An Assessment of the Tidal Energy Potential Deploying a Tidal Current Turbine at the Jawaharlal Nehru Port Trust

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Received: 1 January 2026 | Revised: 3 February 2026 and 12 February 2026 | Accepted: 13 February 2026

DOI: https://doi.org/10.48084/etasr.17292

ABSTRACT

The present study evaluates the feasibility of deploying a Horizontal-Axis Tidal Turbine (HATT) at Jawaharlal Nehru Port Trust (JNPT) to extract tidal energy from tidal currents and estimate the output power using a simulation of the turbine. Parameters such as tidal speed, depth, and flow direction are considered for the MATLAB simulation of a tidal current turbine. The latter estimates a daily output of 50–100 kWh per turbine, which is suitable for deployment in small to medium-scale energy systems. These findings demonstrate the potential of electricity generation from tidal current speed at JNPT.

Keywords-MATLAB; tidal energy; JNPT

I. INTRODUCTION

Developments in tidal power conversion systems, including turbine concepts, generator technologies, and grid-connected power electronic interfaces, were investigated in [1]. The principles and technologies associated with tidal and ocean current energy conversion were addressed in [2], highlighting the predictability and high energy density of marine resources. The experimental results from full-scale tidal turbine testing indicated that turbulent tidal inflow has a limited impact on power performance but significantly affects thrust behavior [3]. Marine tidal currents are a highly predictable and energy-dense renewable resource, which is well-suited for large-scale electricity generation using marine current turbines [4]. A blockage-aware Blade Element Momentum (BEM) framework has been used to model tidal turbines operating in confined flow passages, where momentum extraction generates a streamwise pressure gradient that enhances thrust and power output. This formulation closely matches blade-resolved numerical simulations, supporting its applicability for performance prediction in realistic tidal environments [5].

Computational Fluid Dynamics (CFD) studies on horizontal axis tidal current turbines have shown that reliable predictions of thrust, torque, and power output can be achieved under site-specific tidal conditions, with mesh independence confirming numerical robustness and practical feasibility for estuarine energy applications [6]. Authors in [7] demonstrated that vertical-axis tidal turbines offer flow-direction independence and compact installation, making them suitable for shallow and confined tidal sites. Their CFD investigation indicated that optimized designs can achieve stable power coefficients above 0.4 within practical tip speed ratio ranges. Authors in [8] developed a MATLAB-based tool to compute and visualize global tidal energy potential using the high-resolution FES2014b tide model, enabling reliable site-specific tidal resource assessment through harmonic analysis and spatial mapping. [8]. Numerical studies using GAD-CFD models have demonstrated that tidal turbine farm performance is highly sensitive to yaw misalignment and upstream turbulence, with optimized array layouts improving wake recovery and increasing overall power output by more than 10% [9]. Experimental validation at the FloWave facility has shown that the generalized actuator disk CFD model can reliably predict tidal turbine power, thrust, and wake behavior under realistic flow conditions, supporting its application in efficient turbine and array-scale simulations [10].

The MeyGen Project in Scotland, the world's largest tidal stream array, delivers over 6 MW of power and has set benchmarks in subsea cabling, environmental monitoring, and turbine reliability [11]. The SeaGen system is an HATT employing twin axial-flow rotors aligned with the tidal current, and its long-term grid-connected operation has demonstrated the technical feasibility and reliability of large-scale HATT technology in real marine environments. [12]. The Bay of Fundy, particularly the Minas Passage, exhibits exceptional tidal current energy potential, where numerical and theoretical analyses indicate that several GW of power can be harnessed using in-stream tidal turbines with limited changes to regional tidal amplitudes [13].

These projects highlight the potential for tidal energy in high-flow environments and emphasize the importance of grid integration, environmental compliance, and maintenance strategy. India is estimated to possess approximately 7,000–8,000 MW of tidal energy potential, primarily concentrated in the Gulf of Kutch, Gulf of Khambhat, and the Sundarbans region [14]. National and international assessments have identified these regions as the most promising locations for tidal power development along the Indian coastline. However, large-scale implementation has remained limited. A proposed 200 MW tidal power project in the Gulf of Kutch was shelved due to financial and techno-economic constraints [14]. Despite favorable tidal conditions and predictable flow regimes across several coastal regions, simulation-based feasibility and performance studies for port-based tidal energy systems are absent, particularly for major commercial ports such as the JNPT [15]. This lack of site-specific numerical and system-level assessment represents a significant research gap, which the present study aims to address.

This work presents a site-specific assessment of tidal current energy potential at JNPT, which has not been previously reported. National Centre for Ocean Information Services (INCOIS) tidal data [16] and a MATLAB–Simulink-based turbine and generator model are used. The feasibility of deploying HATT in a port environment is evaluated, with the results supporting the applicability of tidal energy for small-scale, sustainable port power systems.

II. SITE SELECTION

JNPT, also known as NhavaSheva Port, is India's largest container handling port, located on the eastern shore of Mumbai Harbour in Navi Mumbai, Maharashtra. Strategically, it is situated on the west coast of India on the Arabian Sea. The port has more than 5 million TEUs per annum, playing a significant role in India's maritime logistics network. The port's operations, such as cranes, container handling systems, lighting, and logistics infrastructure, consume significant electricity [15]. Therefore, tidal energy systems can be incorporated to support the power demand of port operations. By doing so, it can reduce dependency on grid-based energy systems, which is also a part of the sustainable development agenda.

To ensure the feasibility of the tidal current turbine, the site should satisfy the following key aspects:

- Strong and cyclic tidal currents.
- Sufficient water depth to allow turbine submersion without disturbing navigation.
- Low wave turbulence to minimize mechanical stress on turbine structures.
- Ease of installation and maintenance.
- Vicinity to grid or local power consumption centers.

The JNPT satisfies most of these conditions, making it a viable location for a feasibility study.

Fig. 1. Location map of JNPT, Navi Mumbai, India.

JNPT is positioned in a semi-diurnal tidal zone, i.e., it faces two ebbs and two flows daily. Statistics from the Indian INCOIS and Central Water and Power Research Station (CWPRS) show the following:

- Tidal range: Approximately 2.3-3.6 m during spring tides.
- Current velocities: Ranges from 0.5 to 2.0 m/s, which are within the operational threshold for HATT (minimum ~0.5 m/s).
- Depth profile: Nearshore depths range from 5 to 15 m, gradually increasing offshore, sufficient for turbine deployment without interfering with shipping lanes. [16]

These hydrodynamic statistics show that there is sufficient kinetic energy in the water column to be harnessed using tidal current turbines.

JNPT was chosen for this study as it has high and consistent tidal activity, which is essential for energy generation. Its proximity to high-energy demand enables immediate local use of generated power. JNPT also has accessible coastal bathymetry and manageable potential environmental impact, while supportive infrastructure and regulatory environment for renewable energy pilots make JNPT an ideal location to simulate and test tidal current turbine systems [15, 17].

III. TURBINE SELECTION AND DESIGN

The selection of a tidal current turbine for implementation at JNPT needs careful consideration of the following technological and environmental aspects:

- Tidal current speed at the field (0.5–2.0 m/s as per INCOIS/CWPRS data).
- Energy output needed for a small-scale project.
- Ease of installation and maintenance.
- Environmental factors and marine traffic.

By considering these aspects, HATT is chosen because of its high efficiency and favorable performance in unidirectional flow environments. [12, 16]. HATTs are similar in principle to wind turbines but are submerged underwater to harness kinetic energy from tidal streams. The rotor is aligned with the direction of flow, and the turbine operates with high efficiency in sites with strong horizontal currents. HATT offers multiple advantages, including high energy conversion efficiency (35–45% under optimal conditions), lower drag and better hydrodynamic performance compared to vertical-axis turbines, compact axial design allowing alignment with current flow, and proven operational history in commercial projects such as SeaGen and MeyGen [12]. The design specifications adopted in the present study, based on [6, 12, 18], are presented in Table I.

TABLE I. DESIGN PARAMETER OF HATT

Parameter	**Value**
Rotor type	Horizontal axis (3-bladed)
Rotor diameter (*D*)	5 m
Blade material	Marine-grade composite (e.g., GFRP)
Rated current velocity	2.0 m/s
Cut-in current velocity	0.5 m/s
Power coefficient (C_p)	0.38 (typical for HATT)
Shaft power output (approx.)	~ 8–10 kW at 2.0 m/s
Mounting	Seabed-mounted monopile
Generator type	Permanent Magnet Synchronous Generator (PMSG)

The theoretical power extracted by a tidal turbine [4] is governed by:

$$P = 0.5 \times \rho A C_p V^3 \qquad (1)$$

where P is the power output (W), ρ is the seawater density (~1025 kg/m³), A is the swept area of the turbine $\left(\frac{\pi D^2}{4}\right)$, C_p is the power coefficient (~0.38), and V is the flow velocity (m/s). At a rated velocity of 2 m/s and 5 m rotor diameter, the swept area and theoretical power output can be calculated as:

$$A = \left(\frac{\pi \times 5^2}{4}\right) = 19.63 \text{ m}^2$$

$$P = 0.5 \times 1025 \times 19.63 \times 0.38 \times 2^3 = 15.3 \text{ kW}$$

Considering mechanical and electrical losses of about 30%, the net deliverable power is estimated at 10–11 kW under peak flow. From the INCOIS data [16], the power coefficient versus tip speed ratio is plotted, as shown in Figure 2.

The power output characteristics of an OpenHydro tidal current turbine were incorporated to evaluate energy extraction potential at the JNPT site. The turbine considered is a horizontal-axis, direct-drive device with a rotor diameter of 16 m and a rated electrical capacity of 1.5 MW, representative of commercially deployed OpenHydrosystems [19]. The turbine power output is expressed as a function of tidal current velocity using a steady-state power curve. The turbine exhibits a cut-in tidal current speed of approximately 0.7 m/s, below which no power generation occurs. For current velocities above the cut-in threshold and below the rated speed, the output power increases monotonically with tidal current speed, consistent with the cubic dependence of extractable kinetic energy on flow velocity. In this operating region, the turbine is assumed to operate under maximum power point tracking, whereby the rotor speed is continuously adjusted to maintain the optimal tip-speed ratio and achieve maximum power extraction.

The rated operating point of the turbine corresponds to a tidal current speed of approximately 2.57 m/s, at which the rated power of 1.5 MW is achieved, as depicted in Figure 3. For higher tidal current velocities, the turbine output power is regulated and constrained to its rated value in order to limit mechanical and electrical loading on the turbine and generator. This behavior reflects practical power control strategies employed in full-scale tidal energy conversion systems.

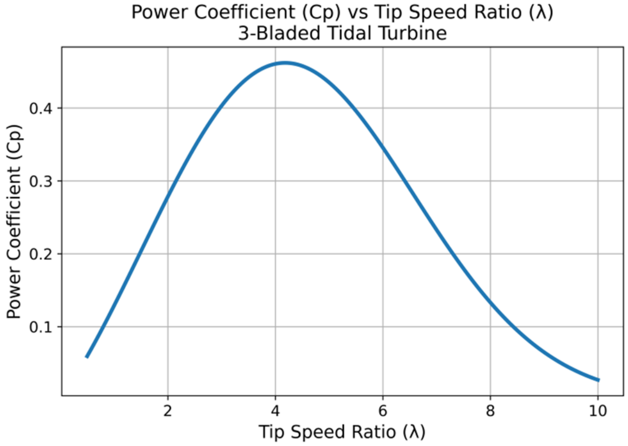

Fig. 2. Variation of power coefficient with tip-speed ratio.

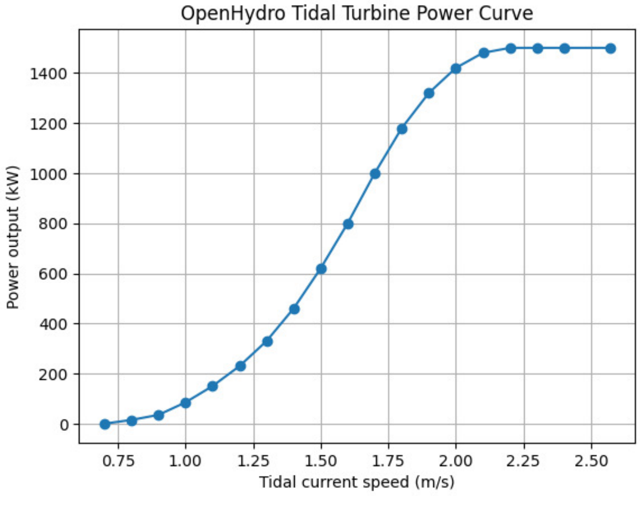

Fig. 3. OpenHydro tidal turbine power curve.

IV. EFFECT OF TURBINE PARAMETER

A. *Velocity–Power Characteristics Based on Tidal Current Equation*

The relationship between tidal current velocity and turbine power output was first examined using the fundamental tidal power equation. For a fixed rotor diameter and power coefficient, the output power exhibits a nonlinear dependence on tidal current speed. As illustrated in Figure 4, power increases rapidly with increasing flow velocity due to the cubic dependence of extractable kinetic energy on tidal speed. [20]

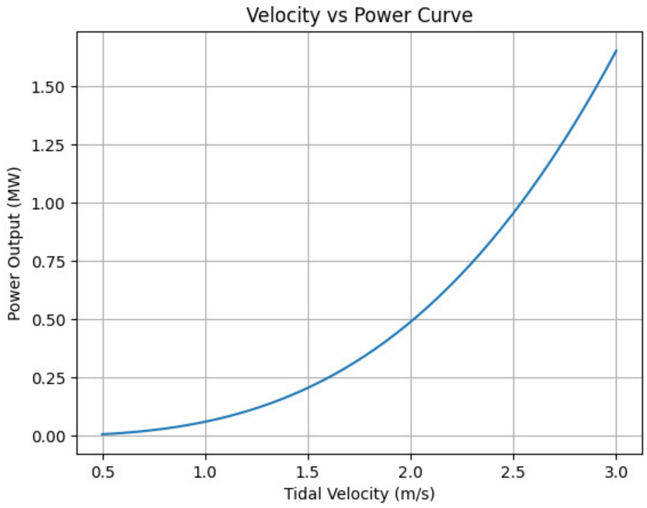

Fig. 4. Velocity–power curve.

B. Effect of Rotor Diameter on Power Output

The effect of rotor diameter on generated power is plotted for a constant tidal current speed, as displayed in Figure 5. The swept area increases with an increase in diameter, resulting in higher power output. Therefore, when selecting rotor size, parameters such as structural strength and installation depth must be considered. [20].

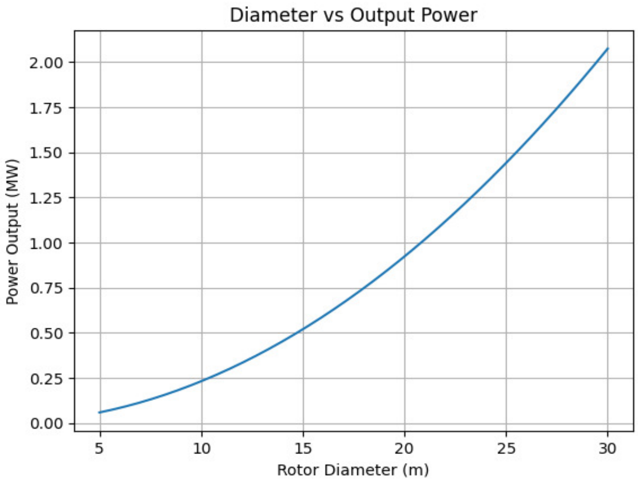

Fig. 5. Variation of output power with rotor diameter.

C. Velocity–Power Characteristics for Different Rotor Sizes

The velocity–power characteristics for different rotor diameters are illustrated in Figure 6. As observed, higher power is achieved for a larger rotor size. The power rises consistently with tidal current speed for a given rotor size. These findings reveal the effect of tidal current speed and turbine geometry on harnessing electricity by tidal current turbines [20].

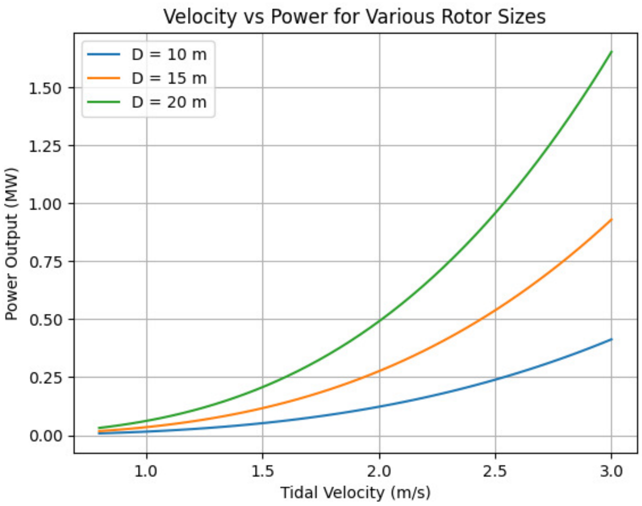

Fig. 6. Velocity–power curve for various rotor sizes.

D. Influence of Blade Pitch Angle at Different Rotor Speeds

The characteristic power output versus tidal current speed is plotted for different blade pitch angles at constant rotor diameter, as portrayed in Figure 7. The power output decreases as the blade pitch angle increases for a given tidal speed range. To maximize output power, it is necessary to choose a low or near-zero pitch angle [20].

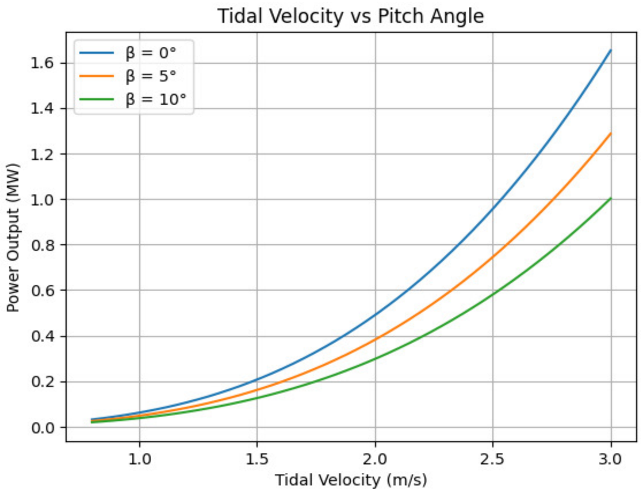

Fig. 7. Tidal velocity for different pitch angles.

E. Relationship between Tidal Velocity and Rotor Speed for Various Tip Speed Ratios

The characteristics of tidal speed versus rotor speed are plotted for different tip speed ratios, as shown in Figure 8. For a fixed tip speed ratio, the rotor speed varies linearly with tidal current velocity. Higher tip speed ratios correspond to higher rotor speeds for the same flow velocity. These results demonstrate the importance of maintaining an optimal tip speed ratio through appropriate control of rotor speed to maximize the power coefficient and overall turbine efficiency [20].

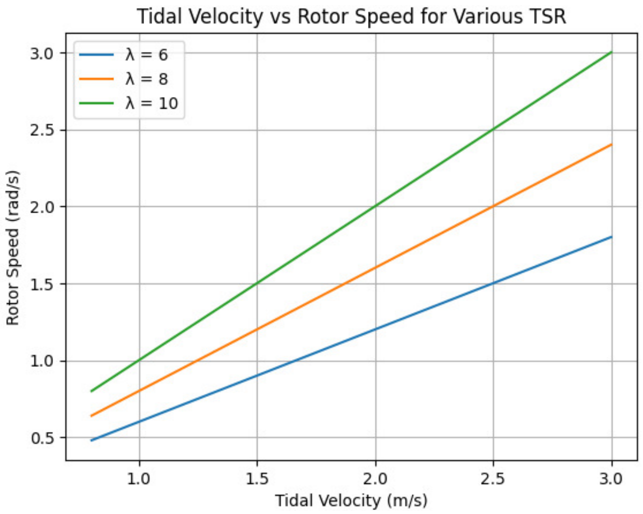

Fig. 8. Relationship between tidal velocity and rotor speed for various tip-speed ratios.

V. SIMULATION METHODOLOGY

The purpose of the simulation is to examine the feasibility of installing an HATT at the JNPT by analyzing the hydrodynamic environment, turbine response, output power, and data from INCOIS. The simulation evaluates power generation in real tidal current speed; analyzes rotor dynamics, torque, and efficiency; examines flow-turbine interaction and structural loading; and offers the best operating conditions. The outcome of the simulation can be used to verify the viability of the turbine design and prototype implementation.

The simulation was developed using MATLAB–Simulink with Simscape Electrical blocks, as presented in Figure 9. The tidal turbine model converts tidal velocity into mechanical torque, which drives a PMSG, as shown in Figure 10. Electrical output parameters are measured using standard Simulink blocks, and a variable-step solver is used to ensure numerical stability.

The output power, current, and voltage are illustrated in Figures 12-14, respectively, at 1m/s tidal current speed.

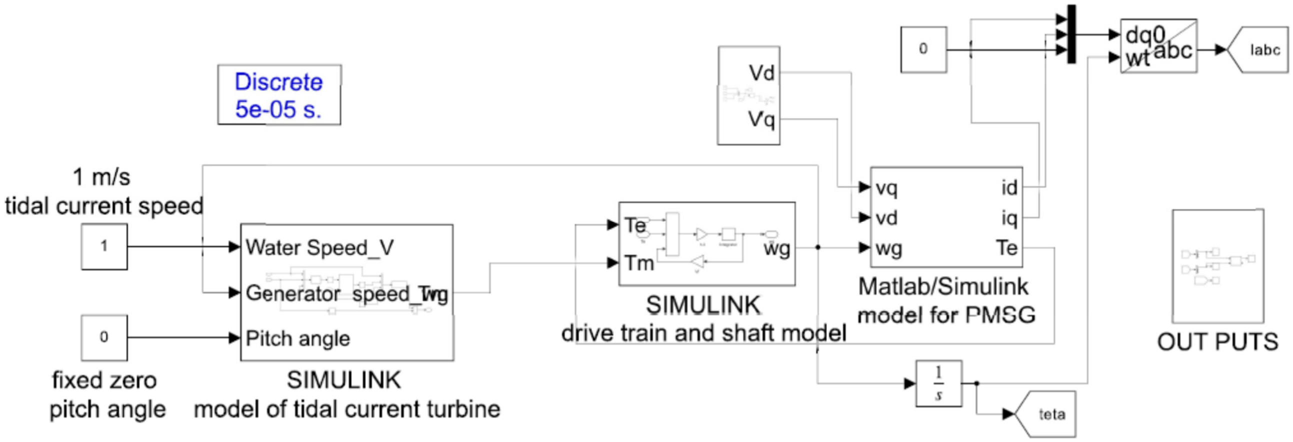

Fig. 9. MATLAB–Simulink with Simscape model for Tidal current turbine.

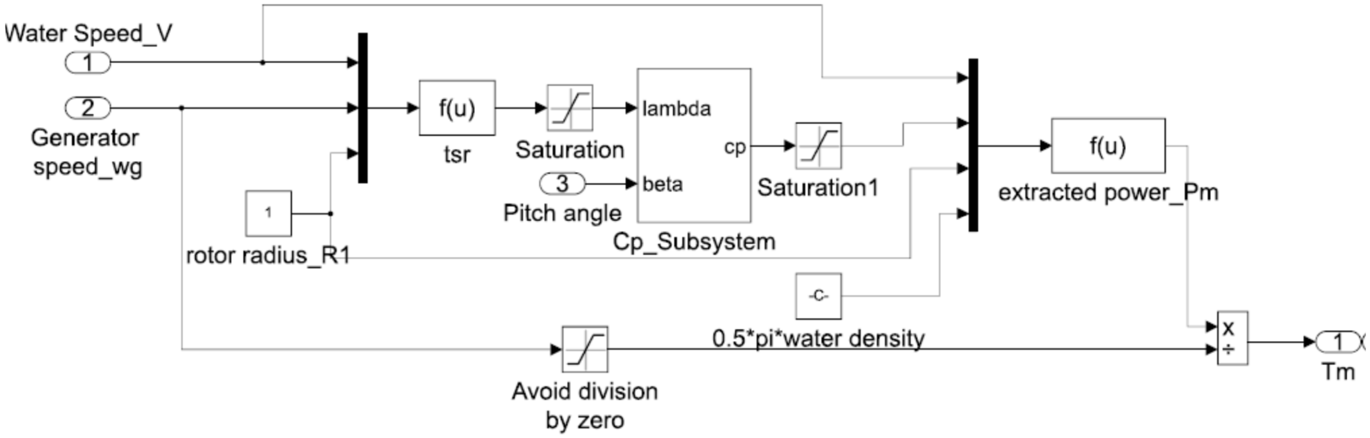

Fig. 10. Simulink Model for Tidal Turbine.

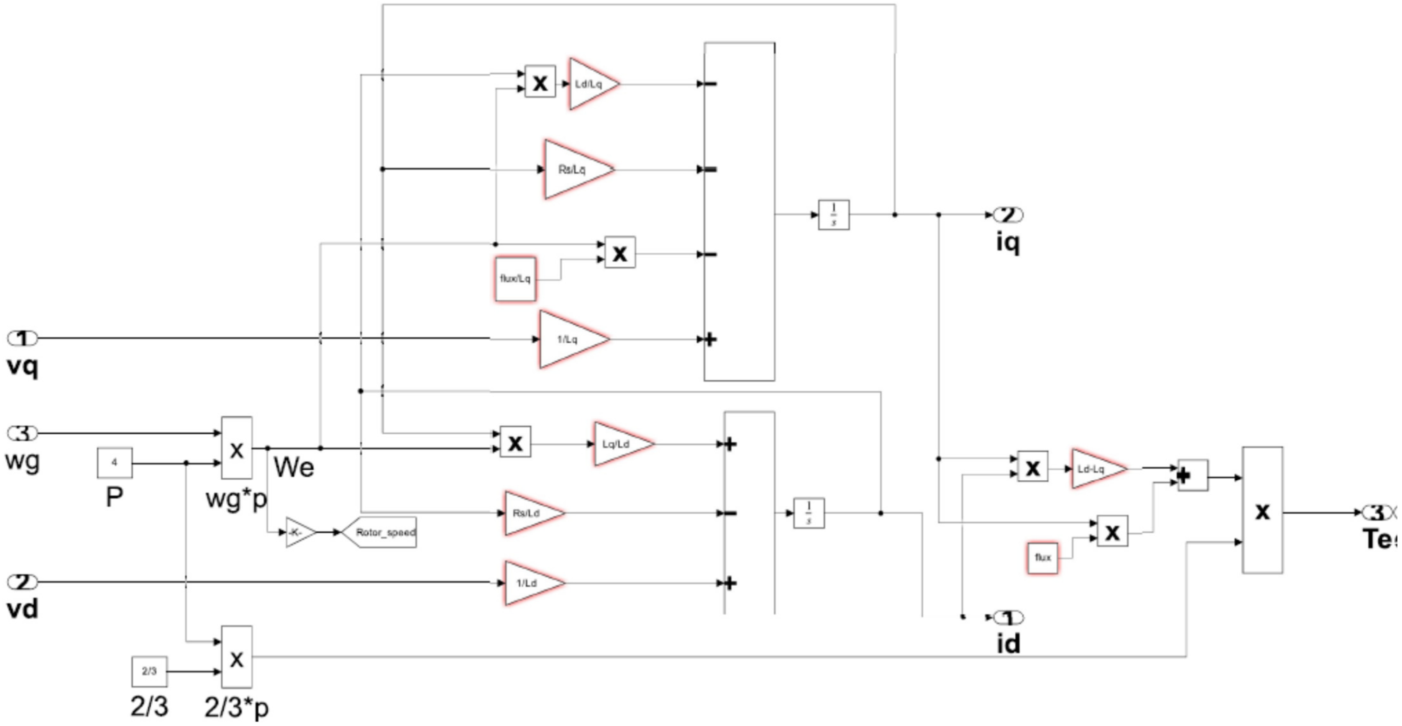

Fig. 11. Simulink Model for PMSG.

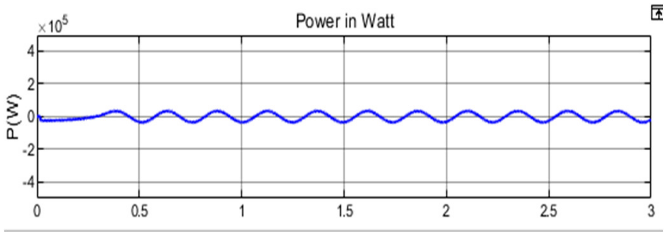

Fig. 12. Output power waveform.

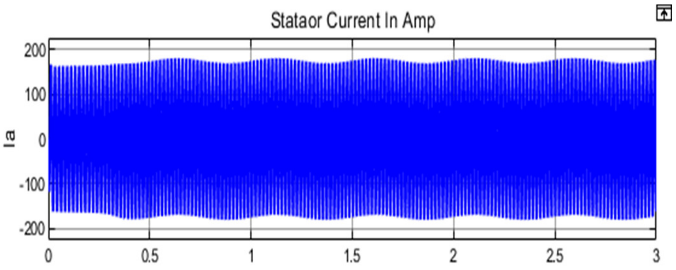

Fig. 13. Output current waveform (A).

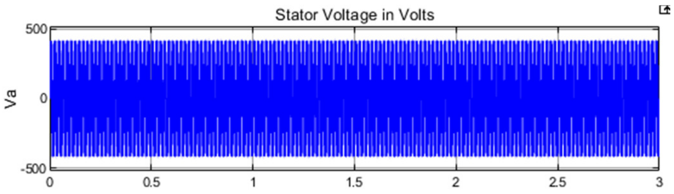

Fig. 14. Output voltage waveform (V).

A. *Tidal Speed–Tide Height Characteristics*

Tidal current characteristics at JNPT were analyzed using one year of tide elevation data obtained from INCOIS [16]. The current speed was estimated from the temporal variation of water level and processed through elevation-based averaging and controlled smoothing to obtain a continuous representation. The resulting relationship shows minimal current speeds near high and low tide and increased velocities during intermediate tidal stages. This continuous speed–height relationship provides a stable hydrodynamic basis for subsequent tidal energy assessment and numerical flow modeling. Figure 15 demonstrates the relationship between tidal current speed and tide height.

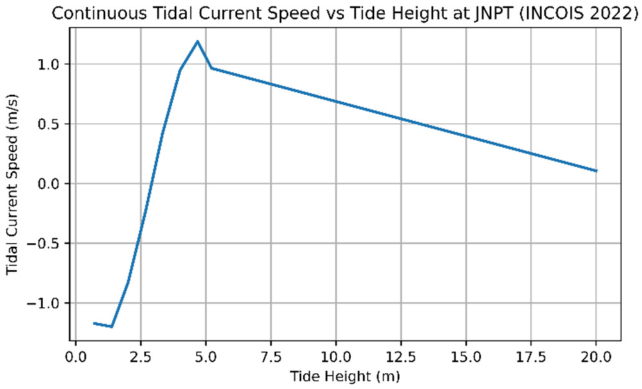

Fig. 15. Relationship between tidal current speed and tide height.

B. *Tidal Power–Tidal Speed Characteristics*

Turbine power output at JNPT shows a strong dependence on tidal current speed, increasing rapidly as the flow velocity rises, as presented in Figure 16. Owing to the cubic relationship between power and current speed, negligible energy is generated during low-velocity conditions near slack tide, while most energy production occurs during mid-tide phases. This behavior highlights the importance of sustaining moderate to high current speeds for effective tidal power generation.

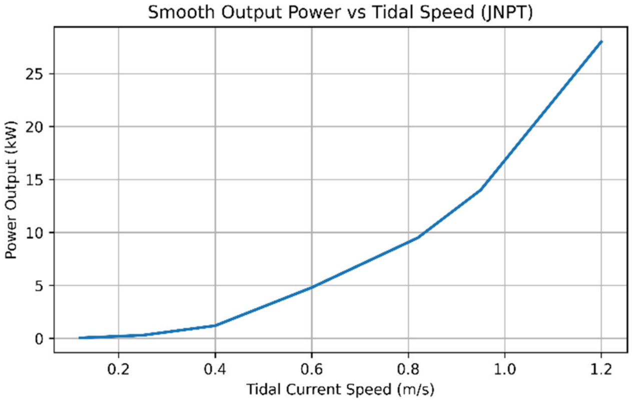

Fig. 16. Relationship between tidal power and tidal speed.

VI. RESULTS AND DISCUSSION

Using the turbine parameters outlined in Table I ($D = 5$ m, $C_p = 0.38$, $V = 2$ m/s), and applying the theoretical power relation defined in (1), turbine output over a 24-h tidal cycle was simulated with semi-diurnal flow (2 high and 2 low tides). Table II summarizes the estimated instantaneous power outputs at key velocities.

TABLE II. INSTANTANEOUS POWER OUTPUTS AT KEY VELOCITIES

Current velocity(m/s)	Power output(kw)
0.5	0.24
1.0	1.93
1.5	6.51
2.0	15.3

Considering the average effective power of 6 kW during high tides and assuming 12 h in a day for useful tidal current speeds, the daily and monthly electricity generation can be calculated as:

$$E_{day} = 6kW \times 12\ hours = 72\ \text{kWh/day}$$

$$E_{month} = 72\ kWh/day \times 30 = 2160\ \text{kWh/month}$$

This generated power can be utilized for port lighting, powering auxiliary electrical systems such as security, signals, and sensors, and for a control and monitoring station.

The findings of the study demonstrate that:

- A small-scale HATT system is viable at JNPT for renewable energy generation.
- The estimated power output is consistent with similar flow regimes globally.
- The system can contribute to green port initiatives and decarbonization goals.
- Turbine operation is non-intrusive and suitable for pilot-scale deployment in India.

This study, however, has some limitations, including the exclusion of real-time variations in sediment load, marine growth, and turbulence. In addition, the multi-turbine array effects (e.g., wake interference) are unmodeled.

VII. CONCLUSION

This study presented a comprehensive site-specific assessment of tidal current energy potential at Jawaharlal Nehru Port Trust (JNPT) using a Horizontal-Axis Tidal Turbine (HATT) integrated with a Permanent Magnet Synchronous Generator (PMSG)-based generation system. Unlike previous studies that primarily focus on large-scale tidal sites, such as the Gulf of Kutch, Bay of Fundy, or commercial projects like MeyGen and SeaGen, the present work investigates the feasibility of tidal energy deployment in a major Indian port environment, which has not been previously reported.

The novelty of this research lies in the integration of real tidal data from the National Centre for Ocean Information Services (INCOIS) with a MATLAB–Simulink-based electromechanical model that combines hydrodynamic turbine characteristics, drive-train dynamics, and PMSG modeling. While earlier works have addressed Computational Fluid Dynamics (CFD)-based turbine analysis or global tidal resource mapping, this study provides a complete system-level simulation framework suitable for practical port-scale implementation.

The simulation results indicate that the selected 5 m diameter HATT can generate up to 15 kW at peak tidal velocities (2.0 m/s), with an average effective power output of approximately 6 kW during operational tidal periods. The estimated daily energy generation of 72 kWh demonstrates the suitability of tidal energy systems for auxiliary port loads such as lighting, monitoring systems, and small-scale infrastructure. Compared to large commercial tidal farms, the proposed approach emphasizes decentralized, small-scale renewable integration within port infrastructure, contributing to green port initiatives and localized decarbonization strategies. The modeling framework developed in this work can be extended to other Indian coastal ports for comparative feasibility assessment.

Overall, this study contributes to the limited literature on tidal current energy utilization in Indian port environments and provides a practical simulation-based foundation for future pilot implementation and techno-economic evaluation.

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