Simulation of a Dual-Rotor Ocean Current Turbine with Variable Buoyancy and Lifting Surface for Motion Control

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Introduction

- Increased interest in renewable energy production has created a demand for novel methods of electricity production.

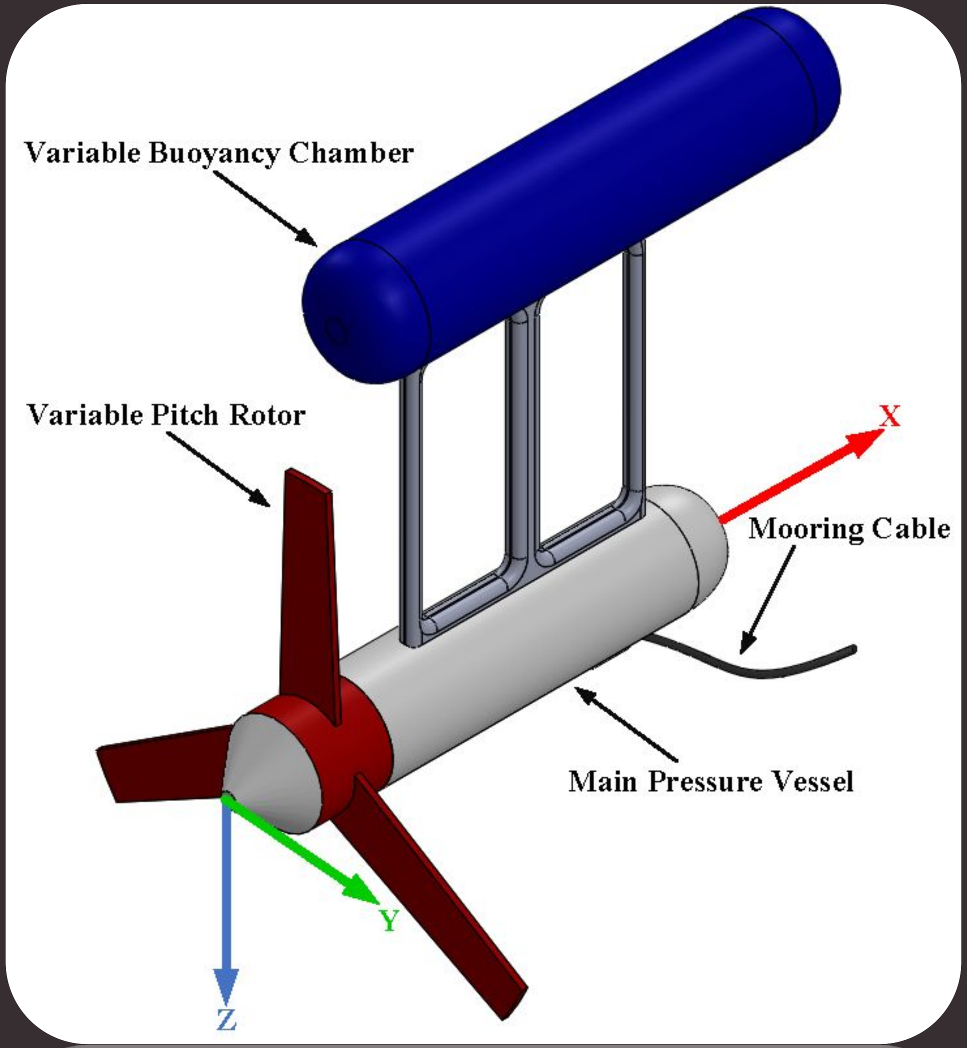
- With a high potential for low cost power generation from the consistent ocean kinetic energy, ocean current turbines (OCTs) can help meet this growing demand.

- Ocean current resources are typically located where the total water depth is in excess of 250 meters, with most of this resource in the top 100 meters of the water column.

Introduction

- As the more electricity power can be harnessed near ocean surface, deploying ocean current turbine near the ocean surface will bring a couple of damages for it, induced by the existence of ocean waves.

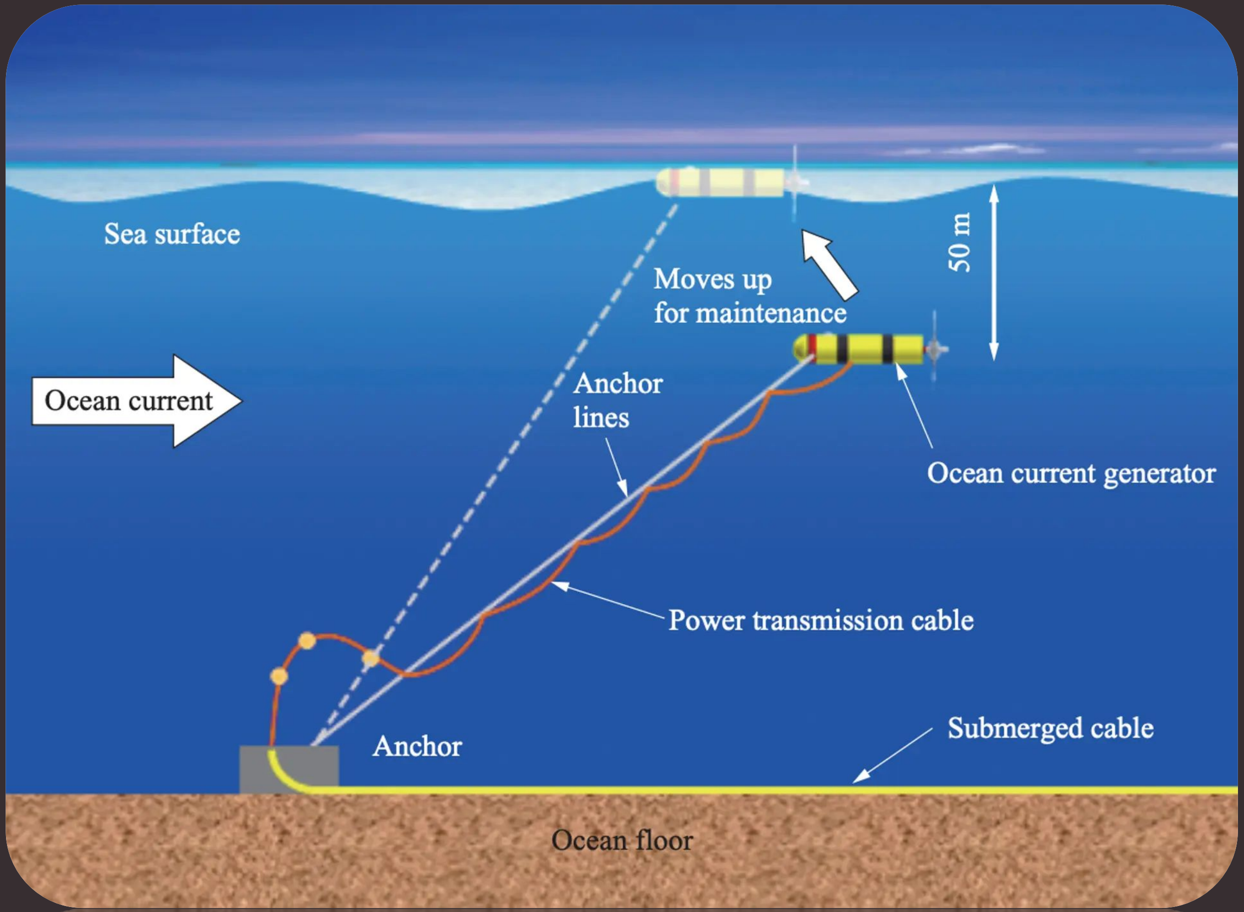
- Therefore, some researches have been done on modeling and controlling the turbine like controlling buoyancy tank water volume to keep the OCT at the correct depth level of the ocean. Based on their results, the maximum power from this type of turbine with the defined parameters like size for its components is captured, if the OCT is kept at 50m to 75m ocean depth.



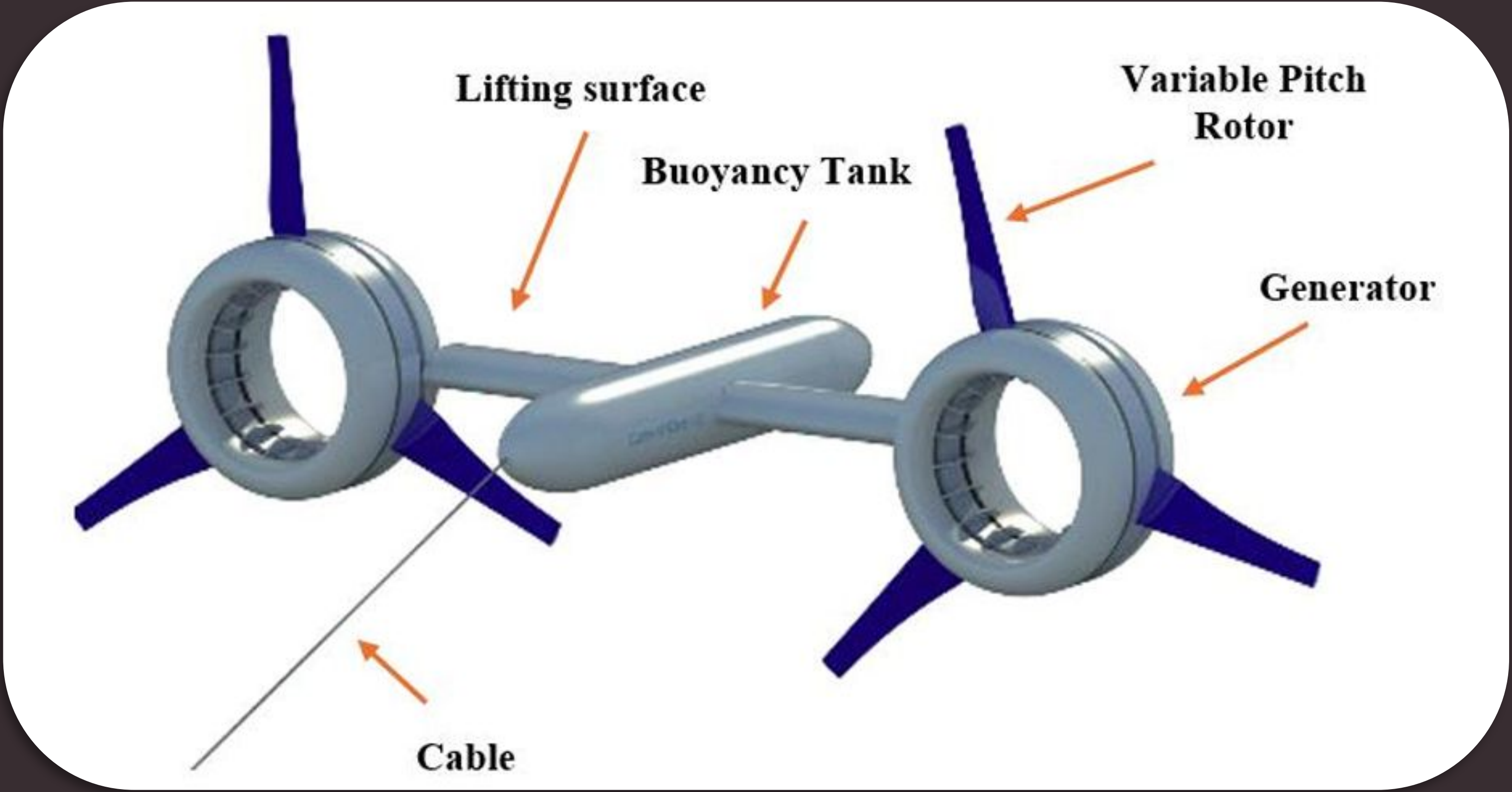
Introduction

- Also, some researches have been done on optimization of physical parameters of this turbine in order to capture the more electricity power from kinetic energy of the ocean.

- Now, it is the time to introduce a new design of ocean current turbine to capture more considerable electricity power from the kinetic energy of the ocean.



Proposed Turbine Model



Equations

❖Coordinate systems

- To numerically simulate the Ocean Current Turbine (OCT), several coordinate systems are employed: an inertial coordinate system ($\bar{O}$), a body-fixed coordinate system ($\bar{B}$), momentum mesh coordinate systems ($\bar{M}$), shaft systems ($\bar{S}$), and rotor blade systems ($\bar{R}$). Vectors are transformed from the inertial coordinate system ($\bar{O}$) to the body-fixed coordinate system ($\bar{B}$) by multiplying the inertial vector by the transformation matrix $L_{\overline{OB}}$, which is defined using the Euler angles as follows:

$$L_{\overline{OB}} = \begin{bmatrix} c_\alpha c_\theta & s_\alpha c_\theta & -s_\theta \\ c_\alpha s_\theta s_\varphi - s_\alpha c_\varphi & c_\alpha c_\varphi + s_\alpha s_\theta s_\varphi & c_\theta s_\varphi \\ c_\alpha s_\theta c_\varphi - s_\alpha s_\varphi & -c_\alpha s_\varphi + s_\alpha s_\theta c_\varphi & c_\theta s_\varphi \end{bmatrix}$$

where $s_\varphi = \sin(\varphi)$ and $c_\varphi = \cos(\varphi)$, and the transformation matrix from the body-fixed coordinate system ($\bar{B}$) to the inertial coordinate system ($\bar{O}$) is $L_{\overline{BO}} = L_{\overline{OB}}^T$.

Equations

❖Equations of motion

The motion of the numerically simulated OCT is described using 8-DOF. The equations of motion for the 6-DOF movement of the main body (excluding the rotors) of the OCT system such as the OCT's linear accelerations $\dot{u}$, $\dot{v}$, and $\dot{w}$, and angular accelerations $\dot{\omega}_x$, $\dot{\omega}_y$, and $\dot{\omega}_z$ are calculated as:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = m^{-1}F \begin{bmatrix} i_{\bar{B}} \\ j_{\bar{B}} \\ k_{\bar{B}} \end{bmatrix} + \begin{bmatrix} u \\ v \\ \omega \end{bmatrix} \times \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

$$\begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} I_x^{-1} & 0 & 0 \\ 0 & I_y^{-1} & 0 \\ 0 & 0 & I_z^{-1} \end{bmatrix} \left(M \begin{bmatrix} i_{\bar{B}} \\ j_{\bar{B}} \\ k_{\bar{B}} \end{bmatrix} - \begin{bmatrix} (I_z - I_y)\omega_y.\omega_z \\ (I_x - I_z)\omega_z.\omega_x \\ (I_y - I_x)\omega_x.\omega_y \end{bmatrix} \right)$$

$$F = F_G + F_{gb} + \sum_{m=1}^{4} F_{\omega,m} + \sum_{m=1}^{2} F_{r,m} + \sum_{m=1}^{2} F_{n,m} + F_c$$

The total force vector acting on the turbine is the sum of gyroscopic force (F_G), gravitational and buoyancy force (F_{gb}), wing forces (F_ω), two rotor forces (F_r) , two nacelle forces (F_n), and cable force (F_c).

Equations

❖Gyroscopic Force

The gyroscopic force (F_G) caused by the rotational speed of each rotor around the x-axis, which is shown as:

$$F_G = I_x^r \begin{bmatrix} \omega_x^r \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

❖Gravitational and buoyancy force

This force F_{gb} is modeled using the transformation matrix from $\bar{B}$ to $\bar{O}$ (i.e., $L_{\overline{BO}}$), which can be expressed as:

$$F_{gb} = F_g + F_b = L_{\overline{BO}} \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + L_{\overline{BO}} \begin{bmatrix} 0 \\ 0 \\ -B \end{bmatrix}$$

where m is the total mass of the OCT, g is the earth gravitational acceleration, and B is the total buoyancy force.

Hydrodynamic Forces

- The hydrodynamic forces acting on the OCT, excluding the cable, are calculated for three types of components. These are defined as the wing forces (F_ω), which include forces on the main wing; the rotor forces (F_r), which encompass forces on the two rotors; and the nacelle forces (F_n), which pertain to the forces on the two nacelles.

❖ **Rotor Forces:** In this numerical simulation, rotor forces are calculated using a Blade Element Momentum (BEM) rotor model that incorporates Dynamic Wake inflow calculations. This model determines the angle of attack for each rotor blade element and rotor mesh element (the mesh elements used to calculate rotor-induced flow perturbations). The angle of attack, denoted as α^{ij}, is computed from the equation $\alpha^{ij} = \varphi^{ij,ik} - \beta^{ij,ik}$, where $\beta^{ij,ik}$ represents the blade section pitch angle, and the relative flow angle $\varphi^{ij,ik}$ is given by $\varphi^{ij,ik} = tan^{-1}(-\frac{V_A^{ij}}{V_T^{ij}})$. Here, V_A and V_T are the axial and tangential components of the relative ocean velocity $V^{ij,ik}$. This relative ocean velocity is defined as the sum of three components: (i) the undisturbed ocean velocity, (ii) the blade motion induced relative ocean velocity, and (iii) the wake induced ocean velocity. Therefore, the forces on each of the two rotors, F_r, can be written as

$$\mathrm{F_{r,m}} = \frac{1}{2}\rho \sum_{j=0}^{N_b}\sum_{i=0}^{N} L_{\overline{SB}}\, L_{\overline{RS}}^{ij} \begin{bmatrix} \delta r^i c^i C_T^{ij}\left(\left(V_A^{ij}\right)^2 + (V_T^{ij})^2\right) \\ \delta r^i c^i C_T^{ij}\left(\left(V_A^{ij}\right)^2 + (V_T^{ij})^2\right) \end{bmatrix}$$

Hydrodynamic Forcing

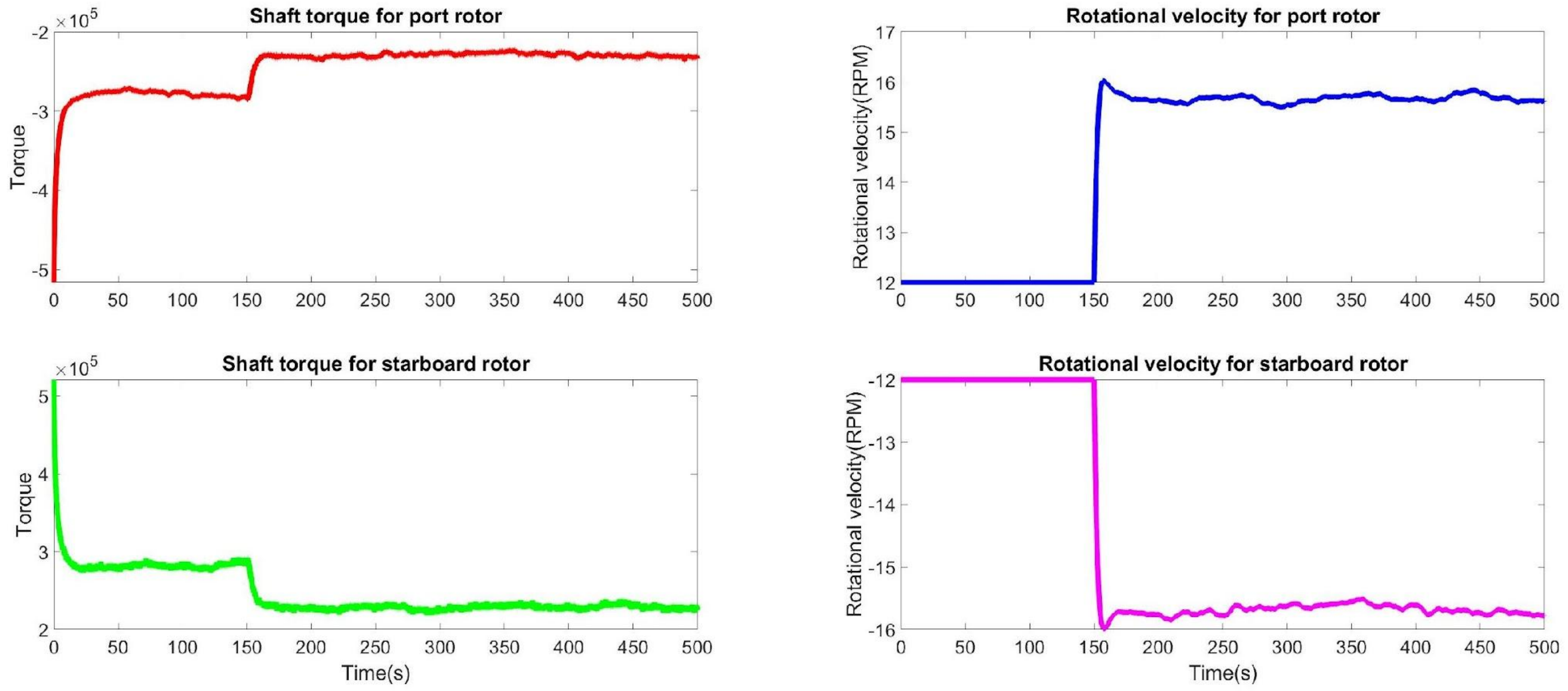
❖ Wing Forces: The main wing is divided into N_ω discrete sections. Therefore, the force on the wing, F_ω, in the tangential, cross, and axial directions relative to the airfoils can be written as:

$$F_\omega = -\frac{1}{2}\rho A_\omega \begin{bmatrix} \sum_{i=1}^{N_\omega} C_t^i(\alpha)(V^i)^2 \\ 0 \\ \sum_{i=1}^{N_\omega} C_a^i(\alpha)(V^i)^2 \end{bmatrix}$$

where V^i denotes the relative water speed with respect to a wing section calculated using only the normal and tangential components of relative water velocity, $\rho = 1030\ kg/m^3$ is the water density, $C_t^i(\alpha)$ is the tangential drag coefficient of a wing section, $C_a^i(\alpha)$ is the axial drag coefficient, where both $C_t^i(\alpha)$ and $C_a^i(\alpha)$ are functions of angle of attack (α). The $C_t^i(\alpha)$ and $C_a^i(\alpha)$ values are calculated using lift and drag coefficients according to $C_t^i(\alpha) = C_D^i(\alpha)\cos(\alpha) - C_L^i(\alpha)\sin(\alpha)$ and $C_a^i(\alpha) = C_D^i(\alpha)\sin(\alpha) - C_L^i(\alpha)\cos(\alpha)$. The wing forces are then converted to forces in the body fixed frame using the pitch angle of the wing with respect to the body fixed coordinate system.

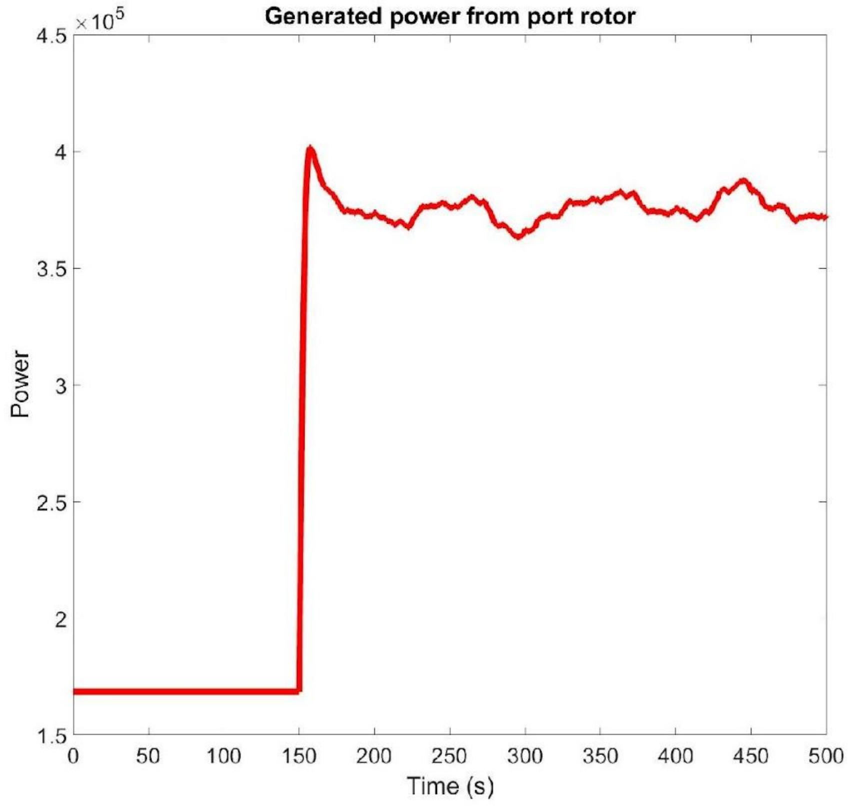
Result

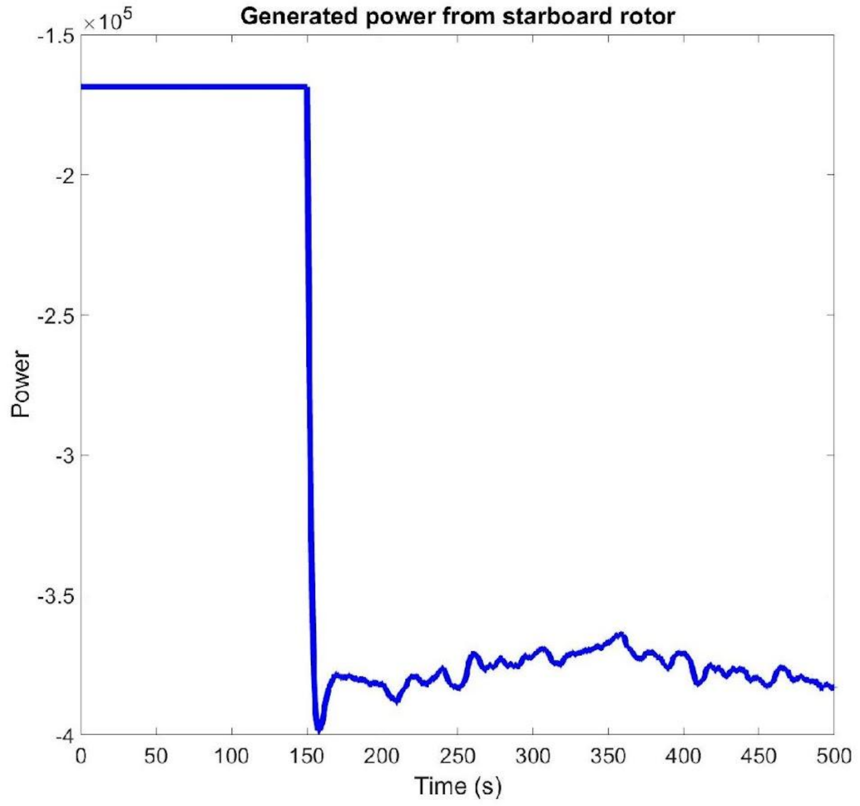
(water speed = 1.6 m/s, current shear = 0, turbulence intensity = 10%)



Result

(water speed = 1.6 m/s, current shear = 0, turbulence intensity = 10%)





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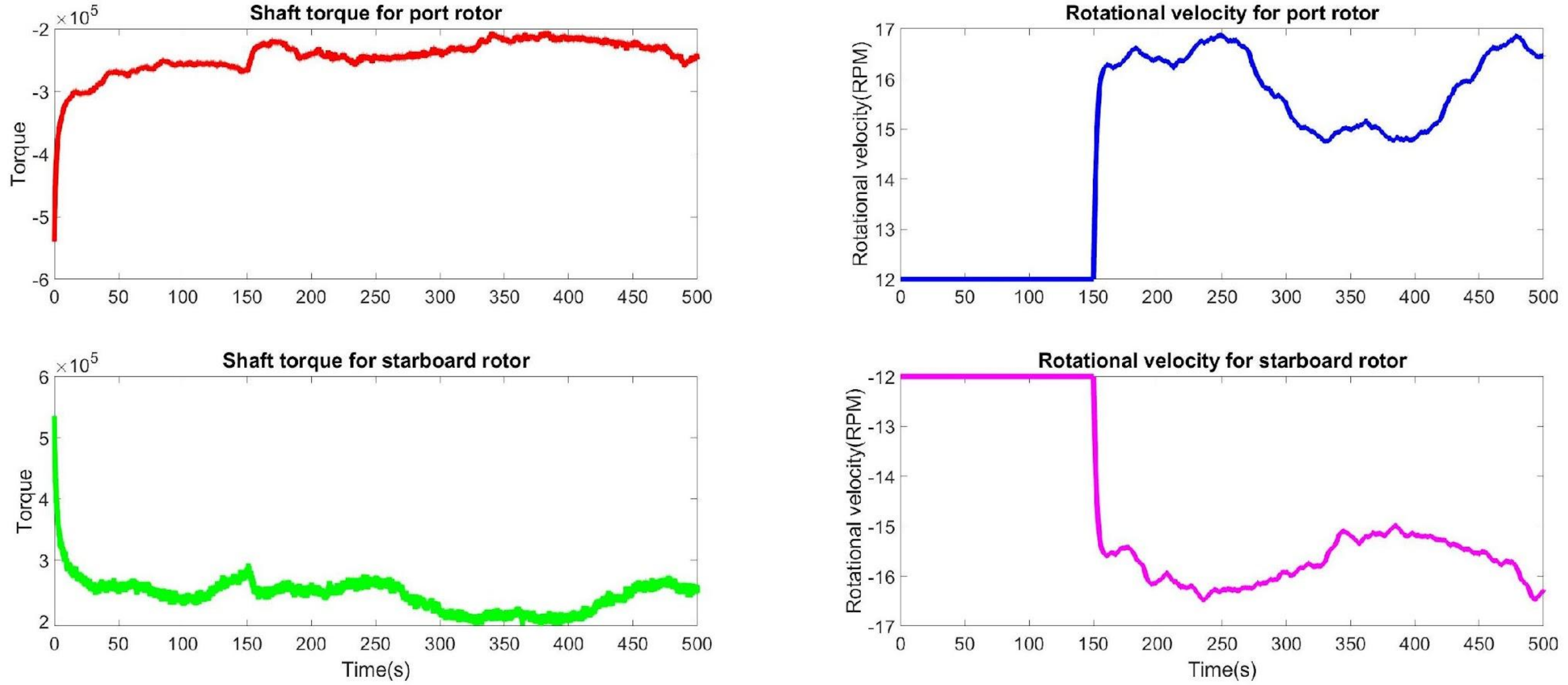
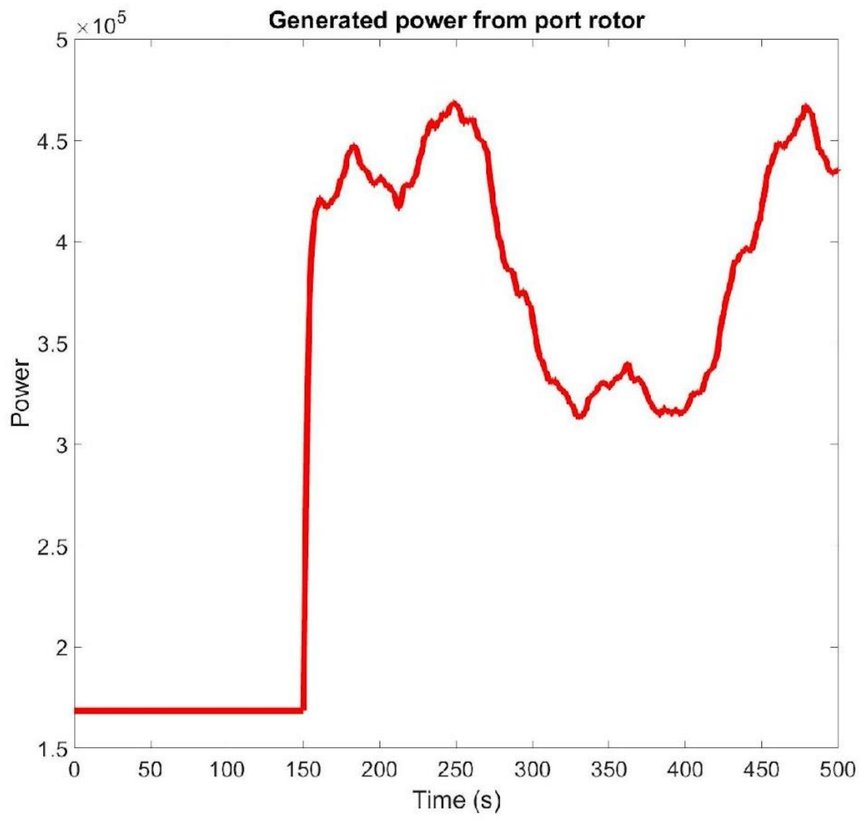
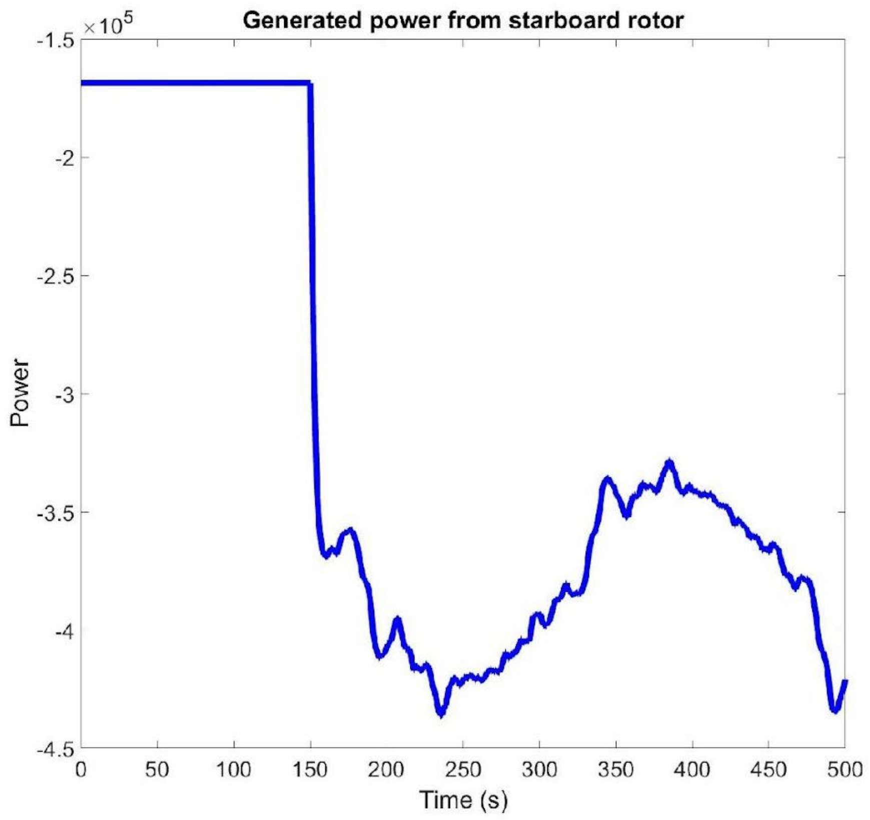


Result

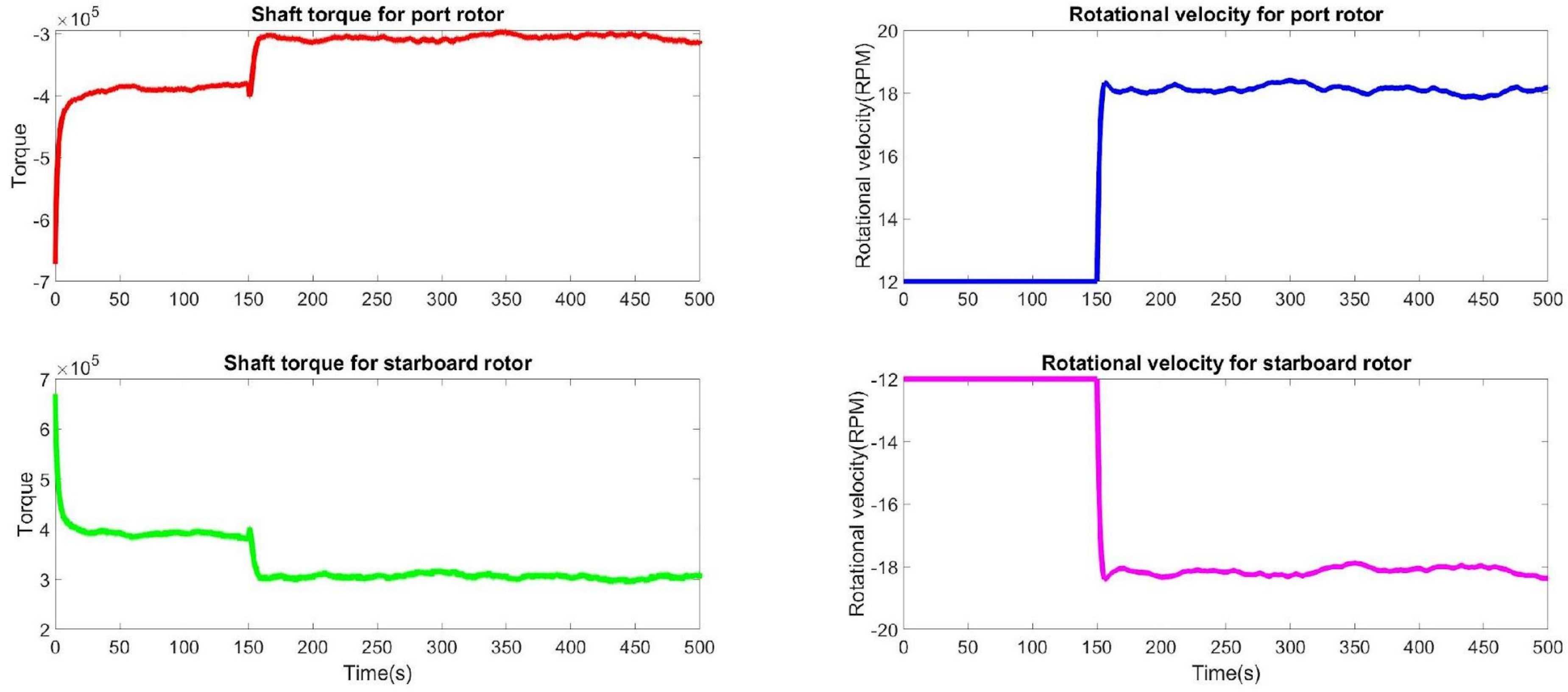
(water speed = 1.6 m/s, current shear = 0, turbulence intensity = 20%)





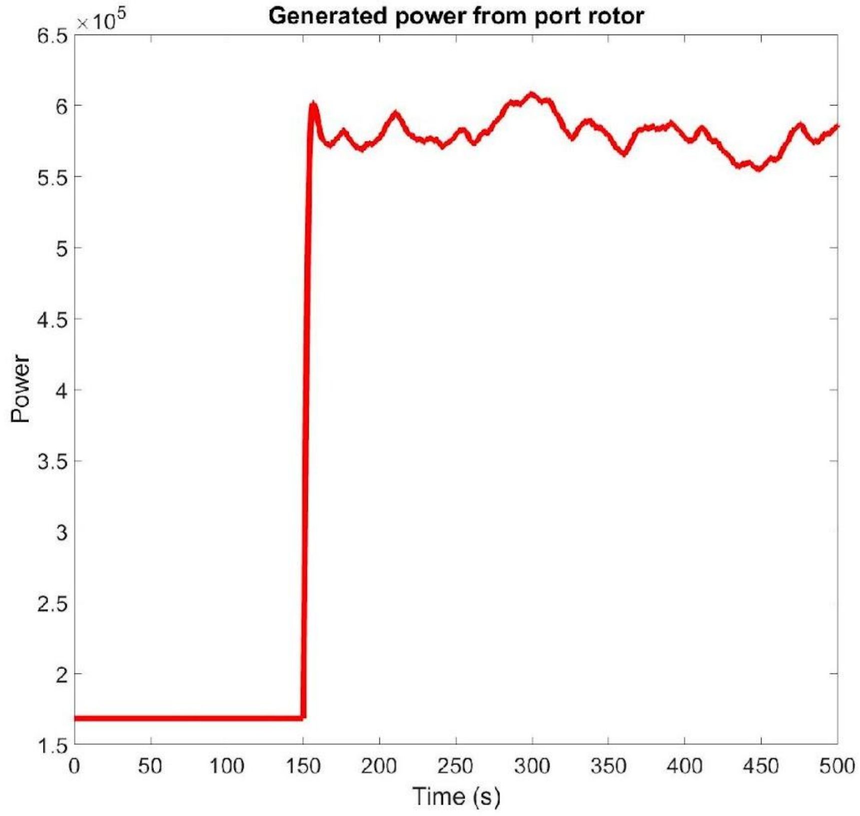
Result

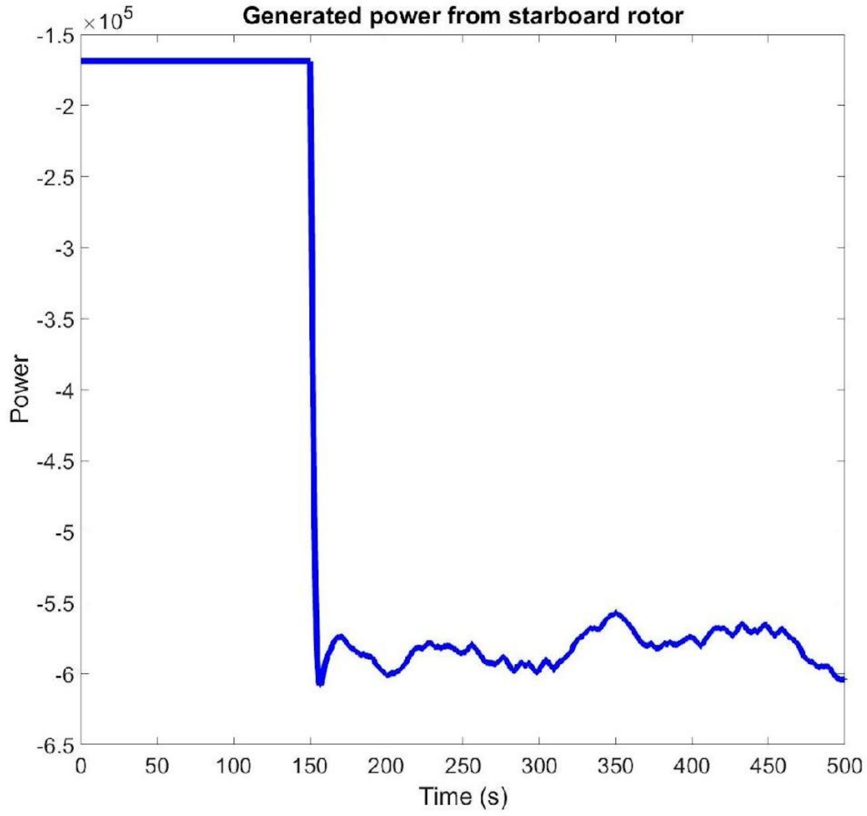
(water speed = 1.6 m/s, current shear = 0.005, turbulence intensity = 10%)



Result

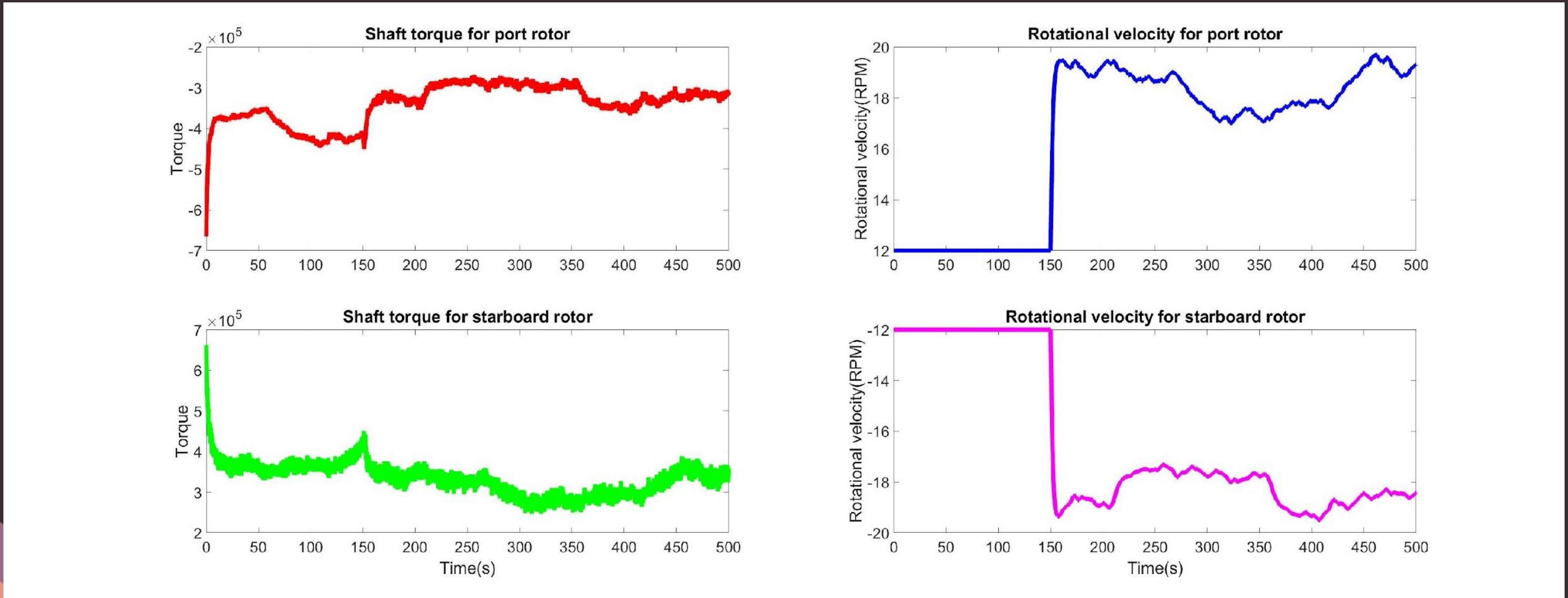
(water speed = 1.6 m/s, current shear = 0.005, turbulence intensity = 10%)





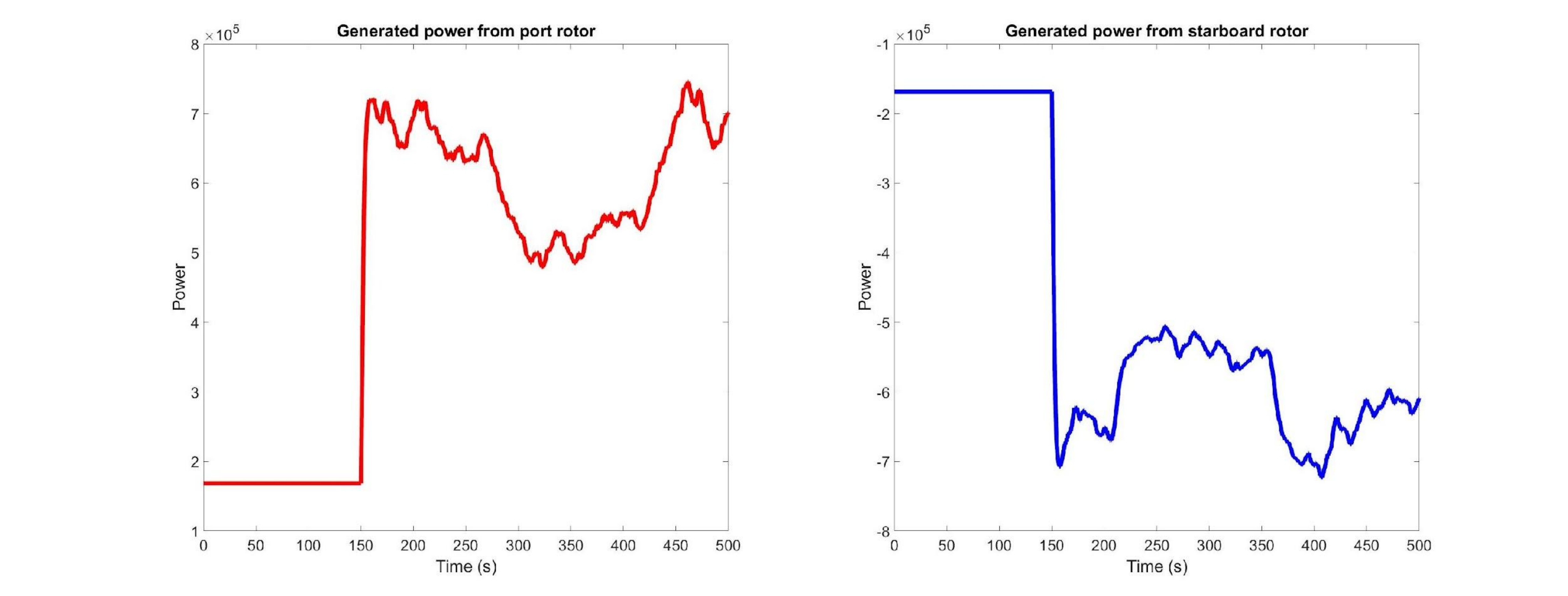
Result

(water speed = 1.6 m/s, current shear = 0.005, turbulence intensity = 37%)



Result

(water speed = 1.6 m/s, current shear = 0.005, turbulence intensity = 37%)



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Thank you for your attention.