# IMPLEMENTATION OF TURBINE EMULATOR

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***Abstract:*** *A Wave Turbine Emulator (WTE) is designed and implemented considering the realistic site data based on Oscillating Water Column (OWC) principle. Wave Turbine Emulator (WTE) is the important equipment for developing the Wave Energy Conversion systems. The Emulator reflects the actual behavior of the wave turbine without reliance on natural wave resources and actual wave turbine. It offers a controllable test environment that allows the evaluation and improvement of control schemes for electric generators which is hard to achieve with an actual wave turbine. The WTE can accurately reproduce the characteristics of real wave turbine. The Emulator can be used for research applications to drive an electrical generator in a similar way as a practical wave turbine. A prototype of turbine emulator is built in the laboratory using a three phase synchronous motor controlled by Rexroth Indra Drive. The system comprises of Simulink model of the Turbine, model of the oscillating water column, Data Acquisition card Instruments, Digital to Analog Converter, 3-phase Permanent magnet Synchronous motor driven by Rexroth Indra Drive Controller.*

***Key words:*** *oscillating water column, wave turbine emulator, ,permanent magnet synchronous motor.*

## 1. Introduction

In today’s world the demand for energy is so high that the conventional sources, such as fossil fuels, oil, natural gas and nuclear fuels, are not sufficient. As these resources are soon going to be exhausted renewable energy sources are of significant importance. Research and better utilization of these sources is now becoming a very important issue.

A very huge amount of energy is available to us in the form of solar, wind, ocean and geothermal energy. All these are different manifestations of solar energy. Of these forms ocean energy shows a lot of promise. Ocean energy source can be tapped in three forms namely ocean wave energy, ocean thermal energy and ocean tidal energy. Among these promising and important renewable energy source is ocean wave energy conversion, which is more effective than thermal and tidal energy. Also wave energy is environmentally beneficial in terms of cost of generation and of waste disposal. But the economic cost in the phases of early technologies is often too high when competing with fossil fuels where as the operating cost is very low because the resource is free and cannot be depleted. The economics of the wave energy conversion is improved by installation of the onshore devices like Oscillating water columns (OWC), Tapered channel (TAPCHAN).These devices are usually fixed to the shoreline and have a modest electrical capacity. Being fixed structures they provide a perfect frame of reference for the wave forces to act against and hence can achieve higher conversion efficiency. The term 'capture width' is often used instead of efficiency and describes the width of wave front captured by the structure as a function of its own width. Maximum capture width quantifies the peak conversion efficiency of the device and will occur at a particular wave spectrum of frequency. [1]

Oscillating water columns are the most popular devices for the conversion of wave energy and are usually designed as shore-mounted structures having fixed frames of reference. The OWC operate in response to the incoming wave activity and are essentially resonant devices. An incident wave crest increases the pressure of the water inside the column, forcing the internal water level to rise and in turn pushing air out from the top of the column. The air turbine extracts energy from this air flow. The air flow reverses to refill the column when the wave trough appears at the mouth of the device [2,3].

The Oscillating Water Column (OWC) based wave energy plant has a three stage energy conversion process –the OWC converts the variations in sea surface elevations to pressure, a bidirectional turbine converts pneumatic air power into mechanical shaft power and an electrical generator coupled to the turbine provides electrical power that is exported to the grid. A configuration of an ocean wave energy converter plant, using the OWC device is shown in Fig1. The overall plant efficiency is the product of the efficiencies of each of these power conversion stages. A wave capture chamber set into the rock face of the shoreline is called the Caisson. The construction of the Caisson is the basic factor which decides the amount of energy that can be extracted. The bigger the size of the Caisson the higher power that can be extracted and also higher investment cost. The Caisson has an opening at the mouth through which the waves are forced in. As the wave is pushed inside the water column height inside the OWC increases and vice versa. Hence the water height oscillates. As the water column height varies, the air column inside is compressed or expanded. This compression and expansion of the air column creates a differential pressure, which drives the turbine[4-6].

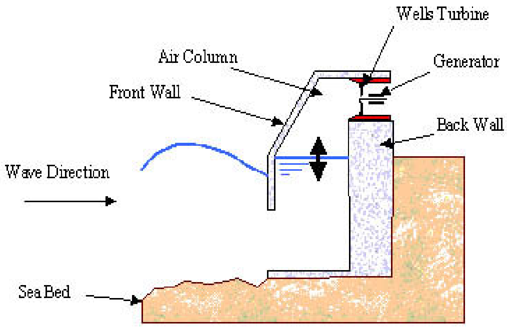

Fig 1 Diagrammatical illustration of an OWC

Emulator is an important component in developing a Wind or Wave Energy Conversion system. A Number wind turbine Emulators have been presented in the literature [7-12]. Emulator can be used for development and Research applications to drive electric generators by reproducing the torque or speed developed by the real turbine for different input conditions. It will allow the testing without construction of costly turbine and help in determining the strength and weakness of energy conversion scheme and the related control technologies. Emulator can be used to drive different kinds of electric generators like Induction generator, DFIG and the permanent magnet Synchronous generator and their performance can be evaluated easily. Emulator should basically mimic the actual turbine characteristics showing the same mechanical behavior of the actual turbine rotor along with generator it is driving under dynamic conditions.

## 2. Modeling of the System

The modeling of the system includes Modeling of Oscillating water column, Modeling of Turbine and Modeling of the turbine generator dynamics.

The Wave characterization is done to distinguish the wave data available in terms of the significant wave height ($H_s$), Significant Time period ($T_s$) and spectral energy density [10]. OWC is modeled based on energy balance concept[ ]. Input to the OWC model is the wave pattern and the output of the model is the axial velocity of air. Wave turbine is modeled in Matlab Simulink for which axial velocity of air is given as input which comes from the OWC model.. The Turbine Torque is given as input to the generator model. The complete block diagram of the system is shown in Fig2.

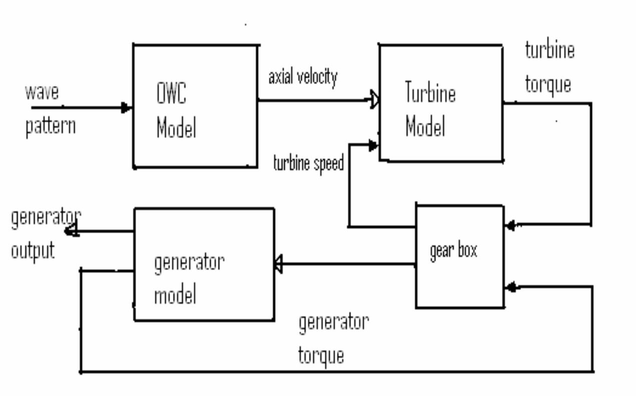

Fig 2 Block diagram of the system

### 2.1 Modeling of OWC

Oscillating water column devices are shore-mounted structures having fixed frames of reference. The OWC operate in response to the incoming sea wave. When sea wave enters the oscillating water column the water level in OWC increases for the first half of the wave and decreases for the next half. When first half of the wave enters the OWC, water level increases. If $h_1$ was the initial height of the water in OWC and $h_2$ is the final height of the water in OWC, then increase in the water level is given by following equation,

$$\Delta h = h_2 - h_1 \qquad (2.1)$$

If the rise in the height of water in OWC is considered as a movement of a water slab from height $h_1$ to $h_2$ then the amount of water displaced $m_0$ can be expressed as

$$m_0 = \rho ab(h_2 - h_1) \qquad (2.2)$$

where a is length of the water column and b is the width of the wave, assumed equal to the width of the chamber and $\rho$ is the density of water.

Energy contained in the half wave is given by

$$E = b\rho A^2\lambda/8 \qquad (2.3)$$

where A is the wave amplitude and $\lambda$ is wave length in meters. E is the energy transferred to the water slab in Joules. This energy is responsible for rise in potential energy of water slab as well as the gain in kinetic energy of air in OWC. So from energy balance E can be equated to the sum of increase in potential energy of water and kinetic energy of air.

$$E = m_0 g\Delta h + V\left(\rho_a v^2\right)/2 \qquad (2.4)$$

where V is the volume of air column, $\rho_a$ is the density of air, g is the acceleration due to gravity and v is the velocity of air near the water surface. Assuming sinusoidal waves and neglecting superposition of waves entering into the water column, wave equation can be written as

$$y = y(x,t) = A\sin(kx - \omega t) \qquad (2.5)$$

where A is the wave amplitude and k is the wave number given by $k = 2 * \pi / \lambda$. $\lambda$ is wave length in meters, $\omega = 2 * \pi / T$ is the angular frequency in rad/s and T is the wave period.

Increase in the height of water level is a function of the wave entering, hence can be related as below using mass conservation,

$$ab\Delta h = b\int_0^{\lambda/2} A\sin(kx - \omega t) \qquad (2.6)$$

Hence $\Delta h = A\lambda\cos(\omega t)/a$ (2.7)

Using equations 2.1- 2.4 and 2.7 the velocity of air near the water surface in the OWC can be found as

$$v = \sqrt{\left(2\rho g\left(\left(bA^2\lambda/8\right) - \left(ab\Delta h^2\right)\right)/(V\rho_a)\right)} \qquad (2.8)$$

Then the velocity near the orifice of the OWC can found from the equation of continuity, assuming incompressible flow of air as

$$V_x = (A_1/A_2)\left(\sqrt{2\rho g\left(\left(bA^2\lambda/8\right) - \left(ab\Delta h^2\right)\right)/(V\rho_a)}\right) \qquad (2.9)$$

where $A_1$ and $A_2$ are area of the OWC and the area of the orifice respectively. $V_x$ is the axial velocity of air in the OWC near the orifice which is fed to the turbine placed at the orifice of OWC.

## 2.2 Modeling of the turbine

The Well's turbine is modeled using MATLAB. The modeling is done based on the equations 2.10 - 2.12 and the characteristics of the turbine.

$$dp = C_a\rho_a b_h l(n/2)(1/a_r)(V_X{}^2 + r\omega_t^2) \qquad (2.10)$$

$$T_t = C_t\rho_a b_h l(n/2)\ r\left(V_X^2 + r\omega_t^2\right) \qquad (2.11)$$

Where dP is the differential pressure in Pascal, $T_t$ is the gross torque produced by the turbine in Nm, $\rho_a$ is the mass density of air in Kg/m$^3$, $b_h$ is the blade height of the turbine in m, *l* the blade chord length in m, n is the number of blades of the turbine, r is the average radius of the turbine, $a_r$ the annular area of the rotor in m$^2$, $\omega_t$ is the speed of rotation in rad/s, $C_a$ is the power coefficient and $C_t$ is the torque coefficient. The variation of the power and torque coefficient with the flow rate used in the model are from[5]. The flow rate $\varphi_t$ is defined as in the equation 2.12.

$$\phi_t = V_x/(r\omega_t) \qquad (2.12)$$

Where $V_x$ *in* m/s is the absolute axial velocity of air in OWC.

## 2.3 Model for the turbine-Induction machine dynamics

Equation of mechanical dynamics of the turbine-Generator set is given by,

$$J(\delta\omega_g/\delta t) = T_t - T_g - T_l \qquad (2.13)$$

Where J is the moment of inertia of the system, $T_t$, $T_g$ are the turbine and generator torques respectively and $T_l$ is a term accounting for losses.

## 3. Realization of Wave Turbine Emulator

A Wave turbine Emulator (WTE) is a demonstration unit of a practical wave turbine in a laboratory environment. The general structure of WTE developed consists of a PC where the characteristics of the wave and model of OWC is realized in Matlab. The turbine model and the model representing the turbine generator dynamics is visualized using Matlab simulink. For the realization of the Wave Turbine Emulator Rexroth Indra Drive Controller driving a 3-phase synchronous motor is used such that 3-phase synchronous motor represents the Wave turbine rotor. The overall schematic of the wave turbine emulator that includes both software and hardware is shown in Fig 3a.

A Photograph of Laboratory setup of Wave Turbine Emulator using RexrothIndra Drive Controller is as shown in Fig 3b.

A prototype of turbine emulator is built in the laboratory using a three phase permanent magnet synchronous motor controlled by Rexroth Indra Drive. The overall system comprises of wave characterization, model of OWC, Well's Turbine model, Data Acquisition card, Digital to Analog Converter, 3-phase Permanent magnet Synchronous motor driven by Rexroth Indra Drive Controller.

The Waves are characterized based on spectral analysis to differentiate different wave pattern data and then to be able to explain the behavior of the emulator developed based on wave pattern. The Oscillating water column is modeled based on Energy balance concept. The data of wave height obtained from wave energy plant located at Vishinjam, is given as input to the OWC model. The output of OWC model is the axial velocity for a particular wave pattern which is given as input to the wave turbine model. The wave Turbine is modeled in Simulink from which the turbine speed is taken as output. The turbine speed from the simulink model is first taken to workspace of the Matlab. Keithley KPCI-3102 data Acquisition card is used as a interface between Matlab and Rexroth IndraDrive Controller to acquire data from the Matlab Workspace. The acquired data is given to STA-300 screw terminal panel provided by Keithley which gives an 8-bit digital data. This Digital data is converted to analog voltage signal using DAC circuit. The Analog Voltage signal ranging 0-10V is given as input to the Control section of Rexroth Indra drive Controller which drives the 3-phase Synchronous motor. The Speed of synchronous motor is controlled in the same way as the turbine model for different input data. The Behavior of wave turbine model and synchronous motor is compared for different values of site data.

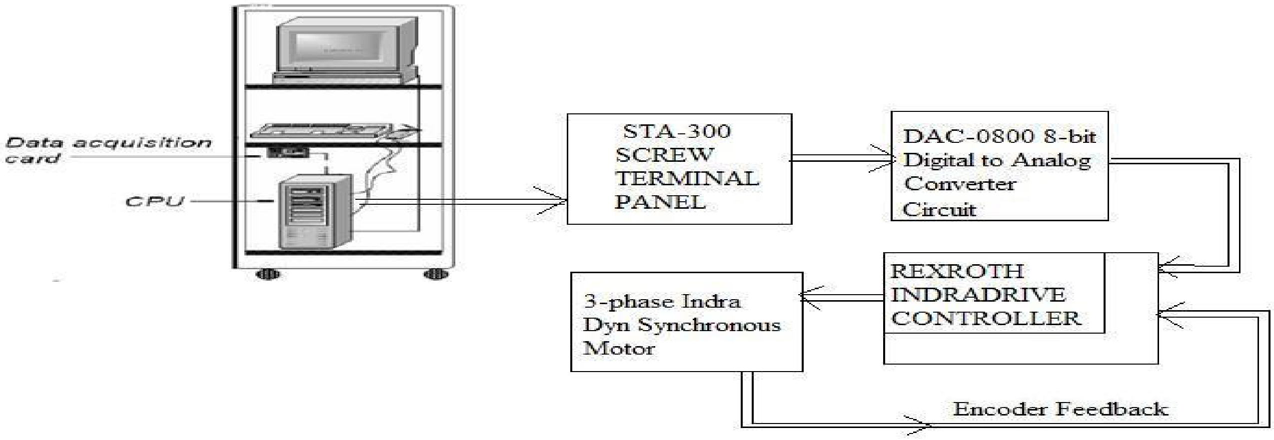

Fig 3a . Block Diagram of Wave Turbine Emulator.

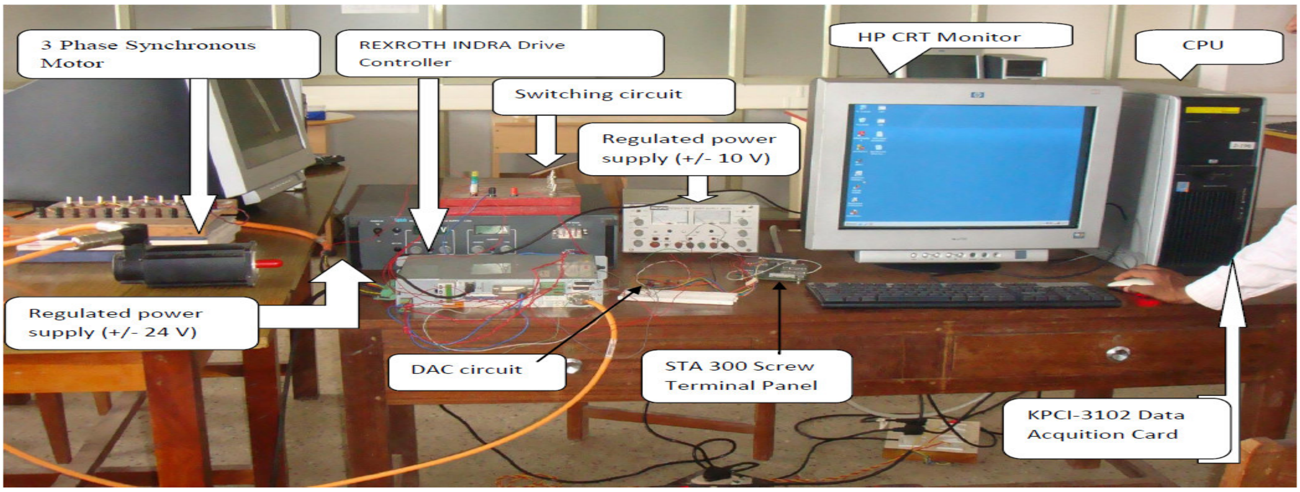

Fig 3b. Laboratory setup of wave Turbine Emulator.

## 4. Results & Discussions

The wave turbine emulator is implemented and tested in the laboratory environment. The speed of synchronous motor is controlled to reproduce the speed of the wave turbine rotor. The response of the Emulator is tested for different cases of Wave pattern and these are presented below.

Fig 4.1 shows a wave pattern input to the model having Significant Wave Height ($H_s$) of 1.0050 m and the corresponding Period ($T_s$) =16.7333sec. This pattern has peak angular frequency ($w_o$) of 0.6545rad/sec. The Spectral Energy Density Curve is shown in Fig4.2.

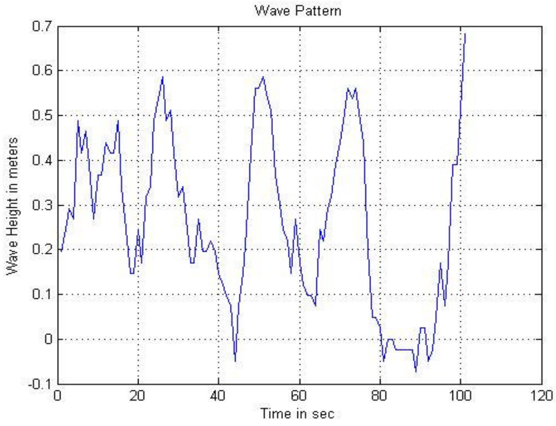

Fig. 4.1 Wave Pattern .

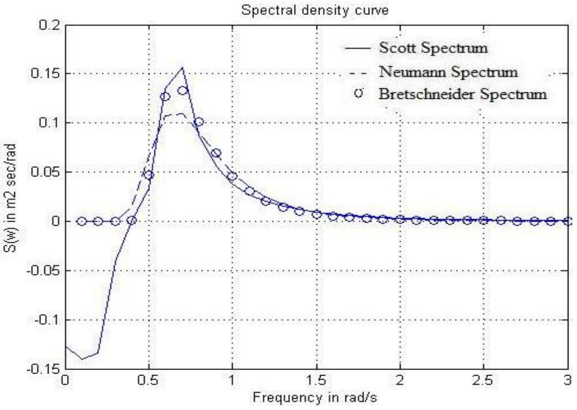

Fig 4.2 Spectral Energy density Curve

With this wave data as input to an Oscillating Water Column model, the Absolute Axial Velocity in the OWC is as shown in fig4.3. The Differential Pressure within the OWC is as shown in Fig4.4 and Power generated by turbine is as shown in Fig 4.5.

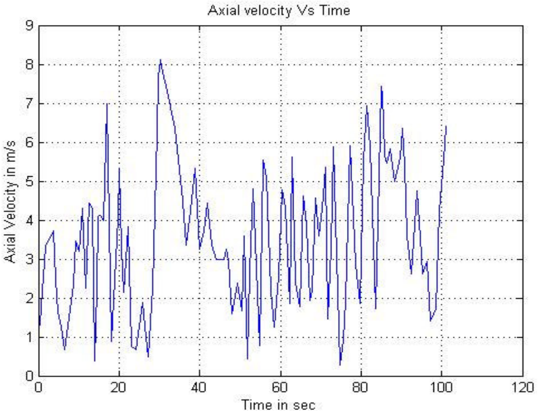

Fig 4.3 Absolute Axial Velocity in OWC

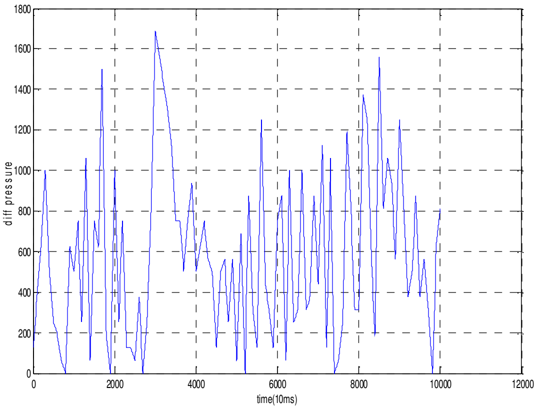

Fig4.4 Differential Pressure Input to Turbine model.

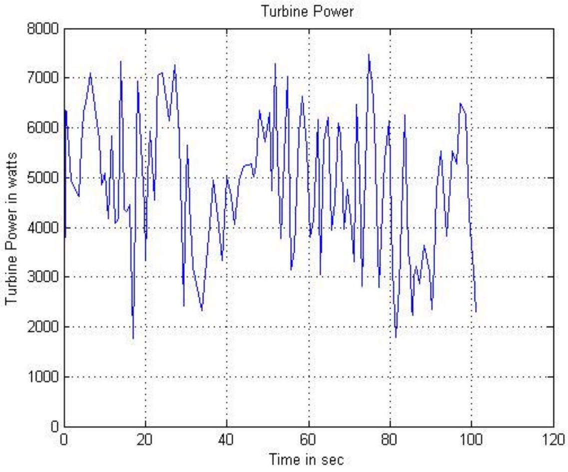

Fig 4.5 Power generated by Wave turbine.

The Speed of the Turbine obtained from the model of Wave Turbine,scaled down by a factor of 100 is as shown in Fig 4.6 and the Speed of the Emulator developed is as shown in Fig 4.7.

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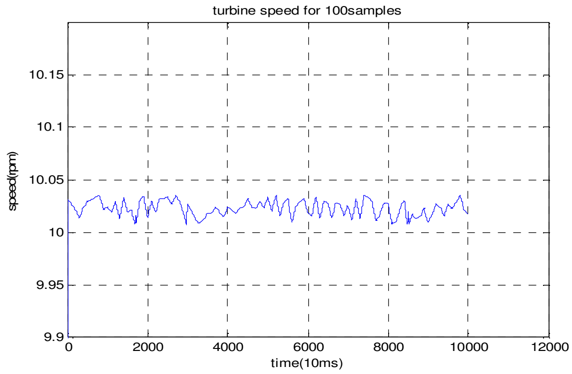

Fig 4.6 Speed response of the turbine model

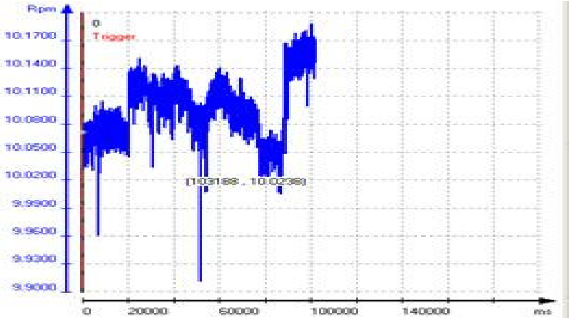

Fig 4.7 Speed response of the Emulator.

## 6. Conclusions

The paper proposed a wave turbine emulator using a three phase permanent magnet synchronous motor. The system in software comprises of wave characterization, model of OWC and the model of Well's Turbine with turbine generator dynamics. Hardware consists of KPCI-3102 Data Acquisition card manufactured by Keithley Instruments, Digital to Analog Converter, 3-phase Permanent magnet Synchronous motor driven by Rexroth Indra Drive Controller. The Speed of the 3-phase synchronous motor follows the speed of the turbine model which justifies the implementation of Emulator with Speed control. It is shown from the results of the OWC model that the axial Velocity of air and the differential pressure in the OWC varies in accordance with variation in wave pattern. These variations are reflected in the turbine speed and power. The differential pressure obtained from the model matches with the measured values from the OWC based wave energy plant located at Vishinjam for given wave pattern which validates the model.

### Acknowledgement

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