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Real Time Simulation Study of DEH for Digital Twin Steam Turbine Generators

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ABSTRACT

Despite the surge in popularity of new energy sources in recent years, the indispensability of thermal power plants remains unwavering. The steam turbine generator digital electro-hydraulic (DEH) control system is a pivotal component in thermal power plants, directly influencing the safety, stability and efficiency of both the plant and the interconnected power grid. Therefore, for better monitoring and control of the DEH, it is necessary to conduct digital twin research on the DEH. This article presents a holistic approach to advancing the digital twin of DEH control systems, mainly including the construction of a dynamic mathematical model, comprehensive digital simulations under varying conditions, and the innovative development of a real-time online simulation platform. Additionally, the integration of a three-dimensional model enhances the depth and visualisation, providing a more immersive understanding of the DEH system's intricate dynamics. The successful implementation of this platform serves as a cornerstone, laying a robust foundation for the eventual establishment of the DEH digital twin system.

1 | Introduction

Thermal power generation, constituting over 50% of the world's power generation industry in both installed capacity and power generation, stands as a cornerstone in meeting global energy demands [1]. This capital-intensive, technology-driven and physically demanding industry plays a pivotal role in ensuring the safety, stability and efficiency of entire nations and societies. The digital electro-hydraulic (DEH) control system, a key component in steam turbine generators, has been a focal point of research efforts [2, 3]. Given its unique characteristics, it becomes increasingly apparent that leveraging digital twin technology presents a promising avenue to enhance various performance indicators within the thermal power generation sector [4].

In recent years, researchers have made substantial strides in understanding and optimising DEH systems. Numerous studies have delved into the modelling, monitoring and control aspects of DEH, recognising its significance in enhancing the overall efficiency and reliability of thermal power plants [5].

Exploring the modelling aspects, researchers have intricately examined the dynamic behaviour of DEH systems, aiming to construct accurate mathematical models that mirror the real-world intricacies [6].

On the monitoring and control front, researchers have implemented diverse methodologies to enhance real-time surveillance of DEH systems [7]. This includes the integration of advanced sensors and data acquisition techniques to monitor critical parameters such as temperature, pressure, flow rate, thermal stress, speed, vibration, voltage, current and power. The goal is to develop robust monitoring systems capable of promptly detecting anomalies, mitigating potential failures and ensuring the smooth operation of thermal power plants [8].

However, as the demand for efficiency and reliability intensifies, the need for a more advanced and adaptable approach becomes increasingly evident. Digital twin technology emerges as a pivotal solution to bridge existing gaps in DEH systems [8, 9]. Unlike traditional methods, digital twins offer a dynamic, real-time representation of the physical system [10]. They provide a virtual mirror that accurately reflects the behaviour of the DEH system under diverse operating conditions, offering a more comprehensive and flexible approach to optimisation.

Current approaches to digital twin systems primarily rely on data sourced from on-site equipment, presenting challenges in consistency due to varied sampling methods and periods across different sources [11]. Moreover, the reliance on actual on-site systems poses difficulties in harsh environmental conditions, limiting the adaptability of these digital twin architectures. Furthermore, existing digital twin models often prioritise the current operating state, making it challenging to switch between different conditions and hindering the effective reflection of abnormal states or serious accidents [12].

Researchers have made efforts in power grid operation mode sand table simulation. A new method for digital deduction of power grid operation modes has been proposed, which is based on digital twin models and electronic dispatching rules. The method involves power grid plan data pre-processing, establishing digital twin model using the latest QS file, and organising the data on an in-memory data grid [13]. The integration of image recognition technology and digital twin technology in the power industry has been explored, and these technologies have been shown to enhance the intelligence and digitalisation of power systems, particularly in equipment defect identification, safety monitoring and system optimisation. The relationship between image recognition and digital twin technologies has been highlighted as mutually promotional and complementary [14]. Also, a modular framework for power system digital twins implementation has been proposed, which emphasises its flexibility, robustness and cost effectiveness [15]. Furthermore, a cybersecurity framework for hydroelectric power plants has been presented by integrating digital twin technology with explainable artificial intelligence, introducing a digital twin model that simulates key operational parameters for real-time monitoring and secure cybersecurity testing [16]. Lastly, locally distributed digital real-time power system co-simulation method using a multi-phase distributed transmission line model is proposed to connect different digital real-time simulator racks and scale up the power system under test [17]. Although these studies have made significant advancements in digital twins and real-time simulation technologies, driving the intelligence and security optimisation of power systems, challenges, such as insufficient technical integration, limited cross-platform collaboration capabilities and inadequate validation of adaptability in complex scenarios persist, requiring further exploration and breakthroughs.

In response to these challenges, our work introduces a novel approach to digital twin system architecture. We propose a real-time digital twin system that addresses the limitations of conventional models by simultaneously incorporating data from both native physical systems and real-time simulations [18]. This innovative architecture aims to enhance the adaptability and accuracy of digital twin representations for steam turbine generator systems. The main contributions of this article can be summarised in the following three parts:

1. Development of a novel digital twin architecture: This article proposes an innovative digital twin architecture that integrates data from both physical systems and real-time simulations. This approach effectively overcomes the limitations of conventional simulation models, which typically rely solely on data sourced from on-site equipment. By incorporating real-time simulation data, the adaptability and accuracy of digital twin representations for steam turbine generator systems are significantly enhanced.
2. Establishment of a comprehensive real-time simulation platform: A real-time simulation platform for DEH systems has been developed based on the RT-Lab platform. This platform not only achieves real-time simulation of the DEH system under various operating conditions but also validates its effectiveness through experiments. It provides a powerful tool for the research and optimisation of DEH systems, enabling more efficient monitoring, control, and prediction of the DEH system's behaviour.
3. Creation of a three-dimensional animated model driven by real-time simulation data: By leveraging real-time simulation data, a three-dimensional animated model of the DEH system has been created. This model achieves an immersive digital twin of the DEH system, offering a more intuitive and in-depth understanding of the complex dynamics of the DEH system. The combination of real-time data with a 3D model contributes to more effective communication and analysis of the system's performance, benefiting both research and practical applications in the field of thermal power generation.

TABLE 1 | Overview of related researches.

Contributions	This paper	[4]	[9]	[13]	[14]
Digital twin architecture	✓	✓	✓	✓	✓
Real-time simulation platform	✓		✓	✓	
3D animation model	✓				✓
Dynamic mathematical modelling	✓	✓	✓	✓	
Real-time data visualisation	✓		✓	✓	✓

The main contribution of this article compared with other recent relevant researches is reflected in Table 1.

To provide a comprehensive exploration of our proposed real-time digital twin system, this article is organised as follows. Section 2 elucidates the functioning of the DEH and introduces mathematical models for its individual components. Section 3 details the creation of a simulation model, enabling the study of the DEH system under diverse operating conditions. Section 4 outlines the establishment of an experimental platform for real-time DEH system simulation, utilising the RT-Lab platform, with specific results discussed in Section 5. Section 6 focuses on the development of a three-dimensional animation model for steam turbine units based on real-time data. Finally, Section 7 concludes this article, summarising the advancements and contributions of our proposed real-time digital twin system for DEH applications.

2 | Working Mechanism and Dynamic Mathematical Model of DEH

2.1 | The Working Mechanism of DEH

The DEH control system, is currently an indispensable control system in large generator sets. It plays an important role in the starting, stopping, normal operation, and handling of accident situations of steam turbines. The principle of the DEH control system is similar to that of a traditional regulating system, but the most obvious advantage is that the DEH system replaces traditional mechanical components with electronic components, achieving more precise control [19]. The DEH system combines computer technology with automatic control technology, making the computer the controller of the system, and making the control ability of the system more intelligent. The actuator still retains the part of the hydraulic actuator. The hydraulic actuator not only occupies a small space, but also responds quickly and smoothly. The detailed block diagram of the DEH control system is shown in Figure 1.

The DEH control device consists of hardware and software components. Hardware is the carrier of software programs, and its reliability determines the lifecycle of the control system. The hardware includes distributed processing unit DPU, various IO cards (including OPC protection card, servo card and other special cards), and operation stations. The hardware determines the real-time, flexibility and progressiveness of the DEH control system.

The DEH control system converts electrical signals into hydraulic signals through an electro-hydraulic converter, and the signals are amplified by amplification elements to drive the actuator of the high-pressure regulating valve and the intermediate pressure regulating valve to operate, adjusting the amount of steam entering the regulating stage [20]. The dynamic characteristics of the speed regulation system and the primary frequency regulation ability of the power grid are closely related to the performance of the electro-hydraulic servo and actuator. The process flow diagram of the controlled object can be shown in Figure 2.

From the perspective of the control system, the controlled object of DEH is composed of the following parts: electro-hydraulic servo valve, hydraulic motor, inlet steam volume, cylinder and reheater, rotor and the power model of the generator should also be considered after being integrated into the power grid.

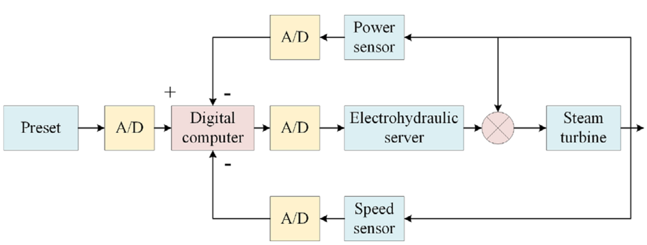


FIGURE 1 | The block diagram of the DEH control system.

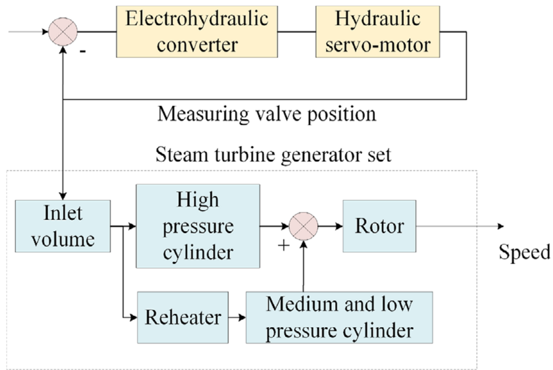


FIGURE 2 | Process flow diagram of the controlled object.

2.2 | Dynamic Mathematical Model of DEH

When establishing the model of the turbine governing system, the internal relationship of the physical process must be analysed, and the original equation of motion is usually established according to the laws of mechanics, mass conservation, momentum conservation, and energy. The actual object is very complex, so some minor problems need to be ignored when building the equation of motion. For the same component, different simplifications result in different equations. The degree of simplification is related to the specific situation of the system and also to the specific problems studied. The DEH principle block diagram can be shown in Figure 3.

The actuator mainly consists of an electro-hydraulic servo valve, a servo amplifier, a linear displacement transformer (LVDT) and a hydraulic motor with quick closing and backstop devices. The servo amplifier board, also known as a valve control card (VCC), has the main function of comparing and generating the deviation between the given signal and the feedback signal. After proportional P or proportional integral PI calculation, it is amplified to control the electro-hydraulic servo valve. The electro-hydraulic servo valve controls the oil inlet or outlet of the hydraulic motor, and the piston of the hydraulic motor produces displacement. The displacement of the hydraulic machine is measured by LVDT and fed back to the input end of the servo amplifier board, until the piston stops moving when it is balanced with the valve position command [21]. At this point, the steam valve has reached the required opening, completing the conversion process from electrical signal to hydraulic pressure to mechanical displacement.

1. Motion equation of torque motor
   A torque motor is an electrical mechanical converter that generates a differential control current ΔI from an external voltage signal through an amplifier, thereby outputting electromagnetic torque and causing the armature to deflect. Therefore, the voltage drop of the resistor, the back electromotive force generated by the movement of the armature in the coil, and the induced electromotive force caused by changes in current in the coil add up to their total control

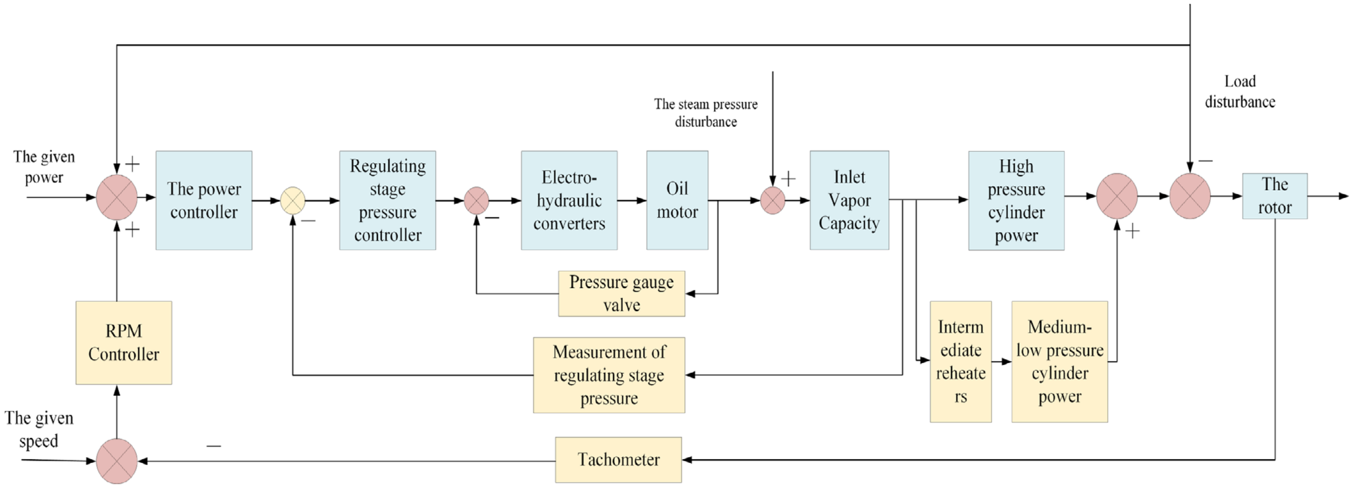


FIGURE 3 | DEH principle block diagram.

voltage. The basic voltage equation of the torque motor circuit:

$$2K_u u_g = \left(R_c + r_p\right)\Delta i + 2K_b \frac{d\theta}{dt} + 2L_c \frac{d\Delta i}{dt} \tag{1}$$

where K_u is gain on each side of the amplifier, u_g is input amplifier signal voltage, R_c is resistance of the coil, r_p is internal resistance of amplifier in coil circuit, K_b is coil back electromotive force constant, L_c is the self-inductance coefficient of the coil, Δi is control current of input torque motor, θ is the angle of the armature.

2. The motion equation of the armature baffle assembly
The armature baffle assembly contains two feedback channels: force feedback and pressure feedback, and the electromagnetic torque output by the torque motor:

$$T_d = K_t \Delta i + K_m \theta \tag{2}$$

where K_t is the median electromagnetic torque coefficient of a torque motor, K_m is the stiffness of the mid position electromagnetic spring in a torque motor.

3. Derive the relationship between baffle displacement and armature angle from literature

$$X_f(s) = r\theta(s) \tag{3}$$

4. The relationship between the displacement of the spool and the displacement of the baffle
Ignoring the steady-state hydraulic force, viscous damping force and feedback rod spring force on the valve core, the transfer function of the baffle displacement to the valve core displacement is:

$$\frac{X_v(s)}{X_f(s)} = \frac{\frac{K_{qp}}{A_v}}{s\left(\frac{s^2}{\omega_{hp}^2} + \frac{2\zeta_{hp}}{\omega_{hp}s+1}\right)} \tag{4}$$

where K_{qp} is flow gain of nozzle baffle valve, A_v is end face area of slide valve core, ω_{hp} is the hydraulic natural frequency of the slide valve, ζ_{hp} is hydraulic damping ratio of slide valve. Usually, the natural frequency of the second-order link of the servo valve is high and the damping is small, so its transfer function can be simplified as first-order inertia:

$$\frac{X_v(s)}{U_g(s)} = \frac{K_a K_{xv}}{\frac{s}{K_{vf}} + 1} \tag{5}$$

where K_a is servo amplifier gain, K_{xv} is servo valve gain, K_{vf} is open loop amplification factor of force feedback loop.

5. The transfer function of the hydraulic motor is:

$$W(s) = \frac{Z(s)}{X_V(s)} = \frac{1}{T_c s} \tag{6}$$

where $Z(s)$ is change in piston stroke of hydraulic engine, $X_V(s)$ is the displacement of the spool of the slide valve, $T_c s$ is travel time of hydraulic motor piston.
In other links of the electro-hydraulic actuator, the transfer function of LVDT is a first-order inertial link, which can be approximated to 1 due to the small measurement time constant. The servo amplifier is a PI controller, but generally only uses proportional action and considers the saturation characteristics of the actuator [22].
Generally, the steam volume of low-power steam turbines is relatively small, so the impact is not significant and can be ignored. However, for steam turbines with higher power and steam parameters, due to their larger volume, the mass of steam stored in the steam volume is relatively large and the impact of volume effect is significant. This section discusses and analyses the dynamic process of steam turbines in two stages: steam volume and rotor.
The volume equation describes the relationship between the opening of the regulating valve and the steam pressure within the volume, and the intermediate reheat unit is divided into the steam inlet volume and the intermediate reheat volume. The inlet volume equation for the nozzle chamber of the

intermediate reheat unit is:

$$T_0 \frac{dX_{P1}}{dt} + X_{P1} = X_{SZ} \tag{7}$$

where X_{P1} is relative variation of high-pressure cylinder steam power. If the reheater and pipeline are considered as concentrated volumes, the intermediate reheat volume formed is very similar to the inlet steam volume of the nozzle chamber, except that the pressure day in the nozzle chamber controls its inlet steam volume, rather than the opening of the high-pressure regulating valve. Referring to the inlet steam volume equation, the equation for the intermediate reheat volume can be obtained as:

$$T_{\mathrm{RH}} \frac{dX_{P2}}{dt} + X_{P2} = X_{P1} \tag{8}$$

where T_{RH} is time constant of reheater volume.

6. About speed feedback, the transfer function of this link is:

$$W(s) = \frac{1}{T_n S + 1} \tag{9}$$

T_n is very small, about 0.2 s.

7. In power frequency regulation systems, power feedback usually designs the time constant of the power sensor to be relatively large, usually set at 0.3 s. Its function is to correct the dynamic characteristics, so the link transfer function is:

$$W(s) = \frac{1}{T_p S + 1} \tag{10}$$

8. Frequency difference amplifier link:

$$W(s) = \frac{1}{\delta_t s} \tag{11}$$

where δ_t is speed governing droop.

This section first introduces the principles followed in modelling the electromechanical hydraulic control system of the steam turbine, and then uses the mechanism analysis method to derive the mathematical models of each link in the power frequency control system of the intermediate reheat steam turbine unit, including the electro-hydraulic actuator, the power of the intermediate reheat steam turbine, the rotor and the generator power, thus obtaining the mathematical model of the entire DEH system.

3 | Digital Simulation of DEH Under Various Working Conditions

The Simulink toolkit in Matlab provides a good simulation environment for control systems. [23] Connect the simulation modules corresponding to each link model obtained in Simulink, and the resulting simulation block diagram is shown in Figure 4.

In Figure 4, $p0$ and $n0$ represent power and speed settings, respectively. PID1, PID2 and PID3 represent the speed controller power controller and regulating stage pressure controller, respectively. w1, w2, w3, w4, and w5 represent high-pressure regulating valve electro-hydraulic converter module, high-pressure regulating valve oil dynamic control module, inlet steam volume module, steam power module and turbine rotor module, respectively.

TABLE 2 | Controller parameter setup.

PID controller	Parameter settings
PID 1	$P = 1/0.05; I = 0; D = 0$
PID 2	$P = 1; I = 0.01; D = 0$
PID 3	$P = 5; I = 1; D = 0$

When only proportional or both proportional and integral inputs are used but the integral gain is very small, and better control performance can be achieved even when the power set value is disturbed, internal disturbance simulation should also be conducted [24]. Therefore, the integral gain should be appropriately increased to ensure that the output of the system can be stabilised again when subjected to internal disturbances. The optimal controller parameters obtained in this article are shown in Table 2. And the start-up process of a steam turbine can be shown in Figure 5.

Cold state start has its particularity because it means that the equipment has been shut down for a long time, so the start-up time is longer. After comparing with literature, the obtained image matches expectations.

When conducting load disturbance tests (i.e., power set value step disturbance tests), the target load command of the unit is increased or decreased by a 15% MCR step, and the rate of load change is set to 3% MCR/min. Based on this, in the step disturbance simulation of the power given value in this article, the slope parameter value of the P0 module (slope function module) is set to 0.03, and the upper limit and lower limit of the saturation module are set to 0.15 and −0.15, respectively [25]. After setting up, start simulation. The output curves of steam turbine power and speed within 30 s are shown in Figure 6.

From Figure 6, it can be seen that when the given power value increases by 15% at a rate of 3%, the actual increase in turbine power after stabilising is 0.75% [26]. The maximum dynamic deviation of power variation during the regulation process is about 1.7%, and the regulation time is about 10 s. At the same time, the turbine speed increased by approximately 0.75%. The simulation results show that the control system is completely consistent with the actual site, and all parameters meet the requirements of actual production.

Set the final value of the L module parameter to 0.2, set the upper and lower limits of the saturation module to 0, set the simulation time to 30 s, and perform simulation to obtain the output curves of the turbine power and speed, as shown in Figure 7.

As shown in Figure 7, the load of the power grid increases by a 20% step, the power of the steam turbine can increase by about 20% in about 10 s, quickly compensating for the increase in electricity consumption, maintaining the balance of the power grid supply, and the overshoot is small. At the same time, the turbine speed can stabilise at the rated value again within

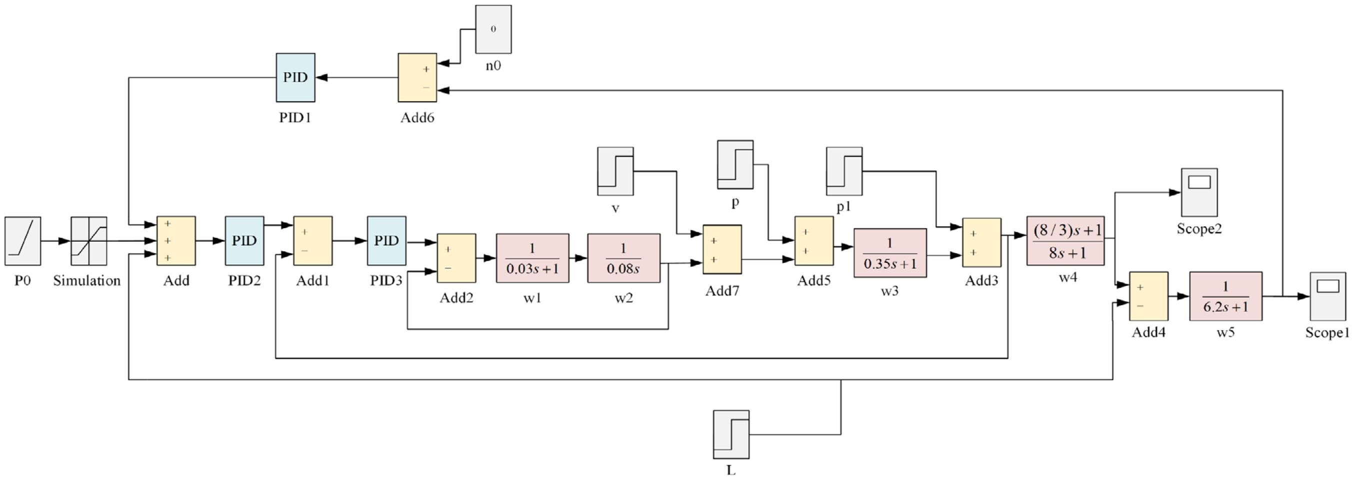


FIGURE 4 | Simulation diagram of digital electro-hydraulic control system for steam turbine.

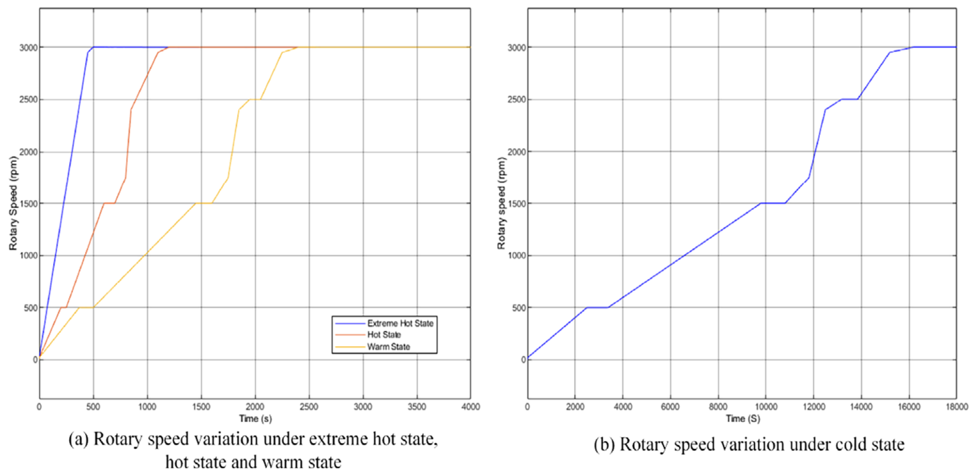


FIGURE 5 | Rotary speed variation under extreme hot state, hot state, warm state and cold state.

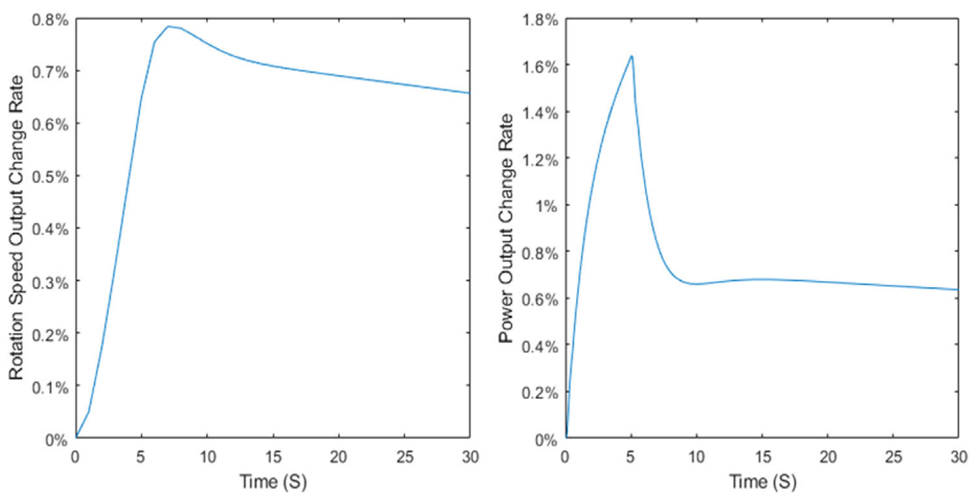


FIGURE 6 | Rotation speed and power output control curve under disturbance of power set value.

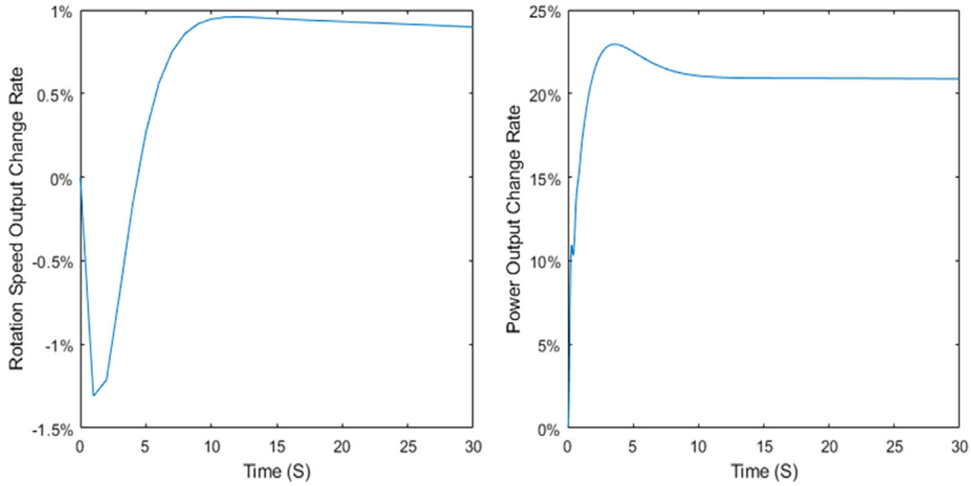


FIGURE 7 | Rotation speed and power output control curve during load disturbance.

about 10 s, ensuring that the grid frequency remains basically unchanged. The maximum dynamic deviation of the speed during this process is about 1.4%, which meets the requirements of actual production indicators.

The dynamic behaviour of the DEH system under varying thermal states can be fundamentally attributed to the interplay between the electro-hydraulic servo dynamics and thermal-mechanical coupling effects. The mathematical model derived in Section 2.2, particularly the transfer functions of the electro-hydraulic actuator (Equations 5 and 6) and steam volume dynamics (Equations 7 and 8) provides a theoretical foundation for understanding the observed experimental trends. For instance, the extended warm-up phase in the cold state is governed by the time constant T_{RH} in the reheater volume equation (Equation 8), which amplifies thermal inertia effects. This necessitates a conservative PID parameter setup (e.g., lower integral gain $I = 0$ in PID1, as shown in Table 2) to mitigate overshoot caused by delayed thermal equilibration. Conversely, in extreme hot states, the reduced thermal inertia (smaller T_{RH}) allows for aggressive proportional control ($P = 1/0.05$ in PID1) to achieve rapid stabilisation.

The distinct acceleration profiles between hot and warm states further reflect the non-linearity in the rotor dynamics (Equations 9 and 10) and steam power equations (Equation 7). The variable thermal stress gradients, quantified by the coefficient of thermal expansion in the cylinder material, induce transient stiffness changes in the hydraulic motor (Equation 4), thereby affecting the system's bandwidth. This justifies the adaptive tuning of PID parameters to compensate for stiffness variations. Additionally, the power-frequency regulation model (Equation 11) reveals that the droop coefficient δ_t directly impacts the system's ability to balance grid frequency deviations during load disturbances, as shown in Figure 6, aligning with the observed 0.75% power deviation.

To enhance model fidelity, future work could incorporate non-linear terms (e.g., hysteresis in servo valves) and higher-order thermal stress models derived from Fourier's law of heat conduction. Such refinements would bridge the gap between the current linearised assumptions and the empirical degradation patterns observed in long-term operations.

4 | Establishing a Real-Time Simulation Platform for DEH Based on Opal RT-Lab

Real time simulation is one of the key technologies for achieving digital twins in steam turbine DEH, as is well known, steam turbine generators are the most valuable, technologically intensive and critical equipment in power plants with extreme physical parameters. The digital twin of the DEH system for steam turbine generators is an important means to achieve efficient training, equipment maintenance, safety production, optimised operation, scientific testing and research. To achieve the digital twin of the steam turbine generator DEH, the first step is to implement real-time simulation of the steam turbine generator DEH. The dynamic data generated by real-time simulation drives the three-dimensional model and its animation to achieve the on-site effect of digital twin. Dynamic real-time data can be generated by dynamic mathematical models or by collecting on-site data. Overall, the specific stages for a digital twin DEH system can be concluded in Figure 8.

For digital twin systems used for teaching and training, the three-dimensional model can be directly driven by data generated by Matlab Simulink or data collected on-site with established historical information. Further, for digital twin systems used for production and operation, real-time running information can be introduced at the production and operation site to drive three-dimensional animation, perform safety monitoring, fault diagnosis and fault prediction functions [27].

The core part of the real-time simulation system adopts a high-speed processor and a real-time multitasking operating system, which can perform real-time simulation of the entire DEH process of the steam turbine generator with multiple parameters. It can achieve real-time simulation of normal start stop and operation, as well as simulation of abnormal situations such as emergency shutdown and load shedding of the unit [28]. Especially for real-time simulation of major accidents, such as

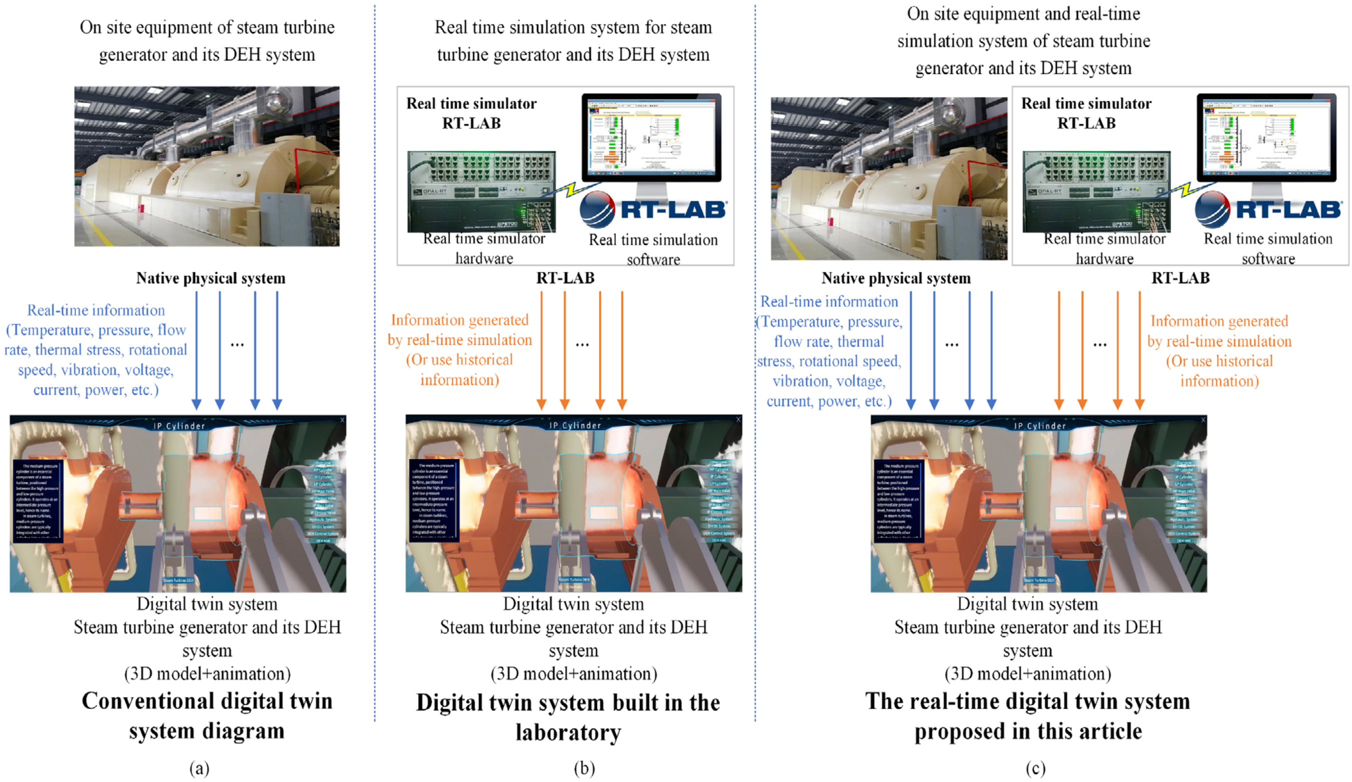


FIGURE 8 | Schematic diagram of the digital twin DEH system at different stages of development.

major destructive accidents such as turbine generator overspeed and rapid operation.

For teaching and training aimed at normal operation, installation and maintenance of the DEH digital twin system for steam turbine generators, the system parameters change slowly, the time constant in the transfer function is large, and the transition process is long. The system can achieve synchronisation and real-time simulation within one sampling cycle [29, 30]. Real time synchronisation can be directly achieved using Matlab related real-time toolboxes or software.

For the scientific research and on-site production of steam turbine DEH, the digital twin system needs to handle the entire operating process, facing various different rates of change such as temperature, pressure, flow rate, speed, thermal stress, vibration, power, voltage, current and a large number of engineering physical quantities. It also needs to face various working conditions of normal and abnormal operation, using a dedicated real-time data simulator. This article uses an RT-Lab real-time simulator.

Figure 9 illustrates a comprehensive real-time simulation platform for the DEH system, centred around the Opal RT-Lab simulation environment. Key components of the setup include multiple operator stations for parameter inputs and control, with commands sent to the RT-Lab system through a Raspberry Pi DA/DO drive board. The RT-Lab handles real-time simulation by interacting with various sensors via Raspberry Pi capture cards that collect crucial data, such as pressure differences and rotational speed values. Data is transmitted wirelessly to multiple workstations where 3D virtual simulations provide a visual representation of system operations. Additionally, an engineering station is responsible for debugging and sending model-related orders to the RT-Lab, ensuring that the system maintains optimal functionality. The platform facilitates seamless communication between physical and digital domains, supporting accurate monitoring and control of the DEH system in real time.

The detailed hardware implementation is provided in Figure 10. As seen, the setup consists of an OPAL RT-Lab system connected to a control desk for real-time system management. A Raspberry Pi unit interfaces with the simulation setup, transmitting data between the OPAL RT-Lab and other connected devices. An oscilloscope is used for monitoring and visualising real-time waveforms and signals, ensuring the accurate performance of the system. This configuration allows for precise data acquisition and control signal output, facilitating effective real-time simulation and debugging of the DEH system.

Beyond DEH systems, our digital twin architecture and methodologies exhibit significant potential for broader application within the power sector and diverse complex industries. Within power systems, the core approach that involves integrating real-time simulation data with physical system information to create a dynamic virtual replica can be directly adapted to other critical components. Crucially, the innovation of using simulation data to drive the twin addresses key deployment challenges, enhancing adaptability and accuracy where sensor data is limited. Furthermore, the inherently modular framework (dynamic model, RT-Lab simulator, simulation-driven visualisation) facilitates extension to entirely different domains, such as chemical processing, robotics or aerospace. The fundamental principles of capturing multi-physics dynamics, enabling safe virtual testing

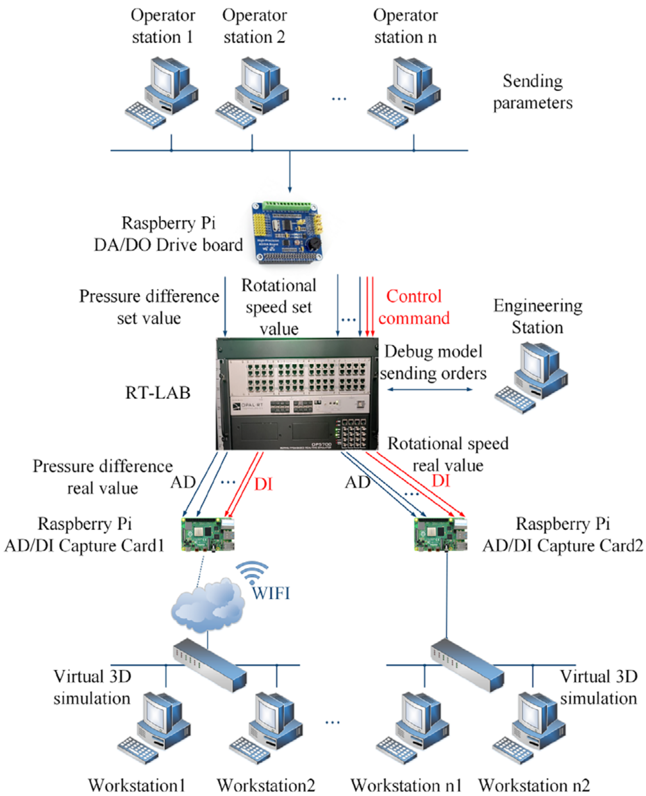


FIGURE 9 | Real-time simulation architecture schematic.

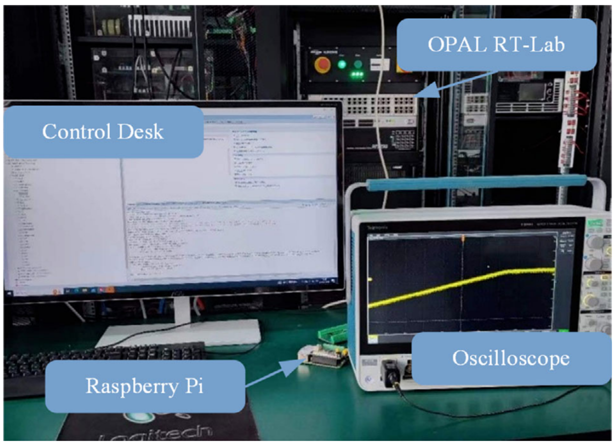


FIGURE 10 | System implementation for real-time simulation.

and providing immersive monitoring remain universally valuable.

5 | Real Time Simulation Testing and Result Analysis

To verify the effectiveness of the proposed strategy on the simulation platform, real-time experiments are performed on RT-LAB OP5700. The workflow begins by converting the existing Simulink model into a format compatible with RT-Lab, allowing for seamless integration with the real-time hardware. Initial simulations are conducted on a platform computer to verify the validity of the control algorithm and the accuracy of the model configuration. Once confirmed, the simulation model is uploaded to the RT-Lab for real-time execution, leveraging its high-performance computation capabilities to replicate real-world conditions accurately.

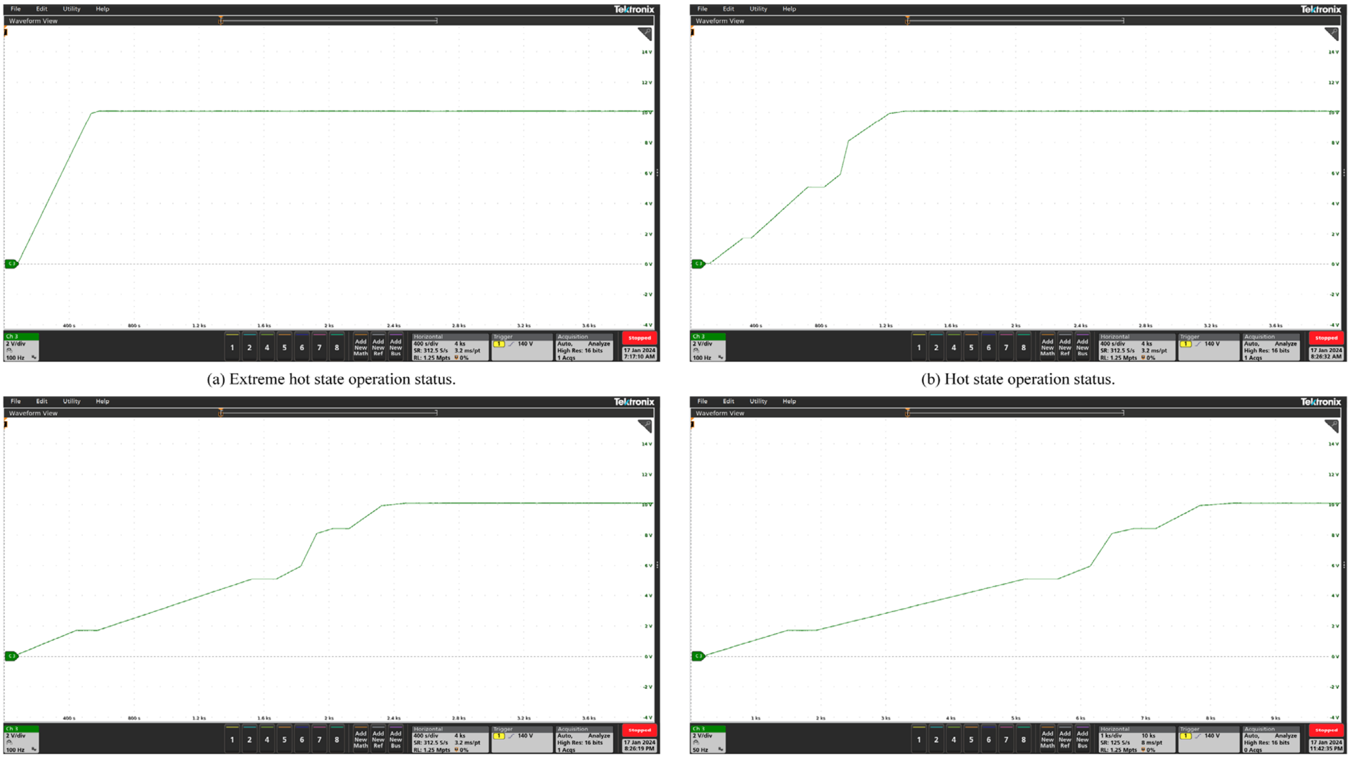
1. Extreme hot state
   In the extreme hot start scenario, the system is tested to observe how quickly and efficiently it could achieve the desired operating conditions. As depicted in Figure 11a, the rotational speed exhibited a rapid increase, reaching the rated speed in a significantly short time frame. The acceleration curve shows a smooth and continuous rise, reflecting the system's high responsiveness under this condition. This behaviour highlights the DEH system's ability to handle extreme thermal conditions without requiring additional adjustments or phase transitions, indicating robust performance with minimal thermal stress. The results suggest that under extreme hot conditions, the DEH system can quickly stabilise, ensuring that steam turbines can be efficiently brought online with minimal delay.

2. Hot state
   Compared to the extreme hot start, the hot state exhibits a more gradual acceleration profile. Figure 11b shows that the start-up process required two distinct warm-up phases to reach the rated speed. This pattern is characterised by two separate slopes in the acceleration curve, indicating pauses for thermal stabilisation during the ramp-up phase. The need for these additional warm-up periods is a safety feature, ensuring that the system can accommodate higher thermal inertia without risking damage to components. Although the overall start-up time is longer in the hot state, this conservative approach promotes greater stability and reduces the risk of mechanical or thermal stress, thereby extending the operational lifespan of key components.

3. Warm state
   In the warm start scenario shown in Figure 11c, the DEH system demonstrates a gradual and steady rise in rotational speed, allowing subsystems to adjust to thermal changes incrementally. Unlike the rapid acceleration in the hot states, the warm start process involves controlled pauses for speed adjustments, ensuring a stable ramp-up without overshooting. This condition highlights the DEH system's ability to utilise residual heat effectively, balancing safety and efficiency for quicker restarts.

4. Cold state
   Due to the extended start-up time required for a cold start, which exceeded the oscilloscope's range, the duration was scaled down to 50% of the original time, as shown in Figure 11d. The cold start scenario requires the most careful and extended acceleration, starting from a cooled-down state. The slow initial speed increase reflected a deliberate warm-up phase to avoid thermal stress. This cautious startup ensures component safety and highlights the DEH system's reliability in handling thermal deficits. The results emphasise the system's resilience and capability to manage slow, stable transitions from a fully cooled state to operational readiness.

To sum up, the analysis of the four operational states—extreme hot, hot, warm and cold—highlights the versatility and accuracy



(a) Extreme hot state operation status.

(b) Hot state operation status.

(c) Warm state operation status.

(d) Cold state operation status.

FIGURE 11 | Real time simulation of the operation status.

of the DEH digital twin platform. In extreme hot and hot states, the platform showcased its ability to simulate rapid and direct responses with precise speed control, crucial for maintaining efficiency and stability in high-temperature conditions. The seamless acceleration to the rated speed in these states demonstrated the platform's fidelity in capturing the nuanced dynamics of fast-response scenarios.

The experimental results under different thermal states reveal key insights into the thermal stress dynamics adaptability of the DEH digital twin platform. In the actual production process, there will be many more operating conditions between two states. For example, when a steam turbine is restarted, its temperature may not reach the extremely hot state, but significantly higher than the hot state. In this case, this state is temporarily referred to as the middle hot state. The start-up process of the steam turbine in this state is shown in Figure 12a, while Figure 12b compares the start-up process of this state with that of the extremely hot and hot states. Furthermore, the distinct acceleration profiles between these states suggest that adaptive control strategies—such as variable PID parameters tuned to real-time temperature feedback—could further enhance operational flexibility. These findings not only validate the platform's fidelity but also chart pathways for leveraging digital twins in lifecycle management and adaptive control of steam turbine systems.

The sensitivity of the model to computational parameter variations has been carefully analysed and is an important aspect of our study. For instance, in the simulation of the DEH system under various thermal states, the model demonstrated robustness to reasonable parameter fluctuations. Specifically, in the extreme hot state scenario, the model maintained stable and rapid acceleration performance even with slight variations in parameters such as the PID controller gains. In the hot and warm state simulations, the model showed a moderate sensitivity to parameter changes, where adjustments to the integral gain could influence the thermal stabilisation phases but did not compromise the overall system stability. Furthermore, during the cold state simulation, which is more sensitive to parameter settings due to the extended startup time and lower thermal inertia, the model exhibited a higher sensitivity to changes in parameters like the time constant of the reheater volume. However, through meticulous parameter tuning and validation against real-world data, the model's sensitivity to computational parameters has been effectively mitigated, ensuring reliable and accurate simulation results across the entire operating envelope.

In contrast, the warm and cold states underscored the platform's robustness in managing slower, more cautious startup processes. The simulation's ability to faithfully replicate the gradual and incremental speed adjustments needed in these lower thermal conditions emphasises the digital twin's capability to handle complex and diverse operational requirements. The DEH digital twin platform effectively mimics real-world behaviours, allowing for comprehensive analysis, debugging and training without risking physical systems. Its accurate and detailed simulation capabilities make it an invaluable tool for understanding and optimising DEH performance across a wide range of conditions, ultimately enhancing decision-making, safety and operational efficiency in power plants.

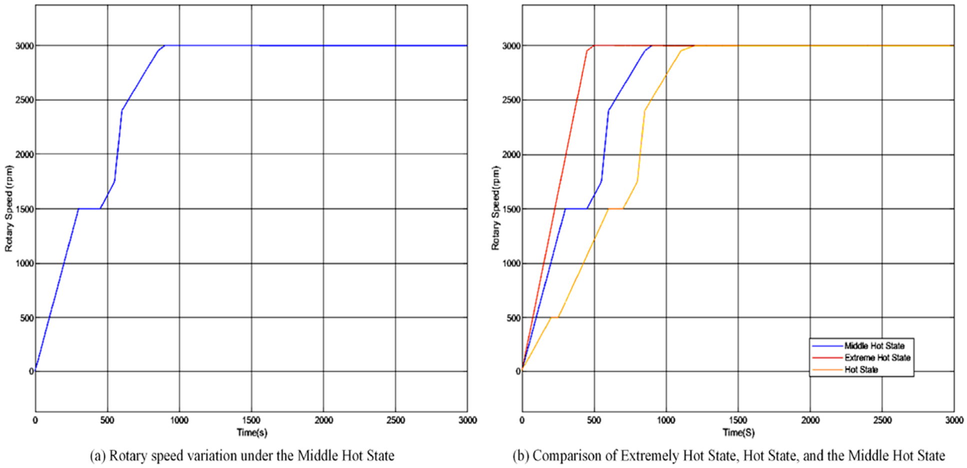


FIGURE 12 | Rotary speed under the new middle hot state.

6 | Real Time Simulation Data Driven Three-Dimensional Animation Models to Achieve Digital Twins

6.1 | Real Time Simulation Information

This study utilises the WebRTC (Web Real-Time Communication) platform for data-driven development. WebRTC is a robust open-source platform specifically designed for real-time communication, commonly employed for the direct transmission of audio, video and data between web browsers and mobile applications. One of its primary advantages is its ability to facilitate seamless real-time data transmission and interaction, making it ideal for high-fidelity simulations. Since WebRTC is web-based, it is compatible with multiple devices without requiring any additional client installation, providing greater flexibility and accessibility for a wide user base. This capability enables real-time simulation data to be transmitted efficiently to remote visualisation platforms, laying the groundwork for accurate digital twin implementation.

6.2 | Three-Dimensional Animation Implementation

The development of a three-dimensional virtual model of steam turbines encompasses the detailed modelling of various components, such as blades, cylinders, bases, shafts and segments related to low-pressure, medium-pressure and high-pressure operations [29, 31]. This comprehensive model accurately depicts the physical attributes of steam turbines, allowing for a realistic simulation of scenarios like steam intake, exhaust processes, rotation, operational adjustments and routine maintenance. These simulations visually represent how the virtual equipment would behave under varying operational conditions, enabling a dynamic understanding of system performance. The three-dimensional animation of steam turbines is driven by real-time data collected during simulations. This ensures that the virtual model's behaviour accurately reflects the true state of the physical system, with key operational parameters displayed live on the interface for better monitoring and analysis.

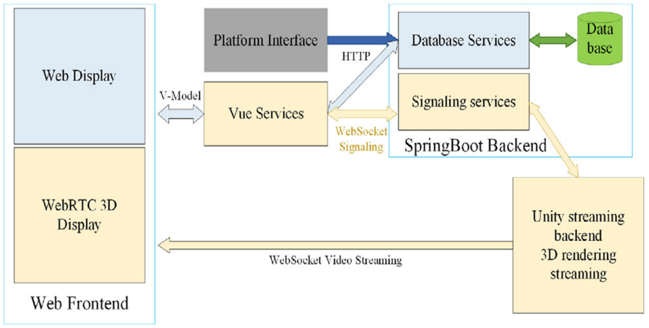


FIGURE 13 | Three-dimensional animation frame structure of steam turbine generator and its DEH system.

In the creation of digital twins, especially during the operation phase of the 3D virtual model, the communication function holds a pivotal position. The communication architecture diagram of the digital twin is illustrated in Figure 13. The 3D model of the digital twin is composed of various modules such as front-end, back-end, data communication and storage. The web front-end encompasses the webpage display end as well as the WebRTC 3D display end. The back-end of the digital twin model is developed using the Spring Boot framework. Interaction between the web front-end and the Spring Boot back-end is facilitated through Vue services and the WebSocket protocol.

6.3 | Real Time Information Driven Three-Dimensional Animation for Digital Twins

The animation effect needs to be synchronised with real-time data to ensure that users can see the real-time operation status of the steam turbine [32]. By collaborating with the real-time data collection module, the animation effect can be synchronously updated with the actual operation of the system. This article chooses Websocket as the transport protocol and it is shown in Figure 14.

The proposed digital twin architecture demonstrates notable advantages in managing uncertainty within steam turbine DEH systems. By incorporating real-time simulation data alongside

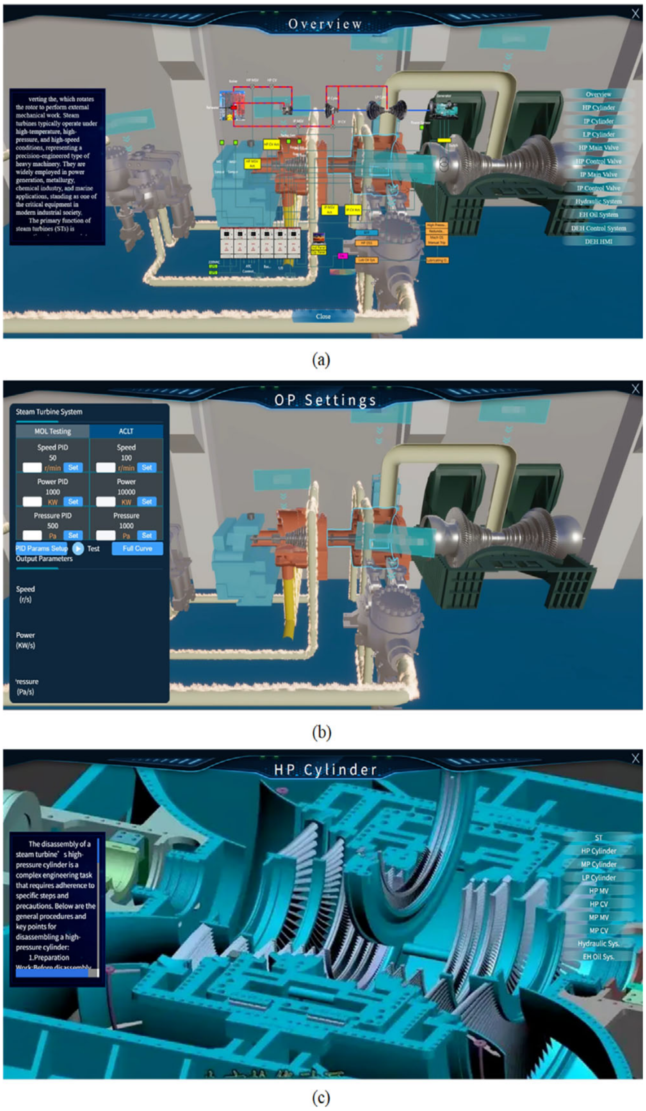


FIGURE 14 | Three-dimensional animations for DEH system. (a) Overall view. (b) Parameter setting interface. (c) Internal structure of the high-pressure cylinder.

physical system information, our approach effectively reduces uncertainties associated with data inconsistencies from diverse sources and sampling methods. This hybrid data framework ensures reliable and accurate digital twin representations across varying operating conditions. Furthermore, the adaptive PID control strategy employed in our design allows the system to dynamically adjust control parameters in response to real-time operational data, enhancing its ability to handle uncertainties arising from changing thermal states and external disturbances.

7 | Conclusion

In response to the complex scale structures, capital-intensive nature, and technology-intensive demands of DEH systems, this study focuses on establishing dynamic mathematical models for DEH. The subsequent digital simulation under diverse operating conditions is seamlessly transplanted onto the RT-Lab real-time simulation platform. This platform not only successfully achieves real-time DEH simulations but also validates its effectiveness. Real-time data generated from the DEH real-time simulation platform is then utilised to drive a three-dimensional animated DEH system, culminating in the construction of a comprehensive DEH digital twin system. This innovative simulation method, effectively bridging the gap between physical and digital domains, proves invaluable for enhancing system understanding in laboratory settings and streamlining debugging processes during onsite implementation.

Based on this study, digital twin technology holds extensive potential for smart grids and renewable energy systems. In smart grids, it enables real-time monitoring, dynamic optimisation, and enhanced resilience; for renewables, it addresses intermittency by predicting output and optimising layout/operation to maximise yield. The core methodologies of real-time data integration and dynamic modelling developed here provide an adaptable framework to drive this transition toward sustainable and intelligent energy systems.

The future research will focus on enhancing the system's role in simulation control decision-making through the integration of advanced algorithms and techniques. This will improve the system's ability to process and analyse complex data in real-time, leading to more accurate and efficient control decisions. Additionally, research will extend to other complex systems within thermal power plants. By using the digital twin technology and methodologies developed in this study, comprehensive digital replicas of these systems will be created, enabling better monitoring, control and optimisation. This will further contribute to the safe, stable and efficient operation of thermal power plants.

Author Contributions

Yiwei Zhou: conceptualization, formal analysis, writing – original draft preparation. **Xiao Guo:** software, supervision, validation. **Xiaoran Dai:** data curation, methodology, funding acquisition. **Zhongcheng Lei:** investigation, software, funding acquisition. **Wenshan Hu:** formal analysis, resources. **Hong Zhou:** project administration, funding acquisition.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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