

Article

Development of a Digital Twin for the Gas Turbine Generator Unit Startup System

Yan Nie ¹, Zhende Zhao ¹, Xiao Fan ¹, Siyu De ¹, Qingshuo Zeng ², Jingsen Yang ², Yiming Lai ^{2,*} and Xiaotong Song ² 

¹ Shandong Electric Power Engineering Consulting Institute Co., Ltd., Jinan 250013, China; yannie@163.com (Y.N.); zhaozhende@spic.com.cn (Z.Z.); fanxiao@spic.com.cn (X.F.); desiyu@spic.com.cn (S.D.)

² School of Electrical and Control Engineering, North China University of Technology, Beijing 100144, China; 2024322050102@mail.ncut.edu.cn (Q.Z.); yjs17812236281@126.com (J.Y.); songxt@ncut.edu.cn (X.S.)

* Correspondence: 2024322050123@mail.ncut.edu.cn

Abstract

The startup process of gas turbines driven by the static frequency converter (SFC) exhibits complicated electromechanical coupling characteristics. Conventional simulation methods fail to integrate physical modeling with sequence of event (SOE) data and cannot support co-simulation of multiple startup schemes at the power station level. In this paper, a hierarchical digital twin architecture oriented to gas turbine SFC startup is established to realize intelligent deduction of sequential control and break through the technical limitations of traditional simulations. Relevant waveforms and data of the F-class heavy-duty gas turbine during startup are obtained via the digital twin. The maximum effective value of voltage is 12.07 kV, the maximum effective value of current is 1.6 kA, and the peak output power of the SFC reaches 15.67 MW. The system achieves the rated speed (3000 rpm) within an acceptable start-up duration, demonstrating satisfactory dynamic response. All the above data conform to the preset startup parameters and operation control logic of heavy-duty gas turbines.

Keywords: gas turbine; static frequency converter; digital twin; sequence control deduction

1. Introduction

Under the current “carbon peak, carbon neutrality” dual-carbon strategy, the engineering field is gradually undergoing a transformation towards high-end, green and intelligent development. This trend has driven the iteration of green power generation technologies and the construction process of new power systems [1]. As the power generation sector increasingly emphasizes environmental protection, gas turbine power generation has emerged as a preferred generation unit due to its high efficiency, eco-friendliness, rapid startup and shutdown capabilities, and flexible regulation [2]. Because gas turbine units lack sufficient torque to self-start from a standstill, external starting mechanisms are required to drive the initial acceleration phase; therefore, selecting an optimal startup method is critical to the startup performance of the gas turbine. With the continuous research and development of gas turbine startup technologies, various methods have been introduced, including diesel generator startup, black start [3,4], variable frequency startup [5], and barring startup [6]. Among these, variable frequency startup facilitates smooth and seamless rotor acceleration through coordinated voltage/power control, averting large



Received: 19 June 2026

Revised: 19 July 2026

Accepted: 21 July 2026

Published: 22 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

inrush currents in the circuit. Furthermore, its optimized structure allows a single variable frequency startup device to drive multiple gas turbine units, significantly enhancing economic efficiency. These advantages have established variable frequency startup as the predominant method for gas turbines [7].

In recent years, gas turbine technology and its startup issues have garnered widespread attention from domestic and international scholars. For instance, a novel static frequency converter (SFC) based on a multi-level cascaded H-bridge topology has been proposed in [8], demonstrating significant improvements in output voltage quality. Compared to traditional SFC with load-commutated inverters, this novel SFC exhibits advantages such as rapid response and a compact structure. Building on these studies, Literature [9] analyzes potential faults during the SFC gas turbine startup process and proposes corresponding troubleshooting strategies. Literature [10] conducts an in-depth study on short-circuit faults, addressing the insufficient integration of mechanical and electrical systems in fault analysis by constructing an electromechanical coupling model to investigate the torsional vibration characteristics of the gas turbine generator shafting. Regarding startup schemes. Literature [11] proposes a novel black start scheme for diesel generator units, ensuring isolated island operation of the gas turbine by integrating supercapacitors as energy storage elements, and achieving coordinated grid connection by controlling the diesel generator unit load. Literature [12] integrates two black start diesel engines into a combined cycle gas turbine system to enable rapid cold startup; these engines not only serve as a startup power source when power plant supply issues arise but also preheat the gas turbine to accelerate its startup.

Traditional gas turbine startup performance analysis methods mostly rely on simplified transfer functions or thermodynamic calculation models. These methods possess distinct limitations. On one hand, the inadequate consideration of the temporal coupling characteristics across electrical, mechanical, and thermal domains during the startup sequence results in simulation precision that falls short of engineering requirements. On the other hand, the rough construction of the key Sequence of Event (SOE) temporal records during the startup process fails to authentically reflect the detailed features of the transient process. Digital twin technology offers a novel approach to resolving these issues by constructing digitized models that achieve cyber-physical mapping and real-time interaction with physical entities [13]. The current trend of intelligent development in energy equipment lies in the profound integration of digital twin and artificial intelligence technologies. This not only enables high-fidelity simulation of complex physical processes but also endows the system with intelligent decision-making and strategy optimization capabilities. To this end, this paper proposes a layered architecture and an intelligent sequential control deduction method for a digital twin based on the gas turbine SFC startup system. This method aims to achieve a mapping from the physical station to the virtual model by constructing a station-level digital twin architecture encompassing a sequential control deduction layer, a data transmission layer, and a multimodal presentation layer. By integrating multi-physics coupled mechanistic models, it achieves a more precise simulation of the physical characteristics and a more authentic construction of SOE information during the SFC startup process.

The topological design of the SFC variable frequency starting circuit and its corresponding simulink modeling framework are developed with reference to recent heavy-duty gas turbine studies [14,15]. Furthermore, to achieve highly responsive motor speed regulation (e.g., maintaining specific intermediate speed stages before reaching the rated speed), the system incorporates advanced vector control principles, including Space Vector Pulse Width Modulation (SVPWM), drawing upon the latest fundamental governing equations in motor drive applications [16].

The temporal logic for the sequential control deduction is strictly designed based on the standard operating procedures and control strategies of advanced gas turbines [17], ensuring the precise, rule-based execution of barring, purging, and ignition commands. During these switching operations, the harmonic conduction behaviors inherent to the power electronics converters are analyzed based on foundational power electronics theories [18].

The methodology for comparative analysis, specifically evaluating waveform errors between the simulated values and baseline reference data, adopts the validated approaches detailed in recent large-capacity gas turbine start-up research [19].

Recently, the profound integration of digital twin and artificial intelligence technologies has significantly advanced the lifecycle management, condition monitoring, and performance optimization of large-scale rotating machinery. In the realm of gas turbines, researchers have extensively explored physics-informed machine learning (PIML) to build intelligent digital twins [20], utilizing advanced algorithms like Physics-Informed Neural Networks (PINN) and Particle Swarm Optimization (PSO) to refine steady-state thermodynamic modeling and parameter estimation [21]. Beyond gas turbines, digital twin architectures have been successfully deployed in steam turbines to create immersive, web-based systems for industrial training and visualization [22]. Similarly, in the wind power sector, digital twins are increasingly driving multi-source data fusion for intelligent fault warning in gear transmission systems [23] and assessing the remaining useful life of offshore turbine structures [24]. However, despite these remarkable achievements in steady-state thermodynamic optimization, fault diagnosis, and mechanical health monitoring, there remains a critical gap in applying digital twin technology to the highly dynamic, electromechanical coupled transient processes, specifically the gas turbine SFC startup sequence.

Different from mainstream CSI and conventional LCI adopted in gas turbine SFCs, this work first applies and precisely models voltage-source inverter topology, greatly boosting modulation flexibility and electromechanical start-up dynamic performance. Unlike prior separate thermodynamic equipment models, this paper integrates all primary electrical devices (grid access, isolating transformers, circuit breakers) into virtual models to accurately characterize high-power electronic–weak grid coupling effects. Unlike conventional approaches relying on simplified transfer functions, this framework integrates full-switching VSI-SFC models with shaft rigid-body dynamic equations, enabling the simultaneous resolution of microsecond-scale electrical transients and second-order mechanical dynamics.

2. Layered Architecture Design of the Gas Turbine SFC Startup System Digital Twin

The gas turbine digital twin primarily comprises a three-layer architecture: the sequential control deduction module, the multimodal information structured presentation module, and the data transmission module. The sequential control deduction module serves as the backend computation layer, executing the gas turbine unit station modeling and temporal simulation. The modeling and simulation tasks for this module are conducted within the Simulink environment of MATLAB 2024a software. The multimodal information structured presentation module acts as the frontend display layer, handling functions such as SOE data processing, multimodal information aggregation, and structured presentation. This module is implemented within the LabVIEW 2025q1 software environment. The data transmission module underpins the dynamic interaction between the sequential control deduction module and the multimodal presentation module. To enhance real-time data transmission performance, this module employs the User Datagram Protocol (UDP) for data communication.

2.1. Paradigm Shift from Equipment-Level to Station-Level Modeling

Traditional gas turbine digital twin research frequently focuses on the thermodynamic and fluid dynamic mechanistic modeling of core components such as the compressor, combustor, and turbine, typically restricting the mirroring scope to the internals of a single piece of equipment. However, in the SFC variable frequency startup scenario, the startup success rate and transient characteristics depend not only on the intrinsic properties of the gas turbine but also largely on the dynamic response of the external electrical system. For instance, SFC commutation failures often originate from grid voltage sags or improper parameter configuration of isolation transformers, rather than from thermal cycle anomalies within the gas turbine itself.

The digital twin architecture proposed in this paper achieves a paradigm leap from the equipment level to the station level. Regarding modeling boundaries, primary equipment at the physical station—including the 220 kV grid connection point, main transformer, SFC isolation transformer, excitation transformer, and generator circuit breaker—is comprehensively incorporated into the virtual mirroring space. This station-level modeling perspective authentically reflects the interactions between high-power power electronic devices and weak grids during startup. It accurately captures systemic transient features such as bus voltage fluctuations, harmonic conduction, and electromechanical coupling oscillations, thereby providing complete data for station-level optimization of startup strategies.

2.2. Three-Layer Decoupled Architecture of the Gas Turbine Digital Twin

To accommodate the real-time requirements of both high-fidelity mechanistic computation and multimodal data visualization, this paper designs a three-layer decoupled architecture consisting of sequential control deduction, data transmission, and multimodal presentation, as illustrated in Figure 1.

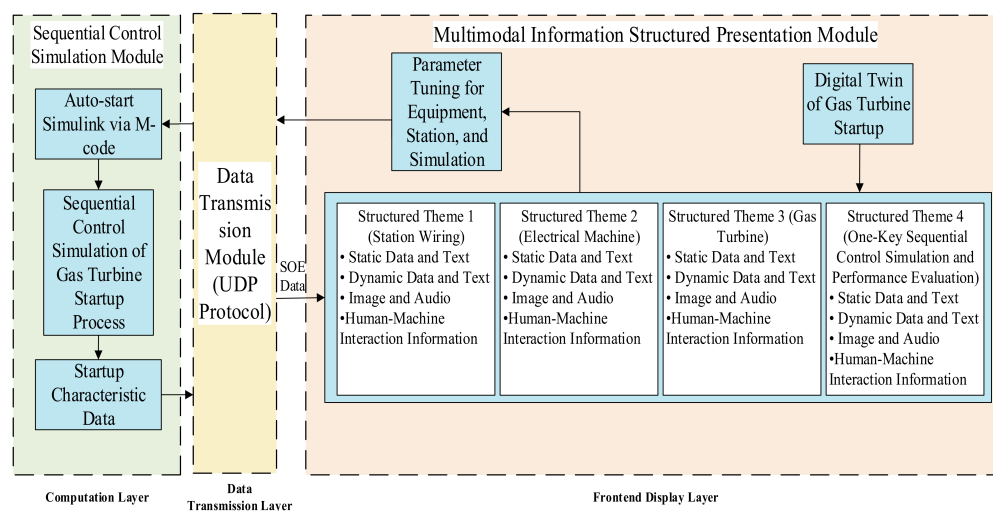


Figure 1. Architecture Illustration of Gas Turbine Digital Twin.

2.2.1. Sequential Control Deduction Layer

Deployed within the Simulink environment of MATLAB software, this layer assumes all mechanically simulation tasks with high computational loads. Its core is a coupled model containing detailed electromagnetic and mechanical transients. Specifically, this layer integrates detailed switching models of the SFC converter, the d-q axis electromechanical transient equations of the synchronous generator, and the rigid body dynamic equations of the gas turbine shafting. By configuring simulation step sizes at the microsecond or millisecond level, this layer precisely replicates the current distortion at the instant the

SFC switches from forced commutation to load commutation, as well as the abrupt torque changes at the moment of tripping.

2.2.2. Multimodal Information Structured Presentation Layer

Developed based on the LabVIEW environment, this layer serves as the exclusive portal for human-machine interaction. Its function is to translate the time-series data generated by the backend into multimodal information with engineering semantics, encompassing static text, dynamic curves, status imagery, and interactive controls. Utilizing graphical programming technology, this layer constructs structured interfaces themed around station subsystems, enabling operators to monitor the dynamic evolution of the entire process, including the barring, purging, ignition, tripping, and grid-connection stages.

2.2.3. Data Transmission Layer

Acting as the hub connecting the frontend and backend, this layer discards traditional file I/O methods in favor of an underlying Socket communication mechanism based on UDP. Compared to Transmission Control Protocol (TCP), the connectionless nature of UDP effectively reduces communication overhead, aligning with the high-frequency data stream transmission requirements during the startup process. Concurrently, to compensate for UDP's unreliability, a custom packet encapsulation strategy featuring timestamps, frame sequence numbers, and checksums is designed at the application layer, ensuring the absolute precision of SOE timing and the smoothness of curve rendering.

2.3. Real-Time Interaction Logic in a Hybrid Programming Environment

The implementation of the architecture in this paper relies on deep hybrid programming between MATLAB and LabVIEW. During the system initialization phase, LabVIEW launches as the master control program and invokes the backend MATLAB engine via the ActiveX automation interface, subsequently utilizing M-scripts to load and initialize the Simulink model.

During the operational phase, Simulink executes solver calculations at a fixed step size and serializes the computation results into binary data frames sent via UDP ports. The LabVIEW frontend employs a multi-threaded parallel processing mechanism: one thread is responsible for listening to the port and unpacking data, resorting and interpolating out-of-order packets based on timestamps; another thread manages the refresh and rendering of the UI interface. This effectively isolates the impact of backend computation delays and network jitter on the frontend display fluency, enhancing the stability of the digital twin platform during prolonged continuous simulations.

3. Mechanism and Modeling of the Gas Turbine SFC Startup Process

The gas turbine SFC startup process is a deeply coupled multi-physics process encompassing electromagnetic transients, mechanical transients, and thermodynamic dynamics. To achieve mapping within the digital twin, this paper constructs a station-level startup model in the Simulink environment of MATLAB. Discarding traditional simplified equivalent circuits and transfer function methods, this model employs detailed mechanistic modeling to precisely reconstruct the complex dynamic characteristics of the entire process, from stationary barring to grid-connected power generation. The sequential control startup process steps of the gas turbine are shown in Figure 2.

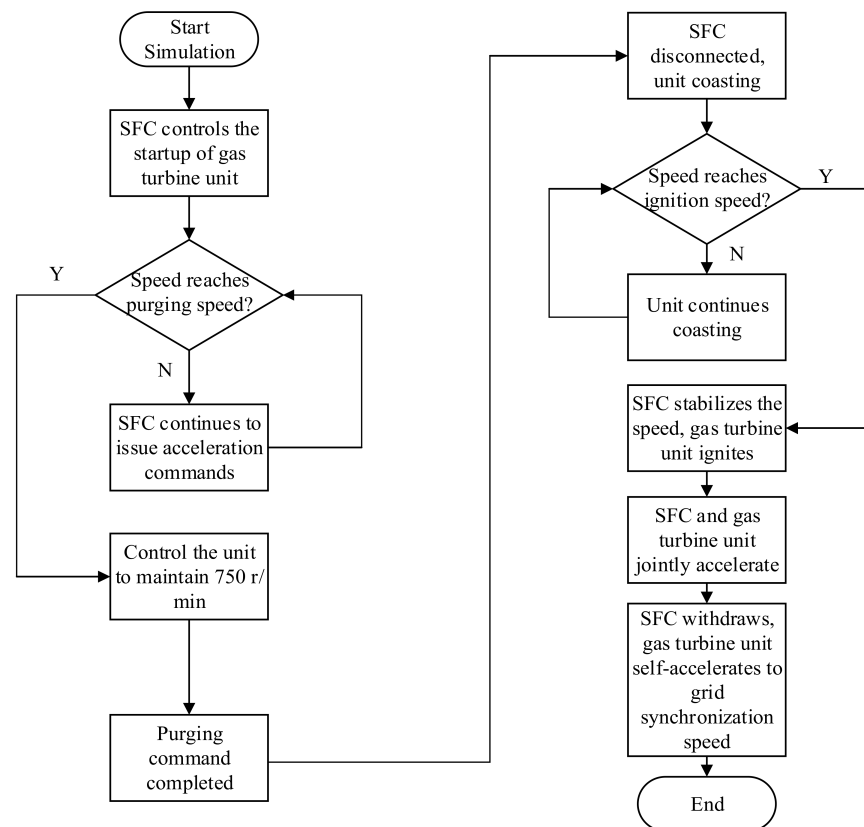


Figure 2. Gas turbine sequential control start-up process.

3.1. Analysis of Electromechanical Coupling Mechanism in the Gas Turbine SFC Startup Process

The core of SFC startup lies in controlling the synchronous generator to operate as a motor via the static frequency converter, driving the rotor above the self-sustaining speed. From the perspective of electromechanical energy conversion, the entire startup process can be divided into the following three stages with significant physical differences:

1. Independent SFC Driving Stage

During the independent SFC driving stage, the gas turbine has not yet ignited, the turbine yields no mechanical output, and the system's power source relies entirely on the electromagnetic torque T_e output by the SFC. This torque must overcome the substantial compressor load torque T_c and the system's friction loss torque T_{loss} . At this point, the SFC primarily adopts a constant voltage-to-frequency (V/f) control strategy to ensure constant excitation magnetic flux at low frequencies, averting stator current overloads.

2. Joint Driving Stage of SFC and Gas Turbine

Once the speed reaches the ignition threshold and purging is complete, the combustor ignites, and the turbine begins generating forward mechanical torque T_t . The system then enters a dual-source drive mode where T_e and T_t act jointly on the shafting. This phase represents the period of most intense electromechanical coupling. The SFC's control objective shifts from simply overcoming the load to synergistically controlling alongside the gas turbine's thermal system to precisely track the preset speed command curve. As the speed increases, the SFC's control strategy must smoothly transition from low-frequency forced commutation to load commutation dependent on the motor's back electromotive force (EMF).

3. Gas Turbine Independent Drive Phase

When the speed reaches the tripping speed and the turbine power is sufficient to sustain system operation, the SFC issues a trip command, disconnecting its electrical connection with the generator. The system relies entirely on the gas turbine's own thermal cycle to continue accelerating until it reaches the rated speed and completes the grid connection operation.

3.2. Construction of the Station-Level Startup Model Based on Simulink

The electromagnetic transient model in this paper is established on the Simulink platform using modules from the Simscape Electrical library and several control signal modules. The model consists of the control system, excitation system and electrical circuit for gas turbine startup. The complete startup process of the gas turbine was reproduced from the perspectives of electromagnetic and electromechanical transient phenomena.

To accurately capture the dynamic processes across the aforementioned multiple time scales, this paper constructs a station-level model architecture comprising four core sub-systems in Simulink. This architecture fully leverages Simulink's advantages in handling stiff systems and discrete power electronics events, achieving synchronous solving of microsecond-level electrical transients and second-level mechanical transients.

To enhance the engineering practicability of the simulation model and develop a more complete digital twin architecture, this paper draws on the electrical single-line diagram of an F-class heavy-duty gas turbine power plant under construction, combined with the design concepts proposed in Reference [14], to compile the primary electrical circuit diagram for the model as shown in Figure 3. On this basis, the circuit structure of the simulation model is constructed and parameter tuning is implemented, with all relevant parameters listed in Table 1.

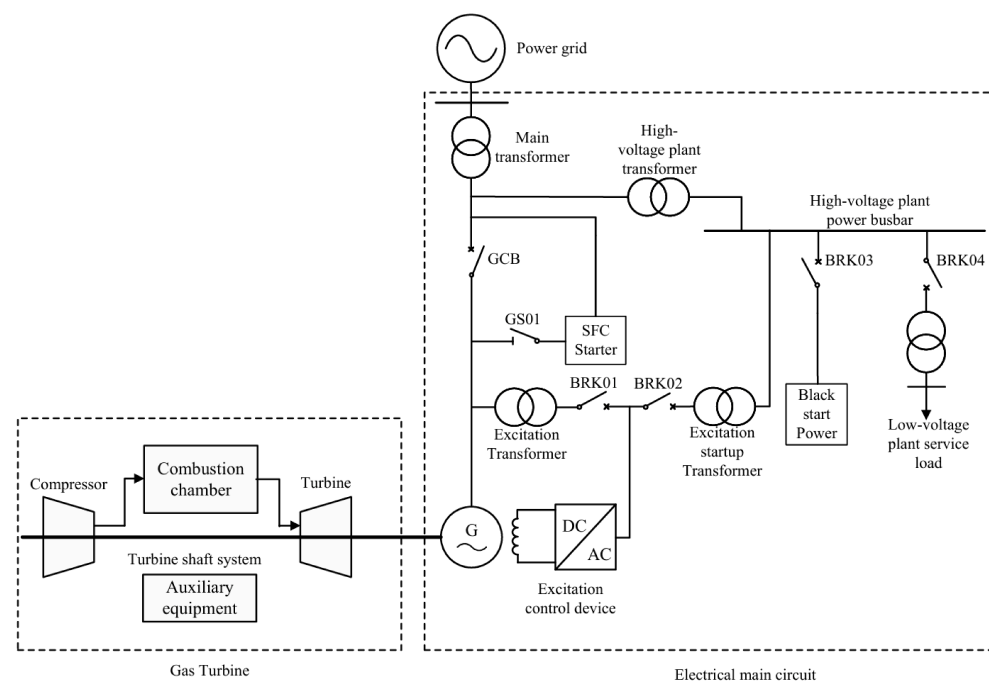


Figure 3. Gas turbine unit starting-up system.

The gas turbine unit startup speed command curve is input into the simulation model as the control target. The model's closed-loop control system (such as the gas turbine speed controller and the SFC current controller) calculates deviations from the target curve in real-time, dynamically adjusting the fuel quantity and SFC output voltage/frequency to track this curve. This dynamic tracking process and the resultant deviations fundamentally

validate the rationality of the command curve. The gas turbine startup speed command curve is shown in Figure 4.

Table 1. Parameters of gas turbine unit starting-up system.

Parameters	Value	Parameters	Value
Power grid voltage level/(kV)	242	High Factory Transformer Rated Transformation Ratio/(kV)	20/10.5
Main transformer rated transformation ratio/(kV)	20/242	capacity of high-voltage transformers/(MVA)	20
Main transformer capacity/(MVA)	400	high-voltage transformers short-circuit reactance percentage/(%)	0.08
Generator rated voltage/(kV)	20	Rated transformation ratio of the excitation transformer/(kV)	20/0.64
SFC starter capacity/(MVA)	10	Excitation transformer capacity/(MVA)	4
Capacity of F-class gas turbine/(MW)	300	Rated transformation ratio of the excitation transformer/(kV)	10.5/0.64
Axial system no-load torque/(p.u.)	0.03	Capacity of the excitation transformer/(MVA)	4
Axial system rotational inertia/(kg·m ²)	27,356	Percentage of short-circuit reactance of the excitation transformer/(%)	0.08
Rated voltage of diesel generator (black start)/(kV)	10		

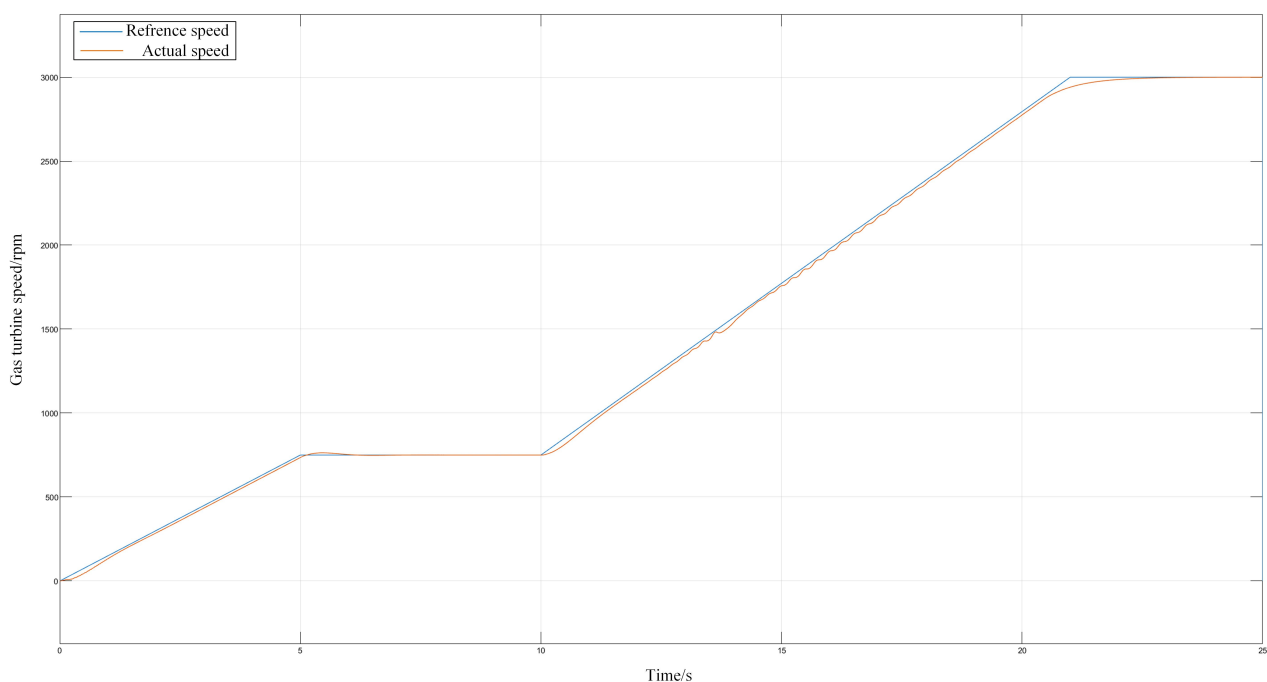


Figure 4. Gas turbine starting speed command curve.

3.3. Synergistic Mechanism Between Shafting Dynamics and SFC Control Strategy

The shafting dynamic equations act as the physical nexus linking the four aforementioned sub-models. They must simulate the gas turbine startup process from standstill to grid-connected power generation. During this process, the power supply of the rotor system will undergo a fundamental change. Specifically, it precisely simulates the dynamic, smooth transition and switching processes among three modes: independent SFC starter driving, joint SFC and gas turbine driving, and independent gas turbine driving.

During the transition process, the fundamental equation of the entire shafting dynamics is established first:

$$J \frac{d\omega}{dt} = \sum T_{\text{drive}} - \sum T_{\text{load}} - T_{\text{loss}} \quad (1)$$

where, J is the total equivalent moment of inertia for the gas turbine, generator rotor, and SFC rotating components; ω is the mechanical angular velocity of the rotor (proportional to the rotational speed n); T_{drive} , T_{load} , and T_{loss} are the driving, load, and loss (friction and windage) torques, respectively.

The gas turbine has not yet ignited, the turbine produces no output, and the SFC acts as a variable frequency power source driving the synchronous machine to operate in motor mode. Thus, the dynamic equation is:

$$J \frac{d\omega}{dt} = T_{\text{SFC}}(\omega, I_{\text{SFC}}, I_{\text{field}}) - T_{\text{Comp}}(\omega) - T_{\text{loss}} \quad (2)$$

where, T_{SFC} is the electromagnetic torque generated by the SFC starter through the motor, functioning as a complex function of the SFC output current I_{SFC} , frequency, and generator excitation current I_{field} , calculated via the d-q axis model of the motor. T_{Comp} is the compressor load torque, and it is the primary load during the gas turbine startup process; its magnitude is approximately proportional to the square of the speed ω , characterizing it as a strong, non-linear time-varying load.

To overcome the massive T_{Comp} and T_{loss} , the rotor must be accelerated from barring speed to above the ignition speed. At that point, the simulation model triggers the ignition command.

Following successful gas turbine ignition, the combustor initiates operation, and the turbine begins producing power. At this point, the SFC remains active, jointly driving the rotor alongside the turbine. Thus, the dynamic equation is:

$$J \frac{d\omega}{dt} = [T_{\text{Turb}}(\omega, F_{\text{fuel}}, T_{\text{exh}}) + T_{\text{SFC}}] - T_{\text{Comp}} - T_{\text{loss}} \quad (3)$$

where, T_{Turb} is the turbine output torque, and it is a function of the speed ω , fuel flow rate F_{fuel} , and the thermodynamic state of the combustor/turbine, typically obtained via gas turbine thermodynamic cycle models or characteristic curves. Once the speed reaches the tripping speed and the system stabilizes, the simulation model triggers the SFC exit command.

The rotor speed has reached or exceeded the self-sustaining speed, and the power generated solely by the turbine is sufficient to overcome the compressor load and losses. The SFC receives the command to exit, mechanically or electrically disconnecting from the rotor. In standard operations, the aforementioned self-sustaining speed and tripping speed can be treated as fixed values. Thus, the dynamic equation is:

$$J \frac{d\omega}{dt} = T_{\text{Turb}} - T_{\text{Comp}} - T_{\text{loss}} \quad (4)$$

where, T_{Comp} is the compressor load torque. It is the main mechanical load during the startup process of the gas turbine. Its magnitude is approximately proportional to the square of the rotational speed ω , mathematically formulated as:

$$T_{\text{comp}} = GJ_p\omega^2 \quad (5)$$

where G represents the aerodynamic structural constant of the compressor. It is essentially determined by the physical dimensions, the geometric shape of the blades, and the inlet cross-sectional area. J_p represents the dynamic torque coefficient. Its value fluctuates during the startup process in response to changes in the aerodynamic pressure ratio and the density of the surrounding gas. Together, G and J_p characterize the strong nonlinear and time-varying aerodynamic load on the SFC.

To fully elucidate the electromechanical coupling mechanism, the mathematical formulation for the electrical subsystem must be established alongside the mechanical equations. Using the Park transformation (d-q-0 transformation), the fundamental constitutive governing equation for the SFC electromagnetic torque (T_{SFC}) generated by the synchronous motor is expressed as:

$$T_{\text{SFC}} = \frac{3}{2}p[\psi_f i_q + (L_d - L_q)i_d i_q] \quad (6)$$

where, p is the number of pole pairs of the synchronous generator. ψ_f represents the excitation flux linkage. i_d and i_q are the d-axis and q-axis components of the stator current. They are precisely controlled and modulated via pulse-width modulation (e.g., SPWM/SVPWM) strategies by the Voltage-Source Inverter (VSI). L_d and L_q are the d-axis and q-axis synchronous inductances, respectively. This equation provides a crucial mathematical link: it clearly defines how the electrical domain variables (i_d , i_q) dynamically generate the driving torque (T_{SFC}). By inputting this into the mechanical rigid body dynamics equation, a formalization of the steady-state level electromechanical coupling model is achieved. Furthermore, to fully capture the dynamic response of the Voltage-Source Inverter (VSI), the d-q axis stator voltage equations must be defined. These equations describe how the modulated voltages output by the SFC drive the stator currents:

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (7)$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f \quad (8)$$

where, u_d and u_q are the d-axis and q-axis stator voltages directly supplied by the VSI. R_s is the stator winding resistance. ω_e is the electrical angular velocity of the rotor ($\omega_e = p\omega$). Together, Equations (6)–(8) form the complete electrical subsystem model. They demonstrate the strict causal chain of the electromechanical coupling: the VSI generates transient stator currents (i_d , i_q) by synthesizing the terminal voltages (u_d , u_q), thereby creating the precise electromagnetic torque (T_{SFC}) required to overcome the mechanical load during startup.

This Figure 5 depicts the mechanical power curve of the gas turbine. Before ignition ($t < 30$ s), the gas turbine lacks self-starting capability and relies on the static frequency converter (SFC) to drive the synchronous unit. In this phase, the gas turbine operates as a load with negative output mechanical power. The load characteristic is governed by internal gas turbine components including the compressor and turbine, formulated as

$$P_m = T\omega \quad (9)$$

where, P_m denotes the net mechanical shaft power of the gas turbine unit. It is equal to the product of T (the net resultant torque acting on the turbine-compressor shaft) and ω (the rotor angular speed).

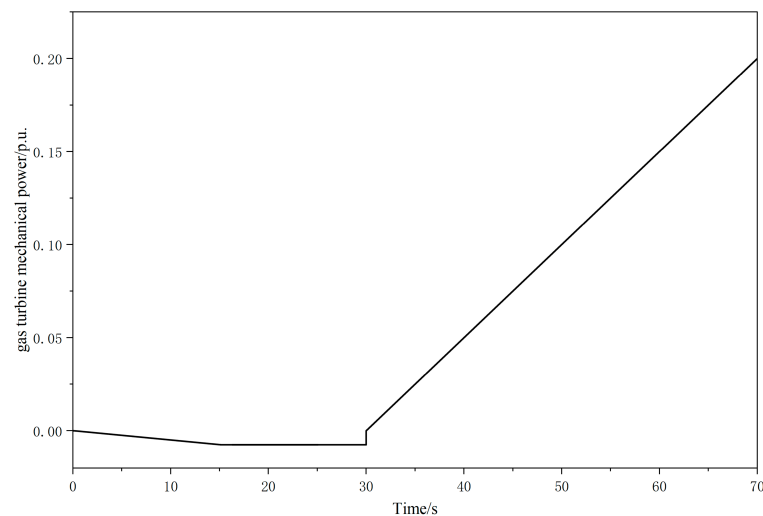


Figure 5. Mechanical Power Output Curve of Gas Turbine.

After 30 s, the gas turbine enters the ignition stage and gains independent speed-up capacity. It delivers mechanical power to the synchronous machine, and the power output rises continuously over time, leading to positive mechanical power in this interval.

To simplify the modeling of the intricate thermodynamic system, segmented linear ramp variations are adopted to approximate the power evolution. This mechanical power curve is fed into the synchronous machine model as an external input to equivalently represent the thermal energy output characteristics of the gas turbine.

Within the Simulink environment of MATLAB 2024a software, the raw data is broadly divided into two segments transmitted to the frontend. Taking the gas turbine startup speed command curve as the control target, and utilizing mechanical switch opening/closing operations or power electronics device switching controls, the typical SOE data generated by the sequential control deduction module during this step are illustrated in Figures 6–9.

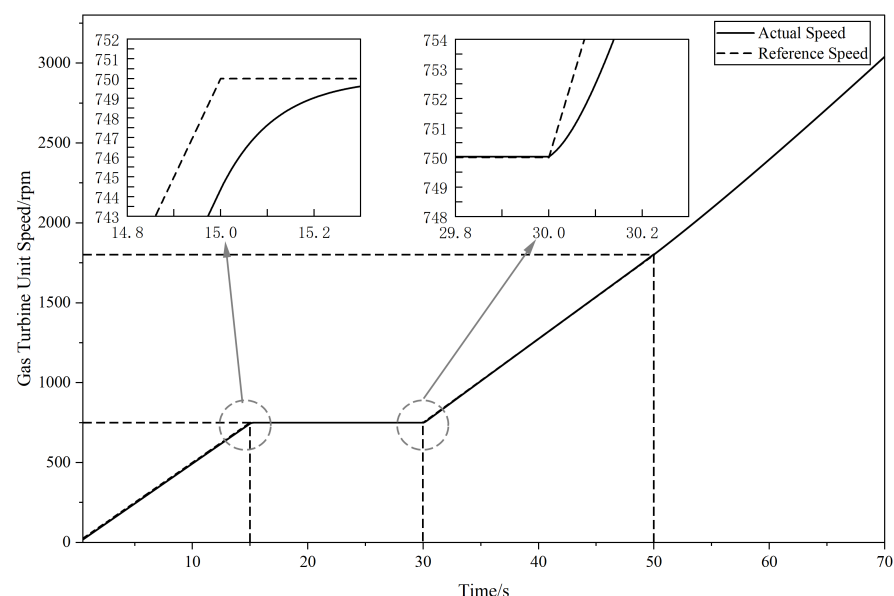


Figure 6. Speed response characteristics of gas turbine during sequential control start-up process.

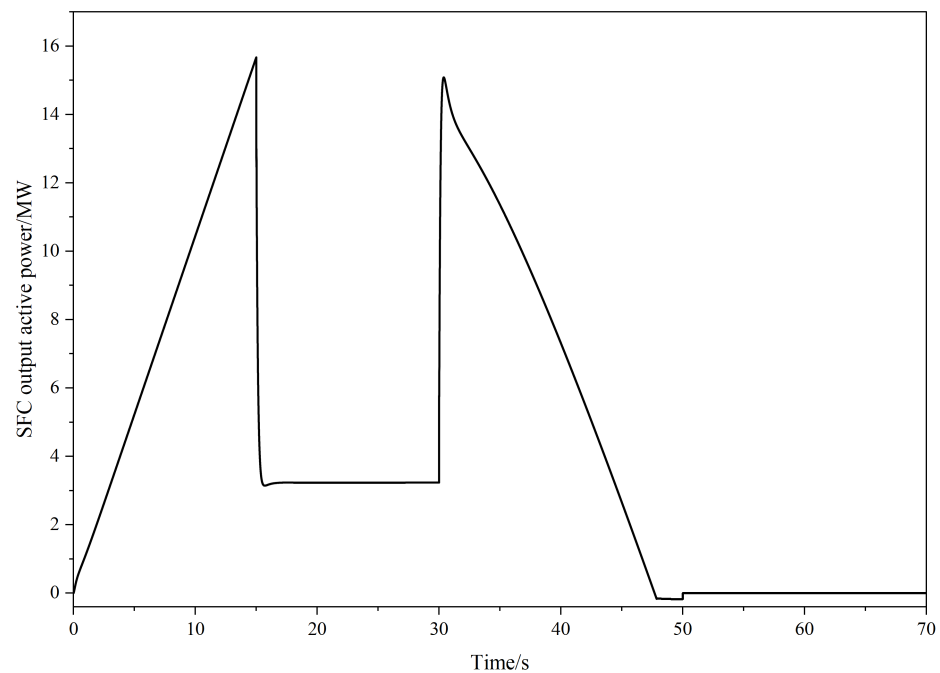


Figure 7. Dynamic characteristics of electromagnetic torque during sequential motor starting.

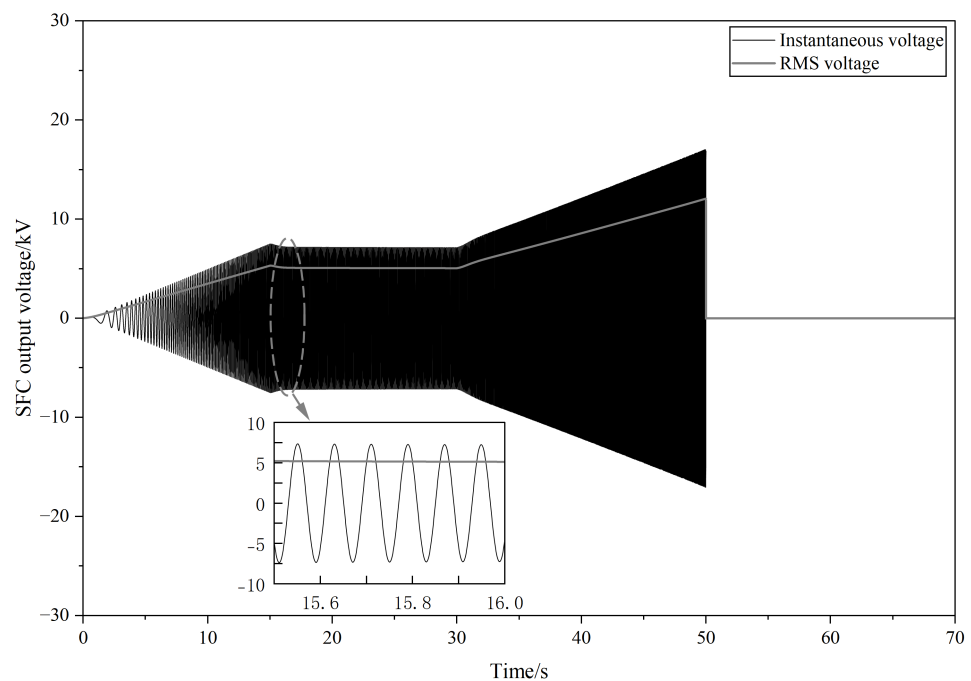


Figure 8. Dynamic characteristics of SFC starter voltage during sequential control starting process.

As can be seen from the electrical circuit design diagram in Figure 1. There are multiple levels of transformer connections between the power grid and the gas turbine. This is to enable the isolation of the devices and provide protection for each device. At the same time, it can also enable each device to operate at its respective rated voltage. However, the connection of multi-stage transformers also led to a voltage sag. Voltage sag refers to the voltage loss caused by the connection of multiple devices. This phenomenon will result in the voltage ultimately input into the gas turbine failing to reach its operating standard voltage. Especially in cases like those involving multi-stage control of gas turbines, voltage sags tend to be more severe than in other equipment. Therefore, in the control structure, we adopted a dual closed-loop structure of speed and current. This structure takes the

SFC voltage as one of the control objects, making the SFC voltage output the voltage in a constant voltage-frequency ratio manner, as shown in Figure 8 above. This strategy enables the voltage to remain within a reasonable range at all stages of the generator's startup process, thereby addressing the issue of voltage sags.

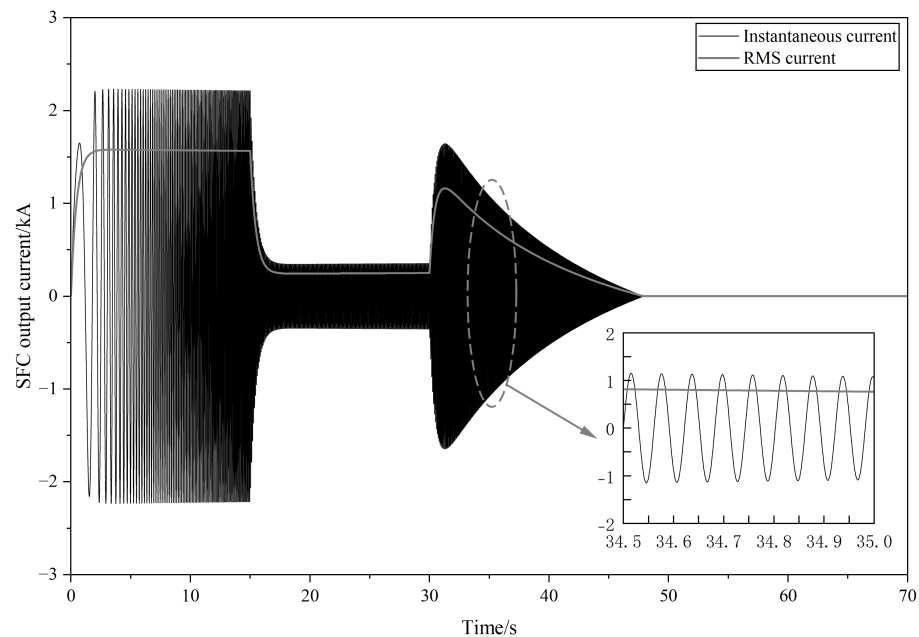


Figure 9. Dynamic characteristics of ideal circuit SFC current during sequential control starting process.

The Figure 10 illustrates the RMS waveform of the SFC output current over the entire gas turbine startup period. Slight oscillations and fluctuations can be observed in the waveform. This result indicates the presence of harmonic components in the waveform. Such distortions stem from the inherent switching characteristics of power electronic devices under control. Fourier decomposition can be utilized to quantitatively analyze these harmonics.

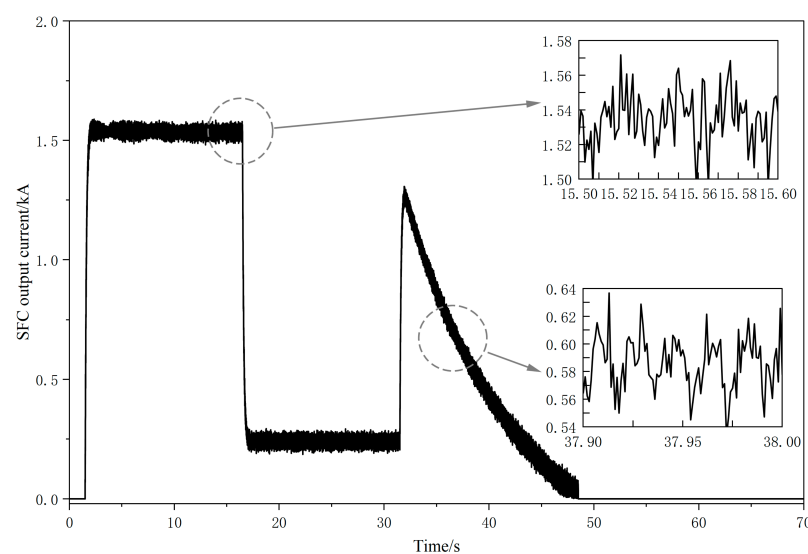


Figure 10. Dynamic characteristics of SFC starter current during sequential control starting process.

The simulation model in this paper aims to accurately reproduce the electromagnetic characteristics throughout the gas turbine startup process. A refined model was constructed

using the built-in modules of Simulink. This model can fully restore the control architecture and circuit topology of the startup loop. The model can truly reflect the actual harmonic characteristics generated during the operation of power electronic devices. In future research, we will further analyze the generation mechanism of harmonics and improve the model to simulate more dynamic characteristics of gas turbine startup.

3.4. Structured Presentation Method of Multimodal Information for the Gas Turbine Digital Twin

Based on the UDP protocol, the data transmission module forwards SOE data from the sequential control deduction platform to the multimodal information structured presentation platform. Employing LabVIEW software, this paper outlines the primary design methodology for the structured presentation platform of the gas turbine digital twin's multimodal data. Concurrently, a structured presentation approach themed around station subsystems is adopted. Specifically, according to the technical elements and functional characteristics encompassed by the digital twin, the gas turbine power plant is divided into four structured themes: the station main wiring sub-page, the motor sub-page, the gas turbine sub-page, and the one-click sequential control deduction and performance evaluation sub-page. This significantly broadens the mirroring scope of the digital twin and bolsters its capacity to support station-level startup strategies and operational schemes.

4. Structured Presentation and Interactive Implementation of Multimodal Information for the Gas Turbine Digital Twin

4.1. Station Electrical Main Wiring Topology and System-Level Dynamic Monitoring

The electrical main wiring serves as the energy transmission skeleton of the gas turbine startup system, and the accuracy of its topological state directly dictates the credibility of the system-level simulation. At the LabVIEW frontend, the platform utilizes standardized electrical symbols to execute a topological replication of the physical station's primary equipment, including the 220 kV grid connection point, main transformer, SFC isolation transformer, excitation transformer, and generator.

The interface actualizes a visual representation of the digital twin's topological and state mapping mechanisms, specifically detailed in Figure 11. Driven by data, discrete devices in the main wiring diagram, such as circuit breakers and disconnect switches, are not merely static icons; rather, they are directly bound to the Boolean logic of the opening and closing operations in the backend Simulink.

4.2. Closed-Loop Configuration of Startup Parameters and Visual Mapping of Sequential Control Flows

Gas turbine startup is a process heavily focused on temporal coupling, where the control strategies at various stages are highly reliant on parameter settings. To realize the digital twinning of parameters between the twin and the physical unit, the platform constructed an interface for startup parameter configuration and sequential control flow monitoring.

As illustrated in Figure 12, the left side of the interface integrates two modules: "Key Startup Parameters" and "Startup Power Supply Settings". The key input parameters module not only encompasses thresholds for stages such as barring, ignition, and self-sustaining, but also supports real-time modification of underlying dynamic parameters like the moment of inertia and startup load characteristic arrays. The power supply settings module offers quick toggle buttons for four typical schemes: ideal power supply, system power supply, diesel generator power supply, and energy storage black start. Any parameter adjustments made by the user on this interface are injected in real-time into the Simulink model variables via the underlying UDP channel. Four-color indicator lights dynamically reflect the unit's health status based on real-time backend computational results, while

the gas turbine SFC startup progress bar at the bottom precisely maps the current startup phase via node signal lights. The right side of the interface synchronously displays the speed ramp curve and the power distribution curves among the compressor, turbine, and load, allowing operators to intuitively evaluate the dynamic balance relationship between SFC output and gas turbine yield across different stages.

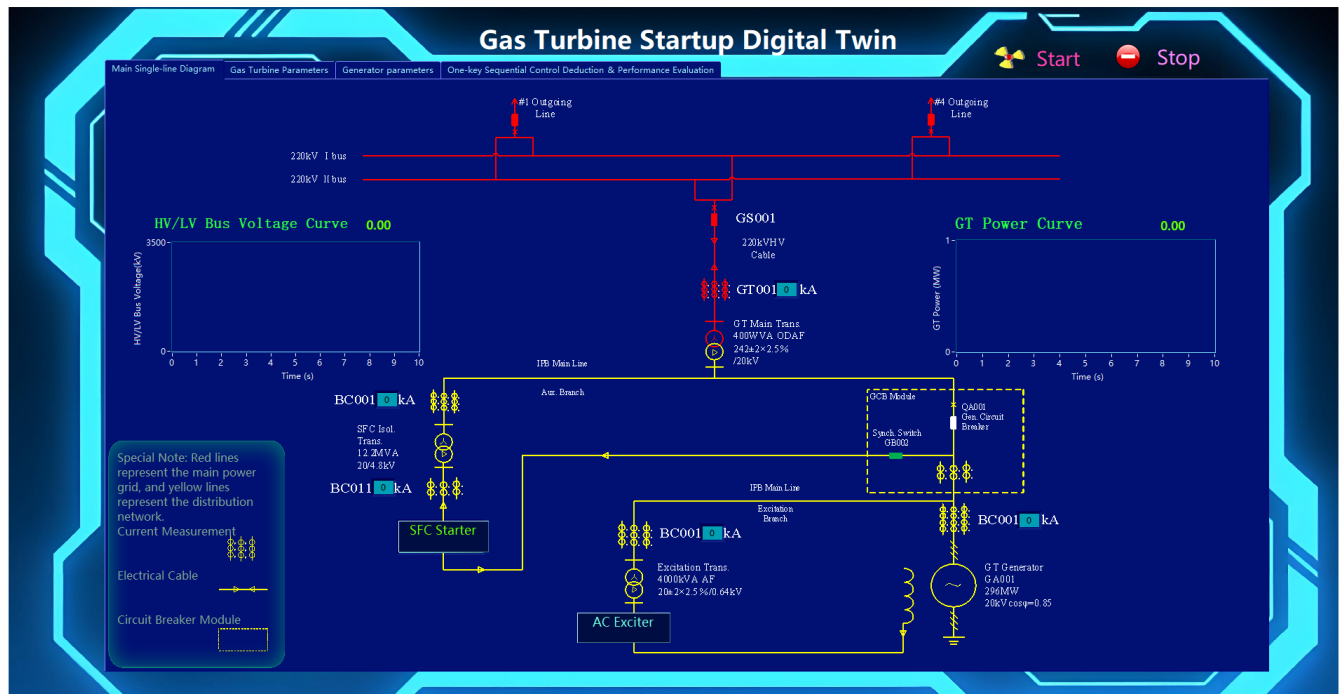


Figure 11. The structured presentation effect of the main wiring theme of the station.



Figure 12. Structured presentation effect of gas turbine theme.

4.3. Multi-Dimensional State Perception of the Unit and Specialized Transient Monitoring of the SFC

At the level of refined equipment management, the platform designs interfaces for real-time unit status and specialized SFC system monitoring, aiming to achieve the digital twinning of the generator's electromechanical transients and the SFC converter's operating conditions.

The left area displays the unit's nameplate parameters while superimposing real-time curves for speed, mechanical torque, and electromagnetic torque in multiple colors, providing a basis for analyzing the electromechanical transient transitions when the motor switches between motoring and generating modes. The central part of the interface embeds an image of the unit facility, supplemented by indicator lights for motor, generation, and grid-connected operating modes, facilitating state perception through both visuals and data. The right area serves as the core of this interface. Specifically targeting the SFC—a critical auxiliary device—the interface extensively monitors the voltage, current, and real-time power on both its DC and AC sides, thereby filling the observational void of the power electronics converter's internal states prevalent in conventional monitoring systems. Furthermore, the bottom of the interface provides configuration ports for high-order electromagnetic parameters, such as the generator's d-q axis reactances and transient time constants, supporting engineering personnel in performing closed-loop calibration of the digital twin model using field short-circuit test data, ensuring simulation errors remain within acceptable engineering boundaries.

4.4. One-Click Sequential Control Deduction and Multi-Dimensional Performance Evaluation

To lower the operational threshold and enhance the efficiency of scheme comparison, the platform developed an overview interface titled “One-Click Sequential Control Deduction and Performance Evaluation” along with its motor sub-page, as shown in Figures 13 and 14, acting as the decision output terminal of the digital twin for end-users.

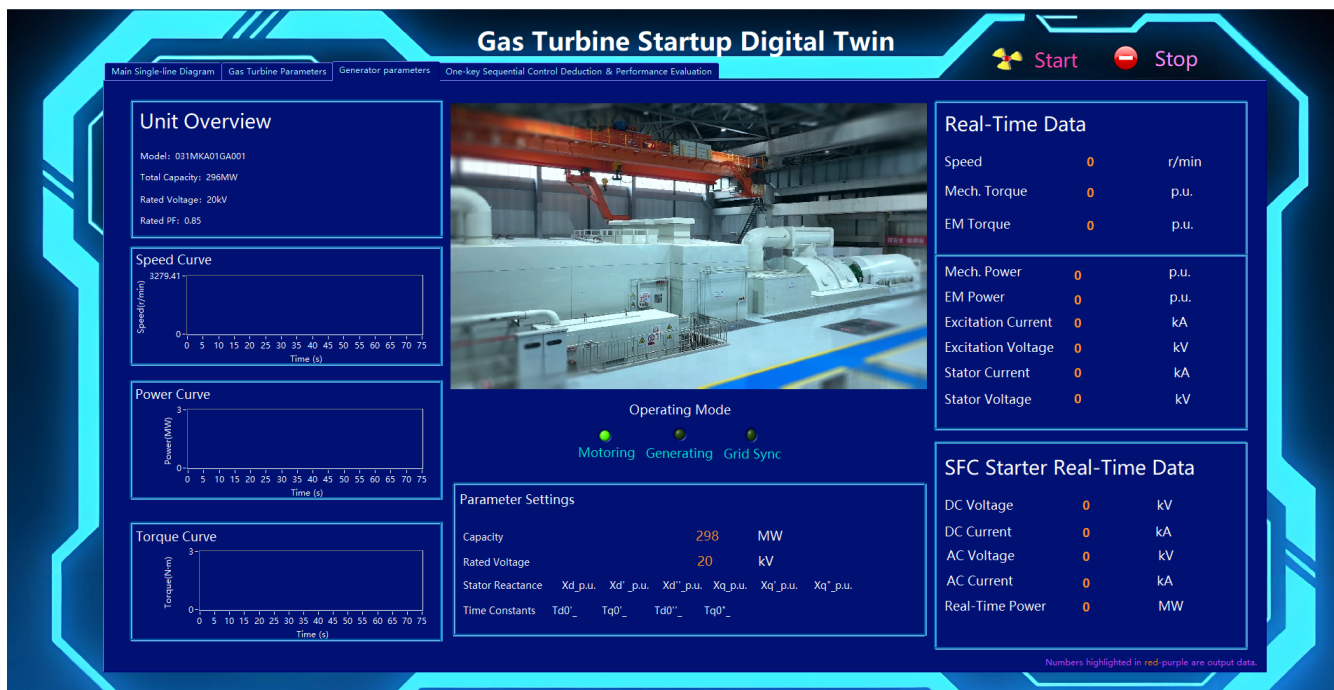


Figure 13. The structured presentation effect of one-click sequential control deduction and performance evaluation theme.

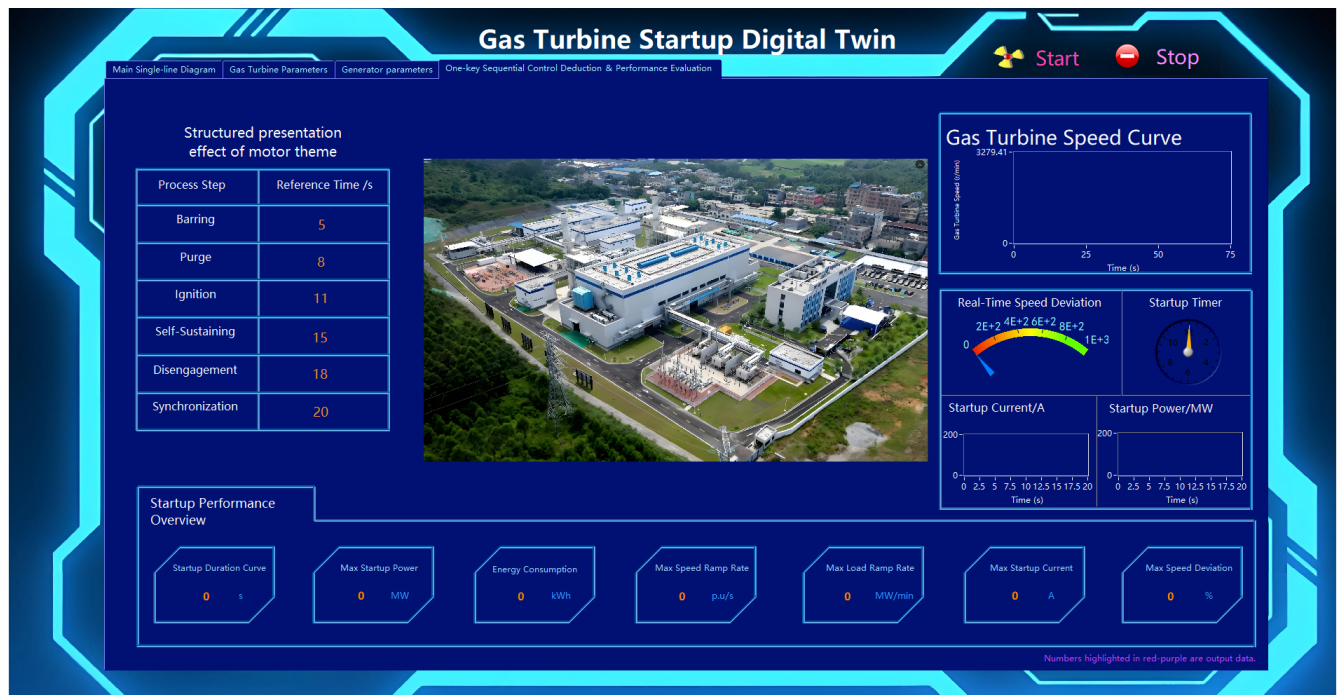


Figure 14. Structured presentation effect of motor theme.

This interface achieves the integration of the startup process from the micro to the macro level. The left area allows users to rapidly configure the reference timing for each sequential control node, generating automated scripts for specific startup strategies. The central area provides a global visual anchor via a bird's-eye view. The right area utilizes a combination of dashboards and trend graphs to dynamically showcase real-time curves of speed deviation, startup timing, startup current, and power. At the bottom, a comprehensive startup performance overview is constructed, wherein post-simulation algorithms automatically extract key performance indicators such as startup duration, maximum startup power, startup energy consumption, and maximum rate of speed increase.

To validate the reliability of the proposed digital twin platform, quantitative evaluations were conducted. In the Simulink modeling environment, the dynamic deviations of various real-time data from their initial input values can be continuously observed. Furthermore, a reference system utilizing an ideal controllable power supply is proposed. This enables the calculation and comparative analysis of operational data between various actual startup power sources and the ideal controllable power supply.

Regarding presentation accuracy, the exact data discrepancy between the backend dynamic speed tracking simulation and the actual frontend digital twin display might be difficult to measure perfectly, largely due to the influence of computer processing and response speeds. Nevertheless, this display error is constrained to be no higher than 2%. In terms of temporal fidelity and communication, the platform achieves a Sequence of Event (SOE) timing precision of 1 millisecond, and the UDP-based transmission layer demonstrates an average latency of less than 5 milliseconds.

5. Conclusions

This paper proposes a layered digital twin architecture and an intelligent sequential control deduction presentation method based on the SFC startup system of gas turbine generators. It facilitates strategy validation, transient characteristic analysis, and performance evaluation regarding the dynamic processes of one-click sequential control startups for gas turbine units. This provides robust decision-making support for design and operational

personnel conducting technical and economic comparative studies on gas turbine startup schemes. Based on the SFC startup characteristics of gas turbines, a sequential control startup analysis method has been proposed. This method provides precise and detailed SOE information as well as the characteristics of the startup indicators changing over time during the unit startup process, helping designers and operators identify the bottleneck constraints that limit the startup performance, thereby improving the startup performance of the gas turbine unit. To resolve the issue of coarse granularity in gas turbine startup transient characteristics, a structured presentation design method for multimodal information is introduced, strengthening the adaptive representation and multi-dimensional presentation capabilities of the digital twin. Simultaneously, by expanding the equipment-level digital twin to a station-level digital twin, the mirroring scope is broadened, bolstering the digital twin's capacity to support the planning, design, and operational phases. And the on-site measured data is crucial for verifying the digital twin. By adjusting the parameters of the digital twin based on the on-site test parameters, consistency can be achieved.

Author Contributions: Conceptualization, Q.Z., J.Y. and X.S.; Methodology, Q.Z., J.Y. and X.S.; Software, J.Y. and X.S.; Validation, J.Y. and X.S.; Formal analysis, Q.Z., Y.L. and X.S.; Investigation, Y.N., Z.Z., X.F. and S.D.; Resources, X.S.; Data curation, Q.Z., Y.L. and X.S.; Writing—original draft, J.Y. and X.S.; Writing—review & editing, Y.L.; Supervision, Y.N., Z.Z., X.F. and S.D.; Project administration, Y.N., Z.Z., X.F. and S.D.; Funding acquisition, Y.N., Z.Z., X.F. and S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shandong Electric Power Engineering Consulting Institute Co., Ltd., grant number: 37-K2024-304.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Yan Nie, Zhende Zhao, Xiao Fan and Siyu De are affiliated with Shandong Electric Power Engineering Consulting Institute Co., Ltd., Jinan, China. The remaining authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that this study was funded by Shandong Electric Power Engineering Consulting Institute Co., Ltd. (Project No.: 37-K2024-304). The funder was involved in the design of the study and collection of data.

References

1. Xie, F.; Wang, J.; Zhou, Y. Independent Research on Key Maintenance Technologies of Hot Passage Components of F-class Gas Turbines under the Background of “Carbon Peaking and Carbon Neutrality”. *Shanxi Electr. Power* **2022**, *6*, 32–35. (In Chinese) [[CrossRef](#)]
2. Chen, Z. Discussion on starting characteristics of SFC in gas turbine power plant. *Shanghai Medium Large Electr. Mach.* **2021**, *3*, 23–26. (In Chinese)
3. Xu, X.; Mao, J.; Shen, Y. Discussion on starting characteristics of SFC in gas turbine power plant. *South. Energy Constr.* **2023**, *10*, 92–100. (In Chinese) [[CrossRef](#)]
4. Wei, J. Scheme and Technical Analysis of Black-Start of Class 9F Gas Turbine Under Different Support Power Sources. *Electrotech. Electr.* **2024**, *18*, 21–25. (In Chinese)
5. Lan, Z.; Peng, X.; Jiang, F.; Yao, P.; Ji, A. Analysis of Non-characteristic Harmonic Characteristics During the Starting Process of Static Frequency Converter. *Power Syst. Technol.* **2025**, *49*, 2087–2095. (In Chinese) [[CrossRef](#)]
6. Han, C. The Cause Analysis and Solution of Siemens SGT5-4000F Gas Turbine Turning Gear Failed Start. *Mod. Manuf. Technol. Equip.* **2020**, *56*, 147–148+154. (In Chinese) [[CrossRef](#)]
7. Niu, L.; Liu, X.; Hong, H. Exploration on characteristics of variable frequency starting-up procedure of gas turbine generators in IGCC power plant. *Mod. Electron. Tech.* **2012**, *35*, 188–191. (In Chinese)
8. Wang, F.; Jiang, J. A novel static frequency converter based on multilevel cascaded H-bridge used for the startup of synchronous motor in pumped-storage power station. *Energy Convers. Manag.* **2011**, *52*, 2085–2091. [[CrossRef](#)]
9. Gong, Z.; Zhang, W. Failure Analysis and Treatment of SFC in the Startup Process of Gas Turbine. *Electr. Eng.* **2020**, *18*, 60–62. (In Chinese) [[CrossRef](#)]

10. Xia, K.; Sun, Y.; Zhang, F. Application of microtremor technology on integrated damage detection of ancient Pagoda structures. *Chin. J. Appl. Mech.* **2016**, *33*, 55–60+180. (In Chinese)
11. Yin, Y.; Sun, G.; Wu, P.; Yan, Y.; Song, T.; Luo, Y.; Qiu, Z. Application of frequency modulation technology in black start system of gas turbine assisted by super capacitor energy storage. *Therm. Power Gener.* **2024**, *53*, 31–37. (In Chinese)
12. Dušan, S.; Jurij, A. Exergy-economic modelling of the integration of two black start diesel engines into the combined cycle gas turbine for rapid-cold start-up. *Appl. Therm. Eng.* **2023**, *227*, 120418. [[CrossRef](#)]
13. Shen, C.; Cao, Q.; Jia, M.; Chen, Y.; Huang, S. Concepts, Characteristics and Prospects of Application of Digital Twin in Power System. *Proc. CSEE* **2022**, *42*, 487–499. (In Chinese)
14. Wang, Y. Design and application of variable frequency starting circuit for heavy duty gas turbine. *Electr. Eng.* **2024**, *25*, 67–72.
15. Hu, K.; Zhang, J.; Zhang, T.; Gao, L. Harmonic Analysis of H Class Gas Turbine Generator Starting with Static Frequency Converter Based on Matlab/Simulink Simulation. *Power Gener. Technol.* **2020**, *41*, 697–705. [[CrossRef](#)]
16. Wang, Y.; Shi, Y.; Sun, G.; Zeng, Q.; Gao, Y.; Zhang, N. Research on Vector Control Method of Permanent Magnet Synchronous Motor Based on SVPWM. *Micromotors* **2024**, *57*, 14–21.
17. Hu, J.; Shi, C.; Wang, X.; Yang, H.; Ji, X. Control Strategy of SFC System for New Generation 9F Gas Turbine. *Large Electr. Mach. Hydraul. Turbine* **2022**, *4*, 89–95.
18. Liu, J.; Wang, Y. *Power Electronics*, 6th ed.; China Machine Press: Beijing, China, 2022.
19. Chen, D. Research on Frequency Conversion Start-Up Technology of Large Capacity Gas Turbine Generator Set. Master's Thesis, Shanghai Dianji University, Shanghai, China, 2020.
20. Farhat, H.; Altarawneh, A. Physics-Informed Machine Learning for Intelligent Gas Turbine Digital Twins: A Review. *Energies* **2025**, *18*, 5523. [[CrossRef](#)]
21. Lim, J.T.; Habibullah, A.; Ng, E.Y.K. Towards a Digital Twin for Gas Turbines: Thermodynamic Modeling, Critical Parameter Estimation, and Performance Optimization Using PINN and PSO. *Energies* **2025**, *18*, 3721. [[CrossRef](#)]
22. Li, Z.; Xiao, H.; Wang, B.; Dong, X.; Shen, L.; Di, X.; Du, X. Design and Implementation of an Immersive Web-Based Digital Twin Steam Turbine System for Industrial Training. *Information* **2024**, *15*, 800. [[CrossRef](#)]
23. Xu, T.; Zhang, X.; Sun, W. Intelligent Fault Warning Method for Wind Turbine Gear Transmission System Driven by Digital Twin and Multi-Source Data Fusion. *Appl. Sci.* **2025**, *15*, 8655. [[CrossRef](#)]
24. Pacheco-Blazquez, R.; Garcia-Espinosa, J.; Di Capua, D.; Pastor Sanchez, A. A Digital Twin for Assessing the Remaining Useful Life of Offshore Wind Turbine Structures. *J. Mar. Sci. Eng.* **2024**, *12*, 573. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.