Performance and Energy Consumption of Paddle Wheel Aerator Driven by Brushless DC Motor and AC Motor: A Preliminary Study

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Abstract. Energy demand for paddle wheel aerator in a shrimp pond is high and brings to second highest cost of operational behind feed supply. Most of wheel aerators are driven by electric motors than diesel engines as their easy operations. The electric motors need high electrical energy to drive wheel aerators along day and night. The common type of motor used is Alternating Current (AC) or induction motor, however Brushless Direct Current (BLDC) motor has potential electrical energy saving which need to be explored. This study objectives to find out performance of BLDC and AC motor as paddle wheel aerator driver. The motor’s performances were compared in term of operation of paddle wheel at various static loads. Both motor also challenged by On/Off running every 5 minutes, the treatment goal was to determine their reliability. Parameters observed included consumption of power, wheel rotary, torque, and efficiency, motor temperature as well. Results showed energy consumption of BLDC motor 51\% lower than AC motor, and BLDC motor attained 89.99\% of maximum efficiency while AC motor efficiency had 73.16\%, however rotary wheel and torque both of them were similar. The On/Off treatment caused rising temperature of AC motor but did not affect the temperature of BLDC motor. Therefore, applied BLDC motor as paddle wheel aerator driver could be alternative way to reduce energy consumption without reducing its performance.

1. Introduction
Fisheries sector is one sector that has an important role in the Indonesian economy, especially shrimp. Aquaculture has become one of the fastest growing food cultivation systems with high potential for further development for shrimp. One of aquaculture in Indonesia is vannamei shrimp culture. After its introduction to Indonesia in 2001, vannamei shrimp (\textit{Litopenaeus vannamei}) or white shrimp has become one of the leading commodities in the national aquaculture sector. The management of vannamei shrimp culture in Indonesia is carried out with various cultivation patterns and systems. Starting from those still using traditional cultivation systems to super intensive ones with various technological applications \cite{1}. Vannamei production in Indonesia increased rapidly from 2014 to
2019 (254,297 tons in 2014 and 664,825 tons in temporary data 2019) with increasing rate of 35.62% [2]. The government of Indonesia targeted vannamei production target increased 12% average per year from 2015 to 2019 with values from 535,200 tons in 2015 to 842,200 tons in 2019.

Overall water quality in the culture environment or physical-chemical factors are important indicators for the comfort of aquatic organisms to live during the cultivation cycle [3]. Thus, indirectly the condition of physicochemical parameters with stable and ideal concentration levels will have a positive influence on the productivity level of shrimp pans [4]. What is meant by harvest productivity indicators are all production variables which include shrimp biomass weight, survival rate value, growth rate, and shrimp feed FCR value [5]. Pond water quality is influenced by physical and chemical parameters including dissolved oxygen, temperature, salinity, turbidity, pH, nitrogen, ammonia, nitrate, phosphate, and silica; and biological parameters, namely chlorophyll-a, faecal coliform, Vibrio, and the number of bacteria [6]. Temperature, salinity, and alkalinity in intensive ponds are water quality parameters that have a close relationship with the efficiency of FCR values in ponds, with temperature parameters being the water quality variable which has a direct influence on the effectiveness of the feed conversion ratio by shrimp [7]. Dissolved oxygen is one of the most important parameter in pond. Reduced pond water quality due to low oxygen levels can cause disease outbreaks for shrimp ponds [8]. For intensive vannamei shrimp ponds in Indonesia, the recommended oxygen level for shrimp farmers is >4 mg/L [9]. So far, Indonesians have used aerators to improve the water quality of shrimp ponds.

Energy demand for paddle wheel aerator in a shrimp pond is high and brings to second highest cost of operational behind feed supply [10]. Cost of vannamei shrimp farms was defined into variable costs and fixed costs [11]. Variable costs are costs that increase with the intensity of production (costs per hectare per year), which is the cost of post larvae, feed, energy use (electricity and fuel), amendments, and labor. Total variable costs per pond, usually increased with the intensity of production and species produced. Total fixed costs per hectare per year which also increase generally with the level of production intensity are costs from investment in equipment such as aeration systems and various types of vehicles. Energy use (electricity and fuel) is generally the second cost behind feed for low and medium production of vannamei in Thailand with each cost/ha/year $5343 and $5850. Energy consumption for aquaculture in Vietnam, mainly shrimp farming industry, has continued rising highly in recent years due to increasing of shrimp production [12]. Most of energy demand for shrimp farms is used by aeration system with electric motors as aerators driver. High energy consumed by electric motors for aeration and pumping systems also brings to high operation cost and related to greenhouse gas emissions. Even though design and operation of aerators have been increased by many improvements and renewable energy resources have been applied, mechanical aerators still need high energy with low oxygen absorbed.

Aeration system is one of the highest energy consumption at shrimp farms. Paddlewheel aerators and propeller-aspirator-pumps are probably most widely used. Amounts of aeration vary from as little as 1–2 kW ha in some types of fish culture to as much as 15 or 20 kW ha in intensive culture of marine shrimp [13]. Most of wheel aerators are driven by electric motors than diesel engines as their easy operations. Moreover, diesel engines (and also internal combustion engines) have lower efficiency and high fuel cost. In shrimp culture, the electric motors still need high electrical energy to drive wheel aerators along day and night. The common type of motor used is Alternating Current (AC) or induction motor, however Brushless Direct Current (BLDC) motor has potential electrical energy saving and many benefits which need to be explored. BLDC motors have less wear and probability of failure and higher efficiency [14]. BLDC motors have a remarkable increasing demand in low powered electrical vehicle and commercial applications as their speed-torque performance, better size
and cost than other motors [15]. BLDC motor also emerges as a better substitute for DC motors and AC Induction Motors in water pumping applications due to high efficiency, high reliability and least maintenance requirement and good dynamic performance [16]. BLDC motors have benefit among others showed in a short-time high-overload BLDC driving system [17] and a control system for a morphing wing model actuated with miniature BLDC motors [18]. Also, robust dynamic speed response, less maintenance and efficient operation make BLDC motors as a clear choice for many driving applications with instantaneous speed control while developing high torque [19]. This study objectives to find out performance of BLDC and AC motor as paddle wheel aerator driver included energy consumption that can be reduced and reliability.

2. Material and Methods

To observe performance, energy consumption and reliability of AC motor and BLDC motor, a series of testing was conducted to both motors with static loads. Each assembly of paddle wheel driven by AC motor and BLDC motor was inserted with hollow irons static loads to approach actual loads in ponds.

2.1. Materials and equipment

In this study, a unit of paddle wheel aerator driven by AC motor and a unit of paddle wheel aerator driven by BLDC motor were tested. The components of each testing unit were one paddle wheel assembly unit, an electric motor (AC and BLDC motor), gearbox, static loads (hollow irons), and measuring tools. AC motor specification was 1 HP / 3 phase, 380 V, 1440 rpm, 0.8 A current and 1:14 gear box. BLDC motor had specification Intelligent Aeromotor Motor 1 HP power, 3 phase/380 V, 60-105 rpm, motor efficiency > 80% and BLDC control system. The measuring tools were an electrical current data logger, an ampere meter (to measure electrical current and voltage), rpm meter (tachometer), a temperature data logger, timer, and scale. Schematic illustration for experimental testing condition was shown in Figure 1.

2.2. Method

The motor’s performances were compared in term of operation of paddle wheel at various static loads for 8 hours or 480 minutes. Static loads were 10, 20 and 30 kgs. Parameters observed were electrical current and volatage to observe consumption of power (electrical power), wheel rotation, torque and efficiency. Electrical current and voltage were measured every 60 minutes by current ampere meterer. Wheel rotation was measured by rotation meter (tacho meter) every 60 minutes. Electrical current and voltage were used to analyze electrical power with equation (1). Mechanical power was defined by the motor power, for 1 HP motor, the mechanical power is equal to 756 Watt. And then, torque can be defined from mechanical power and wheel rotation (rpm) as equation (2).

\[ P_E = \sqrt{3}V.I \cos\phi \]  
\[ T = \frac{P_M}{2\pi(n/60)} \]

Where \( P_E \) is electrical power in Watt (W), \( V \) for voltage in Volt (V), \( I \) for current in Ampere (A), and \( \cos \phi \) for power efficiency.

Where \( T \) is torque in N.m, \( P_M \) for mechanical power in Watt (W) and \( n \) for wheel rotation in rotation per minute.
From electrical power and mechanical power, efficiency ($\eta$) of the motor can be defined by the following equation (3).

$$\eta = 1 - \frac{P_E}{P_M}$$

(3)

Both motor also challenged by On/Off running every 5 minutes for 180 minutes, the treatment goal was to determine their reliability. Parameters observed were motor current and motor body temperature. Electrical current was measured every 15 seconds by current data logger. Body temperature was measured by temperature data logger every 15 seconds.

![Figure 1. Schematic illustration for experimental testing condition.](image)

3. Result and Discussion

The main results in this preliminary study were motor performance, energy consumption and reliability (electrical current and body temperature) of AC and BLDC motor that will be discussed to compare both motors.

3.1. Motor performance and energy consumption

Performance of each motor in various static loads was measured by parameters: electrical current and voltage, wheel rotary, electrical power, mechanical power, torque and efficiency. Testing result for motor performance was shown in Table 1. Electrical current for BLDC motor was from 0.13 A with 10 kgs loads, 0.24 A with 20 kgs and 0.26 A with 30 kgs. Then, electrical current for AC motor was from 0.36 A with 10 kgs loads, 0.6 A with 20 kgs and 0.61 A with 30 kgs. Motor current tends to increase with raising loads for both AC and BLDC motor. Current increase significantly from 10 to 20 kgs, but smoothly from 20 to 30 kgs loads as graphed in Figure 2. Compared to AC motor current, BLDC motor current is lower 0.12 A in 10 kgs loads or 66.7% from AC motor current, lower 0.36 A in 20 kgs loads or 43.3% and lower 0.35 A in 30 kgs loads or 42.6%. Result showed that motor current was reduced significantly by BLDC motor with average 51%.
Table 1. Performance and energy consumption of AC and BLDC motor

| Motor Type | Load (kg) | Current (ampere) | Wheel rotation (rpm) | Voltage (volt) | Electrical power | Torque (Nm) | Mechanical power (watt) | Efficiency (%) |
|------------|-----------|------------------|----------------------|---------------|------------------|-------------|-------------------------|----------------|
| BLDC       | 10        | 0.13             | 105                  | 392.63        | 75.69            | 68.79       | 756.00                  | 89.99          |
|            | 20        | 0.24             | 105                  | 390.77        | 135.71           | 68.79       | 756.00                  | 82.05          |
|            | 30        | 0.26             | 105                  | 390.62        | 151.88           | 68.79       | 756.00                  | 79.91          |
| AC         | 10        | 0.36             | 102                  | 380.56        | 202.92           | 70.97       | 756.00                  | 73.16          |
|            | 20        | 0.60             | 102                  | 394.45        | 350.59           | 70.97       | 756.00                  | 53.63          |
|            | 30        | 0.61             | 101                  | 393.00        | 352.41           | 71.51       | 756.00                  | 53.38          |

Another parameter, wheel rotation, was 105 rpm for BLDC motor and 101-102 rpm for AC motor. BLDC rotation did not fluctuate and stable at 105 rpm. Voltage of BLDC motor was in the range of 390.62 - 392.63 V and 380.56 - 394.45 V for AC motor. This voltage value could be stated stable.

Electrical power of BLDC motor was in the range of 75.69 - 151.88 W (average 121.1 W) and 202.92 - 352.41 W (average 301.9 W) for AC motor. Electrical power or energy consumption was associated with electrical current because current determines power higher than voltage and $\cos \phi$ as described in the equation (1). Voltage of 3 phase source was stable at about 380 V and also $\cos \phi$ at about 0.85. Thus electrical power was mostly the function of current and had value that about linear to current. Like current, electrical power increase significantly from 10 to 20 kgs, but smoothly from 20 to 30 kgs loads as graphed in Figure 3. Result showed that electrical power of BLDC was lower than AC motor as the function of current with values about 66.7% from AC motor current in 10 kgs loads, 43.3% in 20 kgs loads and 42.6% in 20 kgs loads. Torque was calculated as equation (2), as the function of mechanical power and rotation. Mechanical power was defined by the 1 HP motor power or equal to 756 Watt. BLDC had torque at 68.79 Nm and AC motor 70.97-71.51 Nm. Torque value was stable both for BLDC and AC motor because mechanical value had constant value and rotation nearly at the same value.

Figure 2. Current trend due to static loads

Figure 3. Electrical power trend due to static loads

Efficiency of motor was calculated as equation (3), BLDC had efficiency from 79.91 - 89.99% and AC motor from 55.38 - 73.16%. This result is similar to on testing of induction/AC motor under load
with a working voltage of 375 volts, the input power was 2565 watts with losses in the stator and rotor coils of 743 watts, the mechanical power released by the induction motor was of 1823 watts, the torque produced by the rotor is 14 Nm and the efficiency of the motor of 71.07% [20]. Efficiency is the function of electrical power (P_E) and mechanical power (P_M). As P_M had constant value, efficiency was determined only by P_E. Once again, as P_E was the function of current, so that efficiency was mostly determined by current. Lower value of current then lower value of electrical power and higher efficiency. In this study, BLDC motor attained 89.99% of maximum efficiency while AC motor efficiency had 73.16% that was the function mainly from motor current. BLDC motors have less wear and failure probability, higher efficiency [14]. Thus BLDC motor is most suitable for long-term continuous duty for real three-phase electric drive with 3-phase PM motor.

In the demonstration of operation and control of standalone isolated inverter fed BLDC motor with solar PV systems for agric pumping systems, the feasibility of proposed system for agricultural water pumping was verified with simulation and hardware results [21]. BLDC Motor performances with centrifugal pump had constant electrical current, torque and also rotation. Generally, this experiment showed BLDC had lower current and thus lower electrical power or energy consumption than AC motor, and also higher efficiency. Surprisingly, with lower energy consumption, performance of BLDC (torque, wheel rotation) was not reduced compared to AC motor. Results showed that BLDC motor attained 89.99% of maximum efficiency while AC motor efficiency had 73.16%, energy consumption of BLDC motor 51% lower than AC motor, and however rotary wheel and torque both of them were similar.

3.2. Motor reliability

Electrical current and body temperature of motors were observed to determine their reliability. In the treatment On/Off running every 5 minutes for 180 minutes, electrical current and body temperature were measured every 15 seconds by data logger. Electrical power or energy consumption was associated with electrical current because current determines power higher than voltage and cos φ as described in the equation (1). Voltage of 3 phase source was stable at about 380 V and also cos φ at about 0.85. Electrical power was mostly the function of current and had value that about linear to current. Thus, this On/off treatment was important to evaluate the current for reliability. Average electrical current of BLDC and AC motor are shown in Figure 4. BLDC had average electrical current about 0.12-0.13 A at “on” condition and about 0.03-0.07 A at “off” condition. While, AC motor had current about 0.35-0.37 A at “on” condition and about 0.04-0.07 A at “off” condition. Along 180 minutes with 5 minutes “on/off” treatment current was relatively stable at on/off value, except at the starting of “on” BLDC on minute 50, 60, 70, 80, 90, 100 and 110. This higher starting current was still acceptable for BLDC motor with maximum value about 0.47 A. BLDC system designed with current long-time drive scheme has some problems, one of them is high current when starting. Time division switching control method is one of the solutions of the problem of overflow and overheat caused by the heavy load when starting [17].
Figure 4. Average electrical current of BLDC and AC motor.

One of the high current effect to motor is increased body temperature that will be observed. Body temperature of motor is shown in Figure 5. Ambient/air temperature was also observed to see it’s effect to motor body. Ambient/air temperature was recorded at about 29.2-30.2 °C that only increased slightly about 1 °C and could be ignored. BLDC body temperature increased from about 28 to 32 °C after treatment. On/off treatment did not affect significantly to body temperature of BLDC motor. Whereas AC motor body temperature increased from about 29 to 36.3 °C after treatment along the on/off treatment. Beside temperature increasing, AC motor body temperature also fluctuated cyclically, increased up about 1.5 °C when “on” and decreased 1.5 °C when “off”. BLDC motor had lower body temperature than AC motor by about 3-4 °C.

Raising motor body temperature is caused by some factors especially the electric heating or copper loss. Copper loss is defined as heat produced by electrical currents in the conductors of transformer windings (also motor windings), or other electrical devices. Copper losses are an undesirable transfer of energy/loss which result from induced currents in adjacent components. When a motor of resistance $R$ has a current $I$ at voltage $V$, the power (heat rate) absorbed in the motor $P$ is following Joule's First Law or Joule–Lenz law [22]:

$$P = I^2R$$

Power is energy per unit time, thus the energy $U$ delivered in time $t$ is given by:

$$U = Pt = I^2Rt$$

When a motor absorbs electrical energy, it must dissipate this energy in the form of heat $Q$. Higher current and resistance make higher heat absorbed. In this case, AC motor had higher $I$ and $R$, and thus higher $Q$ and body motor temperature. And for BLDC motor, lower body temperature was meant lower $I$ and $R$ and less $Q$ or heat loss. In the electric motor designing process, the power losses from the electric motors are transferred into heat that has to be dissipated effectively to the ambient temperature to avoid overheating and failure of the motor. The better heat transfer dissipation due to smaller thermal resistance results in the lower temperature that occurs in the windings and core. The lower temperature of the windings causes the lower copper losses and ensures operating point beyond demagnetization of the permanent magnets [23]. The On/Off treatment caused rising temperature of AC motor but did not affect the temperature of BLDC motor.
4. Conclusion

Results showed BLDC motor attained 89.99% of maximum efficiency while AC motor efficiency had 73.16% and energy consumption of BLDC motor 51% lower than AC motor in this preliminary study. However, performances of BLDC and AC motors (rotary wheel and torque) were both similar. The On/Off treatment caused rising temperature of AC motor but did not affect the temperature of BLDC motor. Thus, applied BLDC motor as paddle wheel aerator driver could be alternative way to reduce energy consumption without reducing its performance.

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