wind have been widely focused. Nevertheless, one of the promising renewable energy sources is ocean wave, which has several advantages over other renewable energy sources. A 1 m size of solar photovoltaic panel can provide 100 W/m^2 power but the power extraction of similar area from ocean wave is 1000 W/m^2 [8]. Compared to wind energy harvesting, it is known that air density is 832 times lighter than wave density. However, the wave turbine blade is 3 times smaller than that of wind turbine in order to produce the same amount of power [8]. More than 70 percent of the entire globe surface is covered by ocean and sea, where wave is propagating and the tidal wave effect by moon is higher than that of the sun [9]. It is estimated that electricity generated from wave energy can satisfy 4 percent need of the entire electricity demand in the world by 2030 [10] and a total of global wave resource is theoretically forecasted to be 32 000 TWh per annual [11]. Although wave energy has abundant potential, the matured technology is absence in wave technology when it comes to a comparison with solar or wind energy [12].

In recent reported papers, Yuanqi Cai et.al. [12] studied on resonance control of a wave converter and mentioned that reactive control or latching control or wave by wave can maintain the phase control. This phase control and frequency control are important to maintain stability of the wave converter. It has been a few years since new wave converters concept were investigated due to irregular wave and low frequency. The behavior of a guided point absorber in regular and irregular wave was reported by Hollm. et.al. [13]. The improvement of wave converter with the help of minimizing the physical limitation was investigated by Garcia-Teruel et.al. [14]. Shi. et.al. evaluated wave-energy characteristics based on the existing knowledge, compared four wave converters, and explored the better wave converter depending on wave characteristics for china [15]. Sun. et. al. found generation issue in the existing system. To solve this, a solid–liquid-interfaced, tube-shaped tribo-electric–electromagnetic hybrid nanogenerator (TTEHG) was reported [16]. The wave data and wave height forecast system were investigated by [17], and [18] respectively. Afsharfard et.al. discussed a wave converter designing for wave height of 1.2 m, period of 9.5s and depth of 100m [19]. From different generation technical point of views, some energy extraction techniques from the

Md. Zahir Hossain is with the Department of Electrical Engineering, University of Malaya, (Email: zahirhossainovik@gmail.com).
Hazlee Azil Illias is with the Department of Electrical Engineering, University of Malaya, (Email: h.illias@um.edu).

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ocean are thermal (temperature difference) [20], [21], ocean current [22], tidal [23], and wave energy [24], [25], [26], [27]. From the past research, it can be seen that most of the studies of wave energy have focused on wave converter (buoy) design, control and improvement as well as the wave characteristics. A few studies have focused on motion conversion area. Pictures of wave characteristics have ensured that the wave does not follow regular period wave pattern [13]. To alleviate this issue, researchers exploited Archimedes wave swing techniques with aid of the linear generator. Nevertheless, several problems have been figured out in the usage of linear generators at the power generation from wave energy, which are high internal heat loss, lower efficiency and lesser magnetic flux. Thus, linear generators are not suitable for larger power applications. However, it is suitable to run for low power applications [4], [28], [29], [30], [31]. To mitigate this problem, a typical slider crank mechanism based on rotational motion was reported to harvest energy from the ocean wave. Nonetheless, the performance of the slider crank mechanism is affected heavily by its weight, length and space. These effects of slider crank based wave converter hinder from yielding an efficient energy generation, resulting in inability in commercial scale production. Therefore, an alternative motion converter needs to be found.

The aim of this work is to explore an alternative motion converter from the existing knowledge. Apart from typical slider crank mechanism, there are several ways to convert linear motion to rotational motion. Among them, one of the alternative mechanisms to convert linear motion to rotational motion is by using scotch yoke mechanism. The performance of scotch yoke mechanism is free from the effect of its weight, length, and space [32]. Also, scotch yoke system can work at lower applied force [32]. Therefore, scotch yoke-based wave converter is suitable to be applied at onshore area where the wave pressure is low. At present, scotch yoke mechanism is applied at higher pressure area such as gas and oil pipeline, internal combustion engine, hot air engine and steam engine due to the high torque at output terminal, smooth performance, and fewer moving parts [33]. In the case of the recent application of the scotch yoke, it is used in energy harvesters from wind as a motion converter from rotational to linear motion [34]. The main difference between the work in [33] and this work is in the motion conversion. It is mentioned that the scotch yoke is capable of converting both from linear to rotational motion and rotational to linear motion. Hence, choosing scotch yoke can be a better option depending on the mentioned advantages. This drastic change of motion converter would contribute to its efficiency and output performance of the proposed wave converter.

In this work, wave energy harvesting technique is proposed using rotational generator based on scotch yoke mechanism. In the proposed method, a typical slider crank to convert linear motion into rotational motion is replaced by scotch yoke mechanism to yield higher system efficiency. A buoy from lower and higher force of wave energy is added to assist the wave energy harvesting system. A comparison of the performance of wave energy system between employing slider crank and scotch yoke is made to evaluate the superiority of the proposed mechanism.

This paper is arranged as follows: Section 1 briefly describes the existing state of energy harvesting via ocean wave and the techniques of energy harvesting. Section 2 describes the overview of block diagram and working principle of the proposed mechanism. Section 3 explains the methodology of the proposed concept with equations of wave, scotch yoke mechanism and simulation model. Section 4 discusses the results obtained and performance comparison between the proposed mechanism and existing mechanism. Finally, Section 5 concludes the achievement of the work and lists recommendation for future work.

II. METHODOLOGY

In this work, a buoy-like point is considered to receive energy from the ocean. As the wave energy of the ocean passes in a transverse way as cosine wave, the amplitude of the wave contains energy and the time span of extraction of energy from the wave crest is small. Thus, to receive the force continuously on the buoy, it is possible to raise the time of energy extraction by clipping the wave amplitude or by controlling the wave phase, known as "phase control by latching" [31]. In Figure 1, curve "A" represents the amplitude of the machine, curve "B" represents the wave amplitude of the ocean and curve "C" is the output amplitude after clipping. The time span of energy extraction is raised after the clipping.

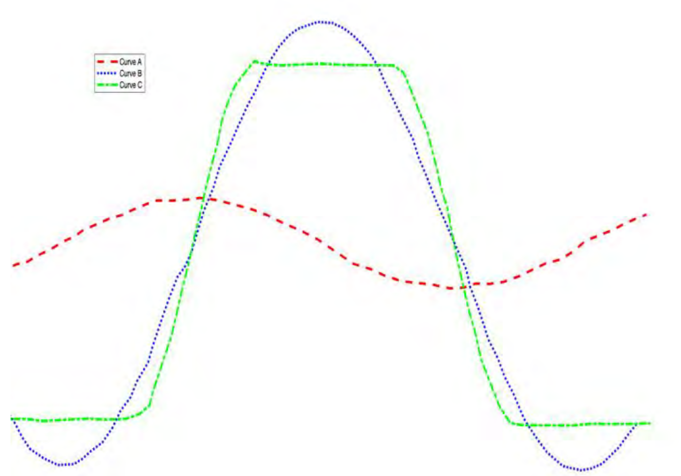

Fig. 1. Diagram of curves of phase control by latching.

In this section, the mathematical equations of wave and scotch yoke, separately excited DC generators and linear generators are shown. The equation of wave power P in Watt per meter is given by

$$P = \frac{\rho g^2 H^2 T}{64\pi} \quad (1)$$

where ρ = density of ocean water (1025 kg/m^3), g = gravitation force (9.81m/s^2), T = time span of the wave (distance between two individual crests) and H = crest height of the wave. For example, if the wave height is 1 m and the

time is 2 s, then the total power per 1 m height crest is 979.20 W/m. This value is referring to the flux of wave energy or the rate of transport of wave energy.
Based on [5], the force equation on buoy F_{Buoy} is given by

$$F_b = \rho g(w - x)\, S_b \quad (2)$$

where ρ = water density of ocean, w = height at the buoy position, x = displacement of the buoy and S_b = area of the buoy.
The gravity force is given by

$$F_a = -mg \quad (3)$$

where m = mass. If m = 1 kg, then F_g = -9.81 N, which is the minimum force. From equations (2) and (3), the applied force acting on the buoy can be calculated as

$$F_A = F_b + F_a \quad (4)$$

The wave and buoy data are shown in Tables 1 and 2 respectively, which are extracted from [4].

Table I: Experimental data for Wave

Wave parameter	Value
Height	4 m
Period	7 s
Length	76.5 m
Water depth	38 m

Table II: Experimental data for Buoy

Buoy parameter	Value
Diameter	8.74 m
Height	1 m
Weight	2689 kg

Basically, the shape of a buoy is a cylinder, and the buoy area is $S_b = 2\pi r(r+h)$, where r = radius of the buoy. It is assumed that the ocean water is in equilibrium position and the position of the buoy is 38 m above the sea ground due to deep water. As the wave height is 4 m, the displacement of the buoy equals to the wave height. Therefore, from equation (17), the value of F_A is 503.827 kN. Since the aim of this work is not focusing on buoy in details, other concern such as the stability is not discussed. Details of the buoy are deeply discussed in [27], [31].
The force acting on the piston of scotch yoke mechanism is equal to the applied force on the buoy and the scotch yoke will experience angular velocity due to the action force of the piston. The relationship between the force and angular velocity is given as

$$F = m\omega^2 r \quad (5)$$

where m = mass of the crank, ω = angular velocity and r = length between the fixed pin on the crank and slider yoke. Table3 shows the calculated angular velocity using equation (5).

Table III: Determined value for the angular velocity

Variable	Value
Force	50 N
Mass	3 kg
Radius	0.1 m
Angular velocity ω	12.91 rad/s

Figure 2 shows the scotch yoke mechanism, where item 1 is the crank, item 2 is the slider yoke and item 3 are the connecting rod of the scotch yoke. The small part of the slider yoke is a moving slot. The connecting rod is directly connected to the slider yoke with a moving slot and the moving slot is directly connected to crank l_{OA}. The total kinetic energy KE of the scotch yoke is given by [33].
The inertial equation can be found by

$$M_{in} = \frac{1}{\omega}\frac{dT}{dt} \quad (6)$$

$$KE = 0.5\omega^2(I_{S1} + m_1 r_{S1}^2 + m_2 l_{OA}^2 + m_3 l_{OA}^2 cos^2\theta) \quad (7)$$

where I_{S1} = axial moment of link 1 = $m_1 l^2_{OA}/12$, l_{OA} = 0.1 m, $r_{S1}^2 = l_{OA}/2$, m_1= crank mass, m_2 = slider yoke mass and m_3= connecting rod mass. Table IV shows the values of mass of the scotch yoke [33].

Table IV: Mass value of scotch yoke mechanism

Mass	Value
m_1	3 kg
m_2	0.5 kg
m_3	5 kg

$$M_{in} = -0.5 m_3 l_{OA}^2 \omega^2 sin2\omega \quad (8)$$

This equation needs to be balanced. The torque input balancing has been demonstrated in [32] in details.
After balancing the torque equation, the output torque equation of scotch yoke can be derived from the input torque equation as [33],

$$T = 0.5r^2\omega^2 cos^2\theta \quad (9)$$

A full cycle is completed by the crank due to the applied force absorbed by the buoy to pass through the slider piston. According to [35], a full cycle is accomplished by both of the piston and crank at the same time. When $\boldsymbol{\theta}$ =360°, from equation (20), it can be written as

$$T = 0.5r^2\omega^2 \quad (10)$$

From the current knowledge of motion converter, Karayaka et. al. proposed a way to convert linear motion to rotational motion with the aid of typical slider crank [8]. A buoy is connected to a typical slider crank, which is connected to a generator to produce electricity. Due to the limitation of typical slider crank, converting linear motion to rotational motion using scotch yoke mechanism is proposed in this work for wave energy harvesting.

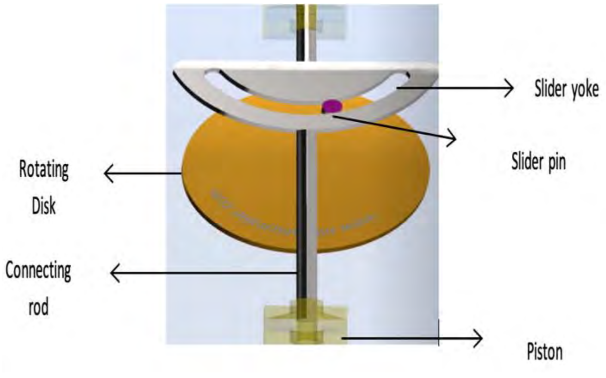

Fig. 1 : Diagram of Scotch Yoke mechanism.

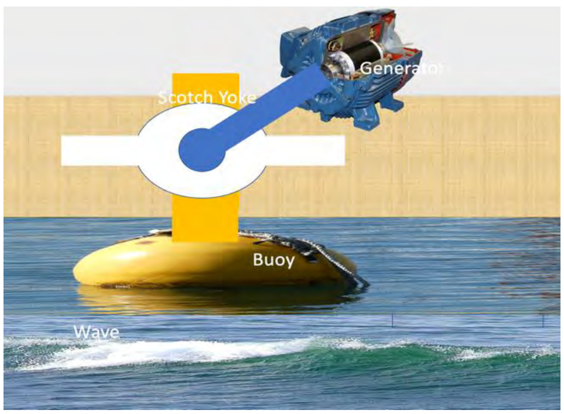

Fig. 2: Schematic diagram of the proposed wave energy converter using scotch yoke.

In the proposed mechanism, the wave force is absorbed by a floating buoy, which is fixed to piston of the scotch yoke. Due to the moving wave, the buoy will continuously move upward and downward, followed by the movement of the piston of the scotch yoke due to its attachment to the buoy. A linear motion is converted to rotational motion by scotch yoke mechanism due to its internal mechanism and the torque is seen at the output terminal, referred to crank, which is connected to a generator. The internal components of the scotch yoke are a crank, a sliding pin, a fixed link, a connecting rod or piston and a sliding yoke with slot. In a scotch yoke, a connecting rod is commenced to move due to the applied linear force of the piston of the scotch yoke, followed by the slider yoke, which is moving towards the direction of the slider pin. It is joined to the crank and is placed in the slider yoke, causing it to follow the direction of the slider yoke and the crank begins to rotate in clockwise direction. The direction is changed by the slider pin when the crank completes one-fourth of its rotation, which is from top to bottom and vice-versa. Figure 3 shows the process from the wave energy harvesting to electricity generation of the proposed mechanism in this work.

Figure 4 shows the overall block diagram of the proposed method for electrical power generation from wave energy by rotational generator using scotch yoke, which has been developed in MATLAB Simulink software. The components of the block diagram as shown in Figure 4 consist of a crank, a DC machine, a resistant load, a DC voltage source, a voltage measurement, and a current measurement. In the model, the force is provided by a cos wave function with certain amplitude and frequency. The first angular velocity is calculated, and the output torque equation of the scotch yoke mechanism is multiplied by -1 to produce a DC output. The function of a buoy in this work is as a force converter.

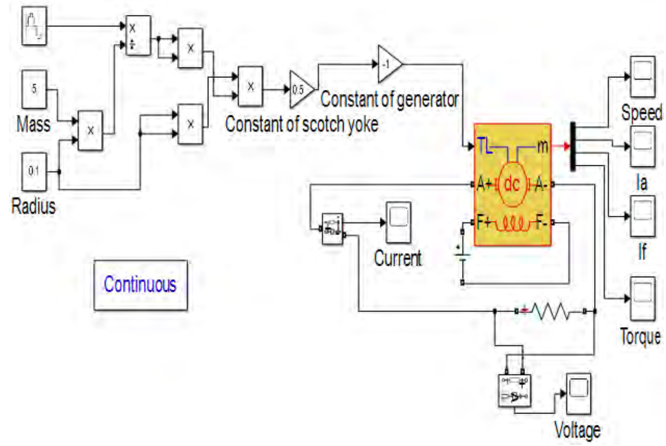

Fig. 3: Overall block diagram of the proposed method for electrical power generation using scotch yoke mechanism.

III. RESULTS FROM THE PROPOSED DESIGN

The simulation result of motion converter using a slider crank is adopted from the work reported in [8]. When the motion converter is a slider crank, the output power is 2W as shown in Figure 5 [8]. The proposed design is receiving a force of cosine wave, the output power is around 3.8 W when a 12 N force and 5 Ω load are connected to the system, as shown in Figure 6. It is mentioned that, for both simulations, the same conditions are applied so that a comparison can be made. Since Figure 5 represents the simulation result of a slider crank based wave converter, it looks different compared to the simulation result of this work. The explanation for the different results between previous work and the proposed work is that the scotch yoke has better mechanisms compared to the slider crank. This comparison between them has been elucidated in the following paragraph.

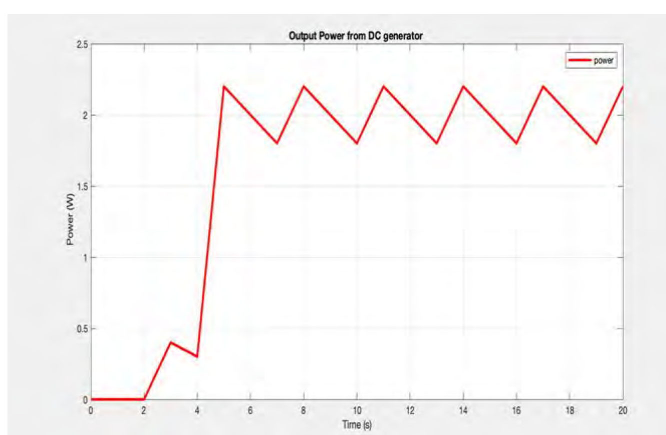

Fig. 5: Output power of slider crank-based wave converter.

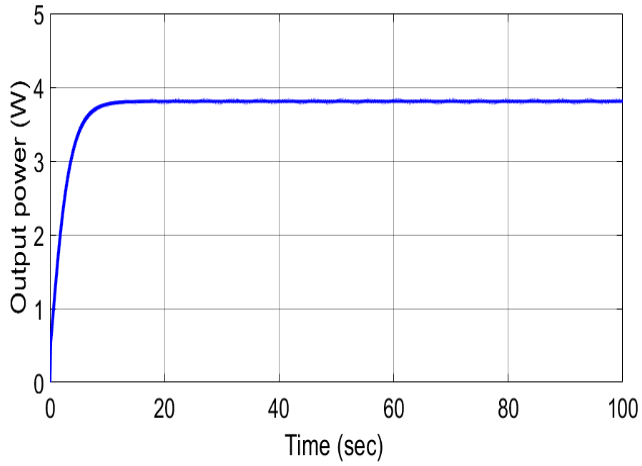

Fig. 6: Output power of scotch yoke-based wave converter when the applied force is a cosine wave.

A balance analysis is performed to understand why scotch yoke and slider crank are yielding different output power for the same input force.The thermodynamics are aiding to understand the theoretical difference between the two mechanisms (slider crank and scotch yoke) and to choose which one is better. A comparison between scotch yoke and slider crank mechanisms is shown in Table V, which is made based on the work reported in [36]. The effect of higher compression ratio ensures that an engine can extract more energy and can produce more output power. Also, higher compression ratio allows the same temperature of combustion to be attained with lower input, such as fuel, and a longer cycle of expansion is provided. The mass and temperature are crucial factors because the temperature and mass can control the energy transfer from one body to another. From Table V, the energy transfer by using slider yoke is higher compared to that of slider crank.

Table V: Comparison of the performance value between slider crank and scotch yoke mechanisms.

Parameter	Slider crank	Scotch yoke
Compression ratio of engine (efficiency) when the swept volume is the same	2.35	2.40
Total work done based on thermodynamic analysis when the mass and temperature are constant	12.09 J	12.91 J
Net work done based on thermodynamic analysis when the same pressure is applied	12.44 J	13.05 J

The ideal gas law states that the pressure of the gas multiply with the volume of a container equals to the number of particles in the gas multiply with the Boltzmann constant and absolute temperature. From the ideal gas, the relationship between the volume and temperature is directly proportional when the pressure is the same. Hence, the pressure-volume work equals to the pressure multiply with the change of volume. Therefore, the work done by an internal engine is the method of transferring energy into and out of a system. This energy conservation principle is known as the first law of thermodynamics. The first laws thermodynamics depends on the pressure and temperature. Thus, the scotch yoke mechanism yields a higher output than the slider crank.

Fig. 7 shows the curves of displacer piston top position vs. crank angle for different mechanism of motion converter. In this figure, the black line is for bell crank, the red line is for slider crank, the green line is for rhombic and the blue line is scotch yoke. Automatic dynamic analysis of mechanical system (ADAMS) was used to generate Figure 7. Based on Table V and Figure 7, it can be seen that the angle position, efficiency and working ability of scotch yoke is higher than slider crank. Therefore, employment of scotch yoke mechanism for motion converter yields higher output power than slider crank mechanism.

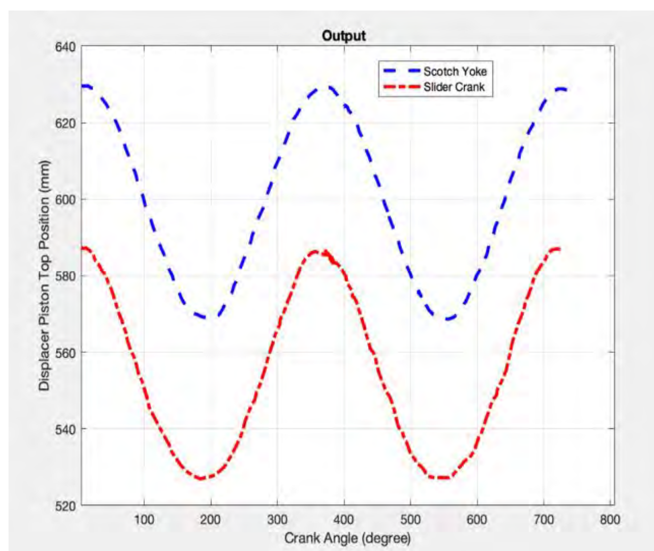

Fig. 7: Displacer piston top position vs. crank angle for different mechanisms of motion converter.

In order to evaluate the performance of the proposed scotch yoke-based linear motion converter, different input forces are applied to the system. The output voltage, current, torque and speed are observed for each of the applied forces. The output is also observed when the load resistance of the system is varied but by keeping the force constant. The output voltage from the proposed mechanism under different load resistance but at a constant force of 50 N and frequency of 100 rad/sec is shown in Figure 8. Referring to this figure, the output voltage across a 2 Ohm load resistance is approximately 30 V while the output voltage across a 5 Ohm and 10 Ohm load resistance is around 80 V and around 150 V respectively. Thus, when a higher value of load resistance is applied, the output voltage across the load is also enhanced.

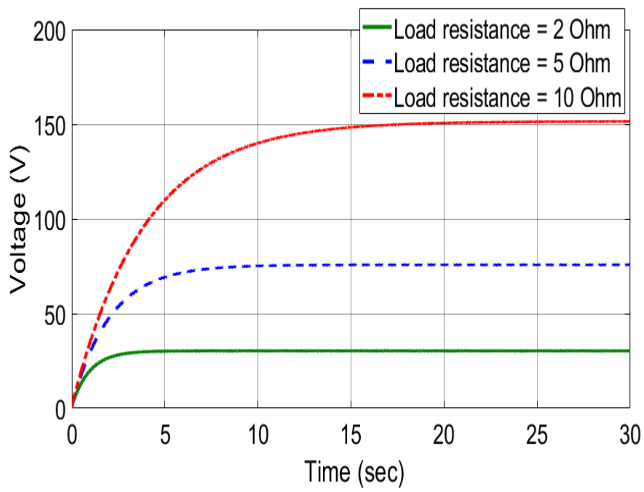

Fig. 8: Output voltage from the proposed mechanism under different load resistance.

Figure 9 shows the output voltage from the proposed mechanism under different input force by keeping the load resistance as 10 Ohm and frequency as 100 rad/s. A 220 V DC voltage is applied for the excitation. From this figure, the output voltage is around 600 V when the applied force is 100 N. The output voltage is around 2 kV and 15 kV when the applied force is 200 N and 500 N respectively. From the analysis of DC generator, the relationship between the output voltage and speed is directly proportional and the speed of the generator depends on the applied torque. Since the relationship between the torque and force is directly proportional, the relationship between the output voltage and the applied force is also proportional.

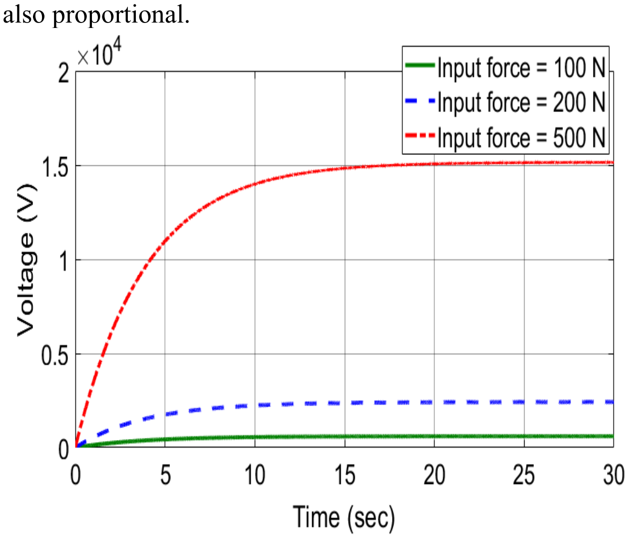

Fig. 9: Output voltage from the proposed mechanism under different input force.

Figure 10 shows the output current from the proposed mechanism under different input force by keeping the load resistance as 10 Ohm and frequency as 100 rad/s. From this figure, the output current is around 60 A, 200 A and 1.5 kA for applied force of 100 N, 200 N and 500 N respectively. The relationship between the current and the voltage is directly proportional. Therefore, the relationship between the applied force and current is also proportional.

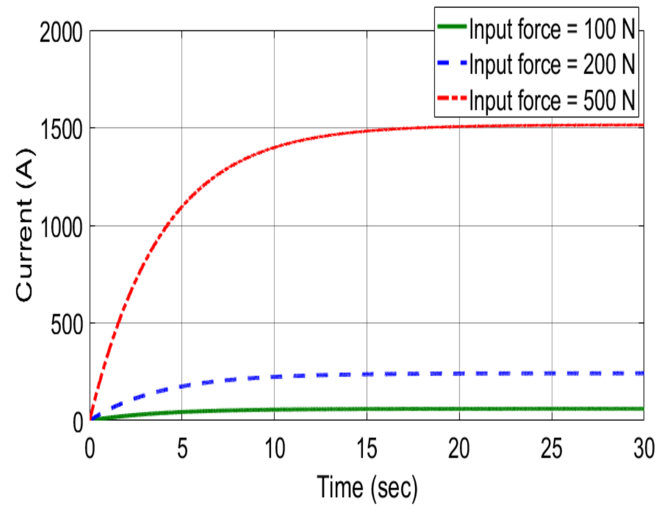

Fig.10: Output current from the proposed mechanism under different input force.

Figure 11 shows the output speed from the proposed mechanism under different input force by keeping the load resistance as 10 Ohm and frequency as 100 rad/s. From this figure, the output speed is around 400 m/s, 1800 m/s and 10000 m/s for applied force of 100 N, 200 N and 500 N respectively. It is found that the speed is proportional to the applied force.

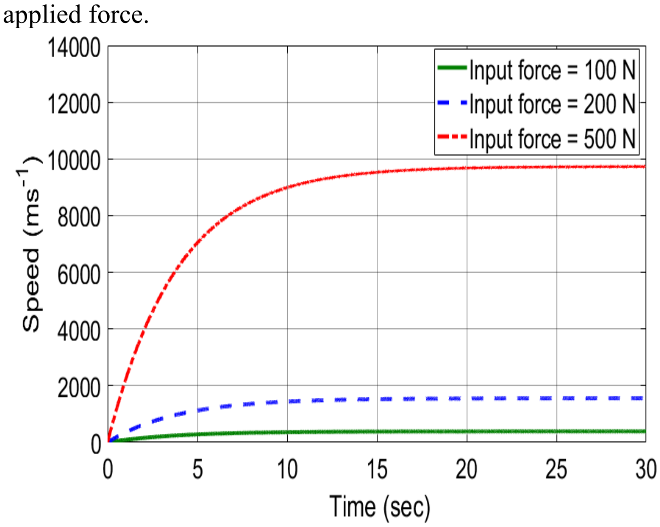

Fig. 11: Output speed from the proposed mechanism under different input force.

Figure 12 shows the output torque from the proposed mechanism under different input force by keeping the load resistance as 10 Ohm and frequency as 100 rad/s. From this figure, the output torque is around 100 Nm, 400 Nm and 2500 Nm for the applied force of 100 N, 200 N and 500 N respectively. It is found that the relationship between the applied force and torque is proportional to each other. Therefore, from Figures 9 to 12, when the applied force is increased, the output voltage, current, speed and torque are enhanced.

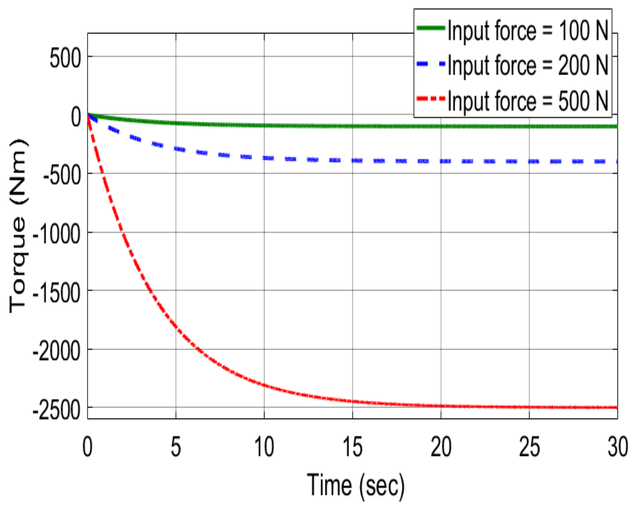

Fig. 12: Output torque from the proposed mechanism under different input force.

Figure 13 shows the output voltage under different input frequency while maintaining the applied force constant. The input frequency is varied at 1 rad/s, 10 rad/s and 100 rad/s. From this figure, the output voltage under lower frequency is oscillating compared to that at higher frequency. From equation (6), the relationship between the frequency and energy is directly proportional. Hence, at higher frequency, the energy is higher. The energy equals to $0.5mv^2$ while the force equals to the mass times the acceleration. The energy is related to the velocity while the applied force is related to the acceleration. Therefore, the applied force is twice the rate of energy change with respect to time and the velocity. Since the relationship between the force and output voltage is proportional, the relationship between the input frequency and output voltage is also proportional.

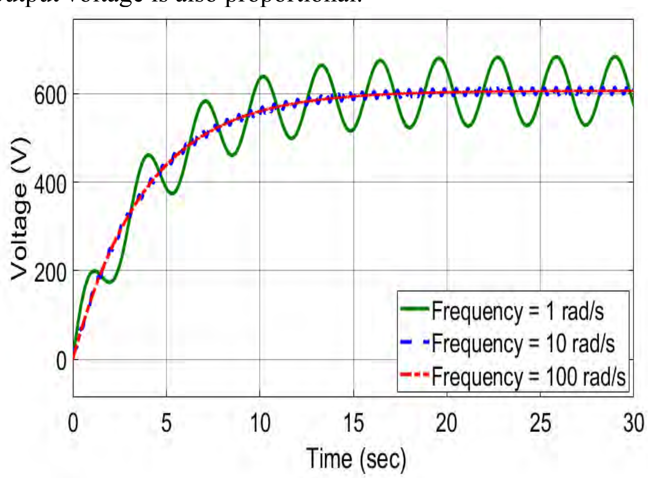

Fig. 13: Output voltage from the proposed mechanism under different input frequency.

In order to support the proposed work's effectiveness, the results from three works reported in 2022 are as follow. A mean power of 1.39 mW has been reported by Tian et al., entitled "Frequency modulated hybrid nanogenerator for efficient water wave energy harvesting," where triboelectric, electromagnetic, and piezoelectric nanogenerators have been exploited [37]. For this reason, generation power is lower than this proposed work result which is 3.8W. Also, another reason is that these results has not been produced under the same condition. The peak power of the work entitled "A wave energy harvesting system based on the double-wing flywheel for unmanned surface vessels" by Dai et. al, is 38.4 mW [38]. They worked on double-wing flywheel electromagnetic transducer. This work result and this proposed work' result have not been generated under the same condition. Another work's output power of 520 mW has been present in "High-efficient built-in wave energy harvesting technology: From laboratory to open ocean test." by Li et.al [39]. It is mentioned that the result between the work by Li et.al and this proposed work has been not yielded under the same condition.

IV. Conclusions

In this work, wave energy harvesting technique using rotational generator based on scotch yoke mechanism has been successfully proposed. A typical slider cranks to convert linear motion into rotational motion is replaced by scotch yoke mechanism to yield higher system efficiency. From the results obtained, the scotch yoke mechanism can perform well at low and high applied force. The relationship between the frequency and the output voltage of the scotch yoke mechanism is proportional but the higher input frequency ensures smoother output voltage of the generator. The relationship between the energy extraction time and input frequency is inversely proportional. The relationship between the output voltage, current and torque and the applied force is directly proportional to each other. Based on the results obtained from this work, rotational generator by employing scotch yoke mechanism can be a promising method for wave energy harvesting and as a motion converter from linear motion to rotational motion. In terms of future work, hardware implementation can be performed. Also, a comparative study between the hardware and simulation results can be done. If there is any difference between them, further studies can be explored for mitigation. Furthermore, future study can consider different locations for further comparison.

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Md. Zahir Hossain was born in Satkhira, Bangladesh. He received his research master's degree in electrical power generation from the University of Malaya, Kuala Lumpur, Malaysia in 2022, and a bachelor's degree in electrical and electronic engineering from the University of Asia Pacific, Dhaka, Bangladesh. Now, he is set to start his PhD in a foreign country. In the past, he worked as a Research Assistant. His

research interests are in optimization, high voltage power, and renewable energy generation.

Hazlee Azil Illias was born in Kuala Lumpur, Malaysia. He received bachelor's degree in Electrical Engineering from the Universiti Malaya, Malaysia in 2006. He immediately joined Freescale Semiconductors (M) Sdn. Bhd. as a product engineer before pursuing his PhD studies in 2008. He obtained PhD Degree in Electrical Engineering from the University of Southampton, United Kingdom in 2011. Since 2016, he has been an Associate Professor at the Department of Electrical Engineering, Universiti Malaya. His main research interests include modelling and measurement of partial discharge phenomena in solid dielectric insulation, condition monitoring, insulation system diagnosis, lightning overvoltage, transmission line modelling, optimization methods and artificial intelligence techniques.