Design and Simulation Validation of Steam Power Systems Based on MBSE

Ruirui Zeng[1] Hui Gao[1] Jian Liu[2] Xingjian Han[2] Wei Liu[1]
Lei Huang[1] Qi Liu[1]
[1]Suzhou Tongyuan Software&Control Tech. Co. Ltd,
Suzhou,China,{zengrr, gaohui, liuw, huangl, liuq}@tongyuan.cc
[2]China Electronic Product Reliability and Environmental Testing Research Institute(The fifth electronic research institute of MIIT)
Guangzhou, China, {liujian,hanxingjian}@ceprei.com

Abstract

Steam power systems, as one of the critical power systems in industrial applications, require rigorous design and verification processes. Model-Based Systems Engineering (MBSE) provides a structured approach to decomposing system architecture from top to bottom and enabling multi-disciplinary collaborative design, ensuring precise requirement management and efficient design processes. To accelerate the iterative design and verification of steam power systems, this paper employs the SysML language to conduct requirement, functional, structural, and parametric analyses, thereby completing the system architecture design. The seamless transformation from system design architecture to system simulation architecture is achieved based on the SysML-to-Modelica tool. Additionally, Modelica simulation technology is utilized to construct simulation models and perform dynamic scenario analyses of the system. Innovatively, this paper proposes a closed-loop technical approach for steam power system design, simulation, and verification, which effectively optimizes system design and improves the efficiency of both design and verification processes.

Keywords: MBSE, Steam Power System, SysML, Modelica

1 Introduction

With the rapid advancement of industrial technology, the complexity of engineering systems has increased dramatically, and traditional systems engineering (TSE) is increasingly showing limitations in addressing the design and verification of complex systems. Meanwhile, the rapid development of information technology centered on modeling has provided new solutions for systems engineering. Driven by requirements and technology, the International Council on Systems Engineering (INCOSE) officially proposed Model-Based Systems Engineering (MBSE) in its Vision 2020 for Systems Engineering in 2007, clarifying the trend of future methodological and technological evolution in systems engineering toward MBSE. As the application of modeling methods in engineering activities, MBSE spans the entire process from top-level conceptual design to physical implementation, relying on interdisciplinary expertise to unify the expression of complex system development methods, thereby promoting interdisciplinary integration and the implementation of large-scale complex systems.

Currently, MBSE is widely applied in the design of complex large systems, particularly in the fields of aeronautics, astronautics, and shipbuilding, where significant achievements have been made. Overseas research institutions have deeply explored the foundational theories and modeling mechanisms of MBSE and conducted application studies. For example, in 2009, the U.S. National Aeronautics and Space Administration (NASA) applied MBSE to evaluate the practicality of new technologies, construct test and evaluation architecture configurations, and develop mission operation concepts[1]. The U.S. Navy has applied MBSE to the configuration management of hardware and software in submarine combat systems, achieving parallel management of internal and external interfaces in the Submarine Warfare Federated Tactical Systems (SWFTS), which includes over 20 projects, 35 subsystems, and 50,000 model elements[2]. In China, the China Shipbuilding Systems Engineering Research Institute, addressing the high complexity and strong integration of ship systems, adopted MBSE methods in the development of shipborne electronic countermeasure systems, successfully resolving design challenges associated with traditional systems engineering[3].

However, despite significant achievements in complex system design, MBSE still faces the following challenges in the specific domain of ship steam power systems: 1) The limitations of traditional systems engineering methods in complex system design, which struggle to effectively address the complexity of multi-disciplinary coupling and requirement management; 2) The potential of MBSE in ship steam power systems has not been fully realized, particularly in the systematic solutions for multi-disciplinary modeling and simulation verification; 3) Existing methods fail to comprehensively cover system performance and reliability assessments during design verification and optimization, leading to long development cycles and high costs.

This paper focuses on ship steam power systems and employs MBSE methods based on SysML and Modelica languages. Using SysML, it establishes models for requirements, functions, architecture, and parameters, completing stakeholder analysis, requirement analysis, functional analysis, structural analysis, and parametric analysis. Modelica is used to build system simulation models to verify system requirement indicators and validate functional logic. This approach integrates forward design processes with bottom-up design and simulation, driving debugging simulation, co-simulation, system verification, and process validation. By exposing design issues early, this method reduces the number of product development iterations, lowers costs, shortens development cycles, and improves the efficiency of complex system design and development. This study provides a systematic solution for the efficient design and verification of ship steam power systems and promotes the application and development of MBSE in complex ship power systems.

2 System design method

2.1 Steam Power System Architecture Design

Steam power systems[4] use thermal energy as the driving force to convert water into high-temperature, high-pressure steam. This steam is then transformed into mechanical energy through turbines and other mechanical components, which drives generators to produce electricity. The system includes functions such as steam generation and transportation, steam condensation, exhaust steam transportation, equipment cooling, equipment lubrication, and steam sealing and extraction. These functions correspond to subsystems such as the steam system, condensate system, exhaust steam system, cooling water system, lubricating oil system, and steam sealing and extraction system. The subsystems interact through thermodynamic equipment. For example, turbines convert high-temperature, high-pressure steam from the steam system into mechanical energy and exhaust steam, which is transported by the exhaust steam system to the condenser. The lubricating oil cooler facilitates heat exchange between the cooling water system and the lubricating oil system, ensuring proper cooling of the lubricating oil. The logical interactions between subsystems in steam power systems are complex, involving a large number of components and design considerations spanning multiple disciplines, including thermodynamics, mechanical design, fluid mechanics, and control systems.

In recent years, traditional document-based methods[5] have shown the following limitations in complex system design: 1) Complex document management, making it difficult to track requirement changes and design iterations; 2) Lack of visualization and structured expression, making it challenging to clearly describe the logical relationships of complex systems; 3) Dispersed design processes, hindering multi-disciplinary collaborative design; 4) Low efficiency in verification and optimization, making it difficult to identify potential issues early, leading to long development cycles and high costs. Due to their lack of flexibility and reusability, traditional document-based design methods are gradually being replaced by model-based systems engineering (MBSE) approaches. Driven by advancements in computer and software technologies, MBSE has been widely applied in system modeling and design. This paper combines SysML language and Modelica simulation technology to achieve design and verification of steam power systems, optimizing system design management. The SysML models were constructed using SysBuilder software developed by Suzhou Tongyuan Soft Control Information Technology Co., Ltd. This tool serves as a system architecture design environment for complex engineering systems, adhering to the SysML specification. By taking user requirements as inputs, SysBuilder employs graphical, structured, and object-oriented methodologies to comprehensively support system development phases, including requirement modeling, functional analysis, architectural design, and verification/validation processes.

The three key elements of MBSE forward design are: modeling tools, modeling languages, and methodology. Among these, methodology, as the core of system architecture design, is the most critical. Based on the traditional MBSE framework (Requirements, Behavior, Structure, Parameters) and combined with the multi - level complex structural characteristics of the steam power system, this paper develops a matrix - based system architecture design method. (as shown in Figure 1). The entire design process is decomposed into three levels: system, subsystem, and equipment, with specific design content divided into four parts: requirements, behavior/function, structure, and parameters.

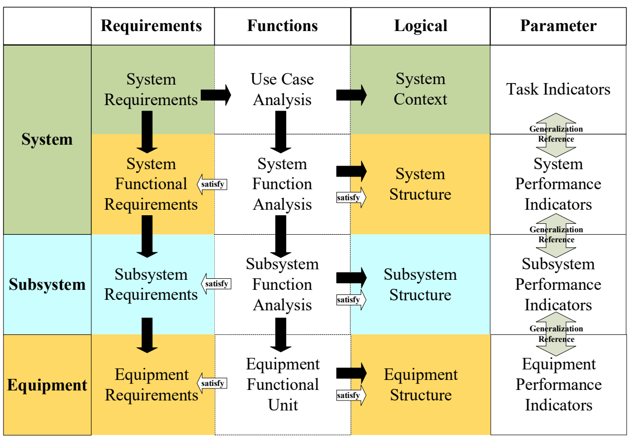

Figure 1. Matrix methodology for steam power system architecture design.

The architecture design of a steam power system starts from the overall requirements articulated by stakeholders

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and can be divided into two parts as inputs to guide the design: one part is functional requirements that describe the system's functionalities, while the other part is non-functional requirements that describe system performance constraints. Functional requirements are translated into the system's external capabilities, states or behaviors, while non-functional requirements are transformed into constrained indicators used for checking and validating system performance. Based on these principles, the functional activities and hierarchical structure of the system level (steam power system), subsystem level (steam system, condensate system, cooling water system, low-pressure steam system, sealing and extraction system, lubrication system) and equipment level (turbine, feedwater pump, condenser, vacuum pump, oil cooler, deaerator, etc.) are analyzed. Requirements are traced throughout the process to ensure that the overall requirements articulated by stakeholders are fully covered, and performance indicators are decomposed and verified through layers of indicators assignment and calculation as design constraints. As shown in Figure 1, black one-way arrows illustrate the process flow of system design, white single-direction arrows represent tracing and verification of requirements, and green two-way arrows represent decomposition and validation of performance indicators.

Based on the steam power system architecture design methodology described above and using the SysML modeling language, this paper models the steam power system using the MWORKS system architecture design software. As shown in Figure 2, this is the logical architecture of the steam power system, which reflects the main components of the steam power system and the logical interactions between them. The differently colored lines represent different object flows.

Further analysis of the system hierarchy architecture, each subsystem and equipment are designed until meeting the requirements of the model granularity. As shown in Figure 5, this is the subsystem architecture of the steam power system, including the cooling water system, lubrication system, low-pressure steam system, sealing and extraction system, steam system, and condensate system. Finally, each equipment and subsystem are simplified and assembled from bottom to top to obtain the overall architecture of the steam power system.

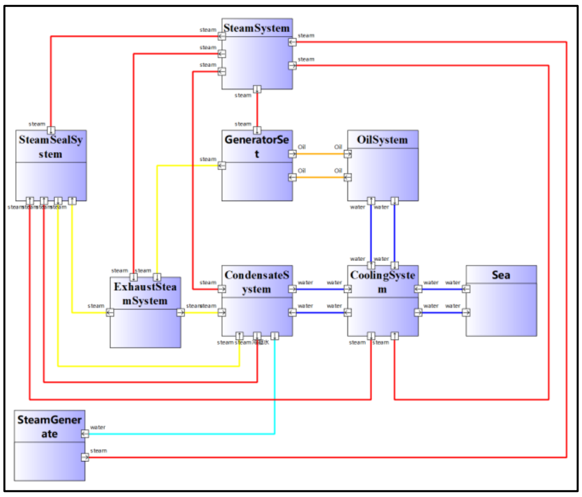


Figure 2. Steam power system architecture

Building upon the steam power system architecture, this study employs the automated SysML-to-Modelica conversion interface within the MWORKS platform to transform architectural models into simulation-ready models. This conversion mechanism operates on the principle of XMI (XML Metadata Interchange)-based model-to-library mapping. Specifically, it parses XMI files generated from SysML to extract critical metadata, including:

- Model organizational hierarchy (XMI, Model, Package)
- Component definitions (ownedAttribute)
- Interface connections (ownedConnector, End)
- Inter-object relational topology

The process extends SysPhs semantics to comprehensively convert parametric constraints, connection dependencies, and governing equations embedded in the design model. Through a GUI-driven workflow, engineers can:

- Select framework templates for physical model encapsulation
- Configure mapping rulesets (type matching, interface binding)
- Generate executable Modelica standalone models or reusable component libraries

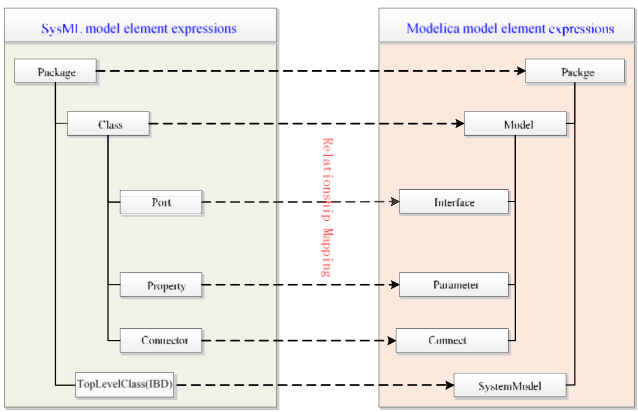


Figure 3 Mapping relationship between SysML model and Modelica model

The platform further provides co-simulation capabilities for iterative debugging and validation of converted models, ensuring behavioral consistency with original architectural specifications[6]. As shown in Figure 4, this is the architecture of the steam power system simulation model.

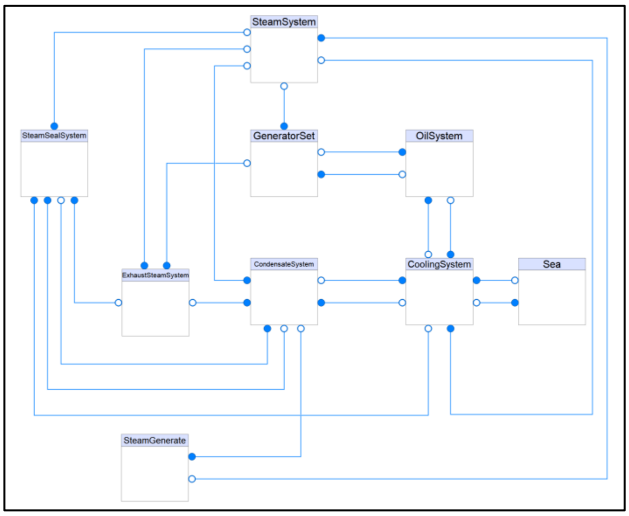
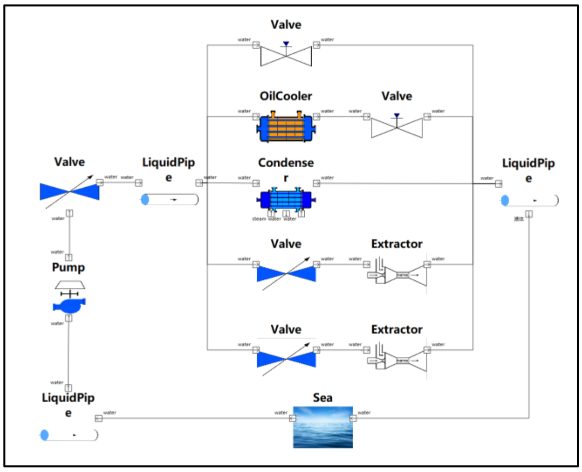
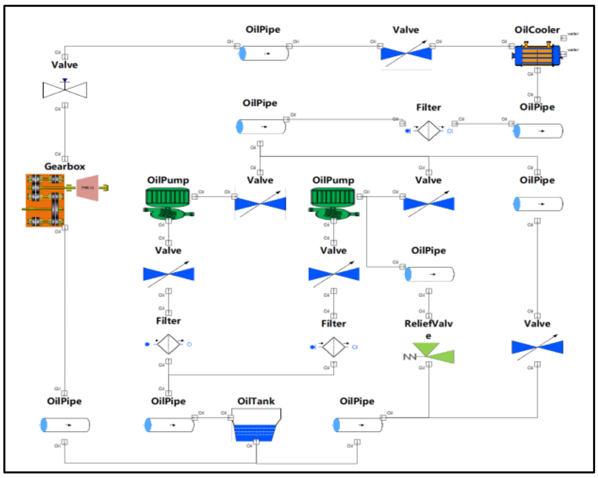


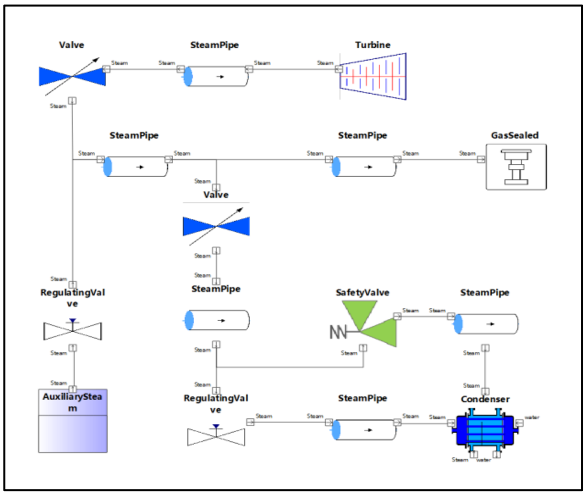
Figure 4 Simulation model architecture for steam power systems



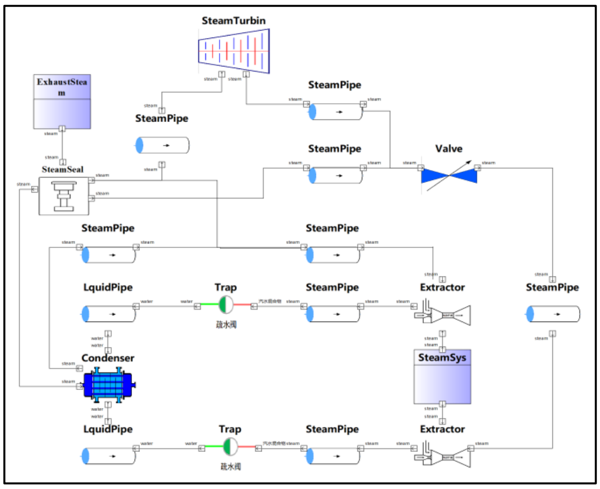
(a) Cooling System



(b) Oil System



(c) Exhaust-Steam System



(d) Steam-Seal System

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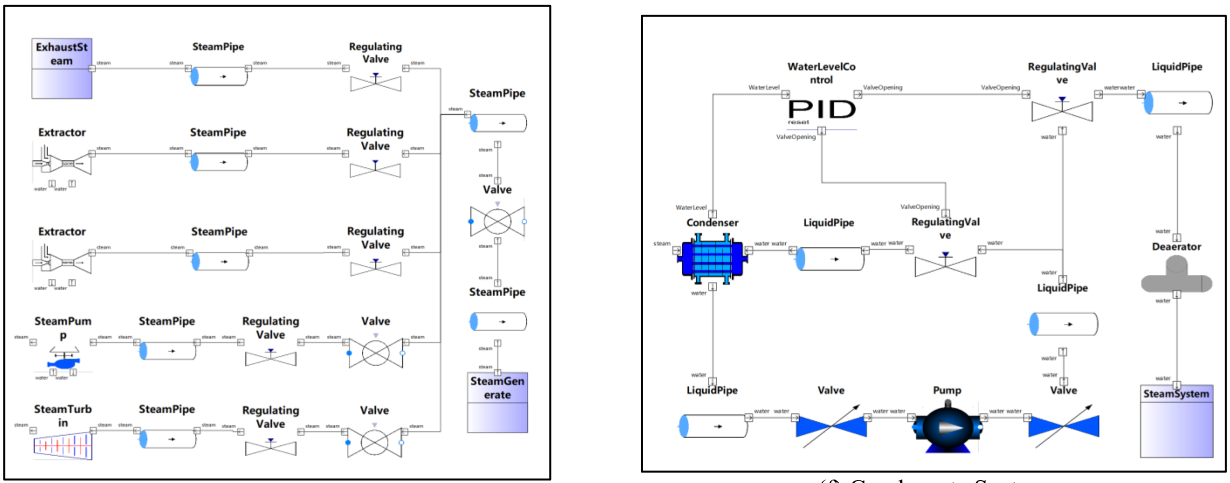

(e) Steam System

(f) Condensate System

Figure 5 Architecture of steam power system subsystem

2.2 Steam Power System Simulation Model Implementation

Modelica is a multi-domain physical system modeling language that uses non-causal and declarative modeling techniques and supports almost all engineering disciplines. The language follows object-oriented programming principles and employs a hierarchical mechanism, component connection mechanism, and inheritance mechanism for model construction, thus simplifying the complexity of the model structure. Unlike Simulink modeling, where mathematical models need to be derived as definite causal relationships with fixed data flow directions, Modelica defines the behavior of variables through equations without artificial division of equation-solving directions. The solver solves unknown variables based on the given conditions. The language models the real physical topology of the system and the component view has a similar structure hierarchy and layout as the real system. Its built-in Modelica standard library includes basic component models in multiple domains, such as mechanical, electrical, hydraulic, thermal, and control, enabling comprehensive performance analysis and evaluation of modern complex engineering systems[7].

Currently, Suzhou Tongyuan Soft-Control Information Technology Co., Ltd. have jointly launched the MWORKS.Sysplorer platform based on the Modelica language for system modeling and simulation. The platform is a modeling and simulation environment for multi-domain industrial products. It fully supports the unified multi-domain modeling standard Modelica. It organizes models hierarchically based on the actual physical topology of products. It also supports various visual modeling methods, including physical, block diagram, and state machine modeling. Sysplorer offers embedded code generation, and supports the integration of design, simulation, and optimization. It is internationally recognized as advanced general-purpose software for system modeling and simulation. For this research, the MWORKS.Sysplorer platform based on the Modelica language is adopted for the construction of the steam system simulation model.

2.2.1 Component Model Construction

Based on the steam power system architecture, a steam power system simulation model library is constructed using the Modelica multi-domain unified modeling specification. The steam power system mainly includes equipment such as steam turbines, condenser, pumps, and valves. Below are the physical principles of some of the main components and equipment models.

a) Steam turbine

The main function of a steam turbine model is to calculate the power output generated by high-temperature and high-pressure steam through expansion. In this article, a mathematical model of the steam turbine is established based on the Rankine cycle formula[8]. The steam flow rate at the outlet of the steam turbine is given by:

$$\frac{G_E}{G_{E0}} = \sqrt{\frac{p_E^2 - p_L^2}{p_{E0}^2 - p_{L0}^2}} \sqrt{\frac{T_{E0}}{T_E}} \quad (1)$$

Steam outlet specific enthalpy:

$$h_L = h_E - \Delta h_i \eta_i \quad (2)$$

Turbine power:

$$P_t = G_E (h_E - h_L) \quad (3)$$

Among them, G_{E0} represents the rated steam flow rate, p_{E0} represents the rated steam inlet pressure, T_{E0} represents the rated steam inlet temperature, p_{L0} represents the rated steam outlet pressure, p_L represents the actual steam outlet pressure.

b) Condenser

The condenser is a common multi-inlet shell and tube heat exchanger in the thermal system. The cooling water flows through the pipe side by the circulating pump, and the steam passes over the outside of the tube in the shell side for condensation and heat release. The heat is transferred to the cooling water through the tube wall, and the lower temperature cooling water keeps the condenser high vacuum through continuous circulation.

Shell side steam mass conservation equation：

$$\frac{dm_g}{dt} = q_{m,in} + \sum q^{OT}_{m,in} + q_{m,HW} - q_{m,p} - q_{m,con} \quad (4)$$

In this equation, m_g represents the steam mass within the condenser, $q_{m,in}$ denotes the steam mass flow rate of exhaust steam from the turbine , $q_{m,HW}$ indicates the steam mass flow rate entering the steam space through the heat well , $q_{m,p}$ is the steam mass flow rate extracted by the extraction steam trap, $q_{m,con}$ refers to the condensate flow rate at the steam space outlet of the condenser.

Shell side steam energy conservation equation:

$$\frac{d(m_g h_g)}{dt} = q_{m,in}h_{in} + \sum (q^{OT}_{m,in} h^{OT}_{in}) - q_{m,p}h_p - q_{m,con}h_{con} \quad (5)$$

Here, h_g denotes the enthalpy of steam in the condenser, h_{in} represents the enthalpy of exhaust steam from the turbine, h_p indicates the extracted steam enthalpy from the extraction steam trap, h_{con} is the enthalpy of condensate at the steam space outlet of the condenser.

Tube side thermal balance equation：

$$Q = KA\Delta T_m = q_{m,W}(h_{W,L} - h_{W,E}) = q_{m,G}(h_G - h_C) \quad (6)$$

Where Q represents condensation heat transfer, K denotes the total heat transfer coefficient , A is the condensation heat transfer area, ΔT_m is the logarithmic mean temperature difference, q_m is the cooling water flow rate, $q_{m,G}$ is the exhaust steam flow rate, $h_{W,E}$ is the specific enthalpy of cooling water at inlet , $h_{W,L}$ is the outlet temperature of cooling water, h_G is the specific enthalpy of exhaust steam and h_C is the specific enthalpy of condensate.

The overall heat transfer coefficient K is calculated as：

$$K = 794 \times 4186 / 3600 \beta \sqrt{v_W} \cdot \sqrt[4]{\frac{T_{W,L} + T_{W,E}}{2} + 17.8} \quad (7)$$

Where β is the fouling coefficient, v_W is the cooling water flow velocity, $T_{W,L}$ is the inlet temperature of cooling water, and $T_{W,E}$ is the outlet temperature of cooling water .

c) Centrifugal pump

The pump model is used to convert mechanical energy into fluid kinetic and potential energy, thereby increasing fluid pressure. Pressure of centrifugal pump:

$$\frac{H}{H_0} = \left(\frac{n}{n_0}\right)^2 \quad (8)$$

Centrifugal pump mass flow rate:

$$\frac{q_{m,z}}{q_{m,0}} = \frac{q_m}{q_{m,0}} \cdot \frac{n_0}{n} \quad (9)$$

Centrifugal pump powe:

$$\frac{q_{m,z}}{q_{m,0}} = \frac{q_m}{q_{m,0}} \cdot \frac{n_0}{n} \quad (10)$$

Centrifugal pump powe:

$$P_p = \frac{\Delta p_p q_{mp}}{\rho \eta_p} \quad (11)$$

$$\Delta p_p = p_L - p_E = H \quad (12)$$

Outlet temperature of centrifugal pump:

$$T_L - T_E = \frac{(1-\eta_0)}{\eta_0} \cdot \frac{H_0}{\rho C_p} \quad (13)$$

Centrifugal pump torque:

$$\tau_p = \frac{30 P_p}{\pi n} \quad (14)$$

Among them, H is the actual pressure head, H_0 is the design point pressure head, q_m is the actual flow rate, q_{m0} is the design point flow rate, q_{mz} is the flow rate converted from the actual flow rate to the design point speed, n is the actual speed, n_0 is the design point speed.

d) Steam regulating valve

Steam control valve is used to control the steam flow rate entering the steam turbine, thereby controlling the output power of the steam turbine[9]. Assuming that the steam flows adiabatically and isoentropically in the valve, only the flow rate produced by the pressure difference between the inlet and outlet is considered. The momentum equation is:

$$q_{m_E} = k_{m_x} k_v \left(1 - 0.367 \frac{X}{X_{cr}}\right) \sqrt{\rho_E p_E X} \quad (15)$$

$$X_{cr} = 1 - \left(\frac{2}{K+1}\right)^{\frac{K}{K-1}} \quad (16)$$

$$k_{mx} = \sqrt{\frac{2KA^2_{max}}{K+1}} \quad (17)$$

q_{m_E} is the steam mass flow, ρ_E is the inlet steam density, p_E is the inlet steam pressure,X is the valve pressure loss ratio, X_{cr} is the critical pressure loss ratio, K is the heat capacity ratio, k_{mx} is the valve characteristic correction coefficient, and A_{max} and is the maximum opening flow area of the valve.

2.2.2 System Model Construction

Based on the general model library of steam power systems, equipment, subsystem, and system models are built from bottom to top according to the system design architecture. Figure 6 shows the sub-system simulation model of the steam power system. The cooling water system includes a lubricating oil temperature control module, and the condensate system includes a condenser water level control module.

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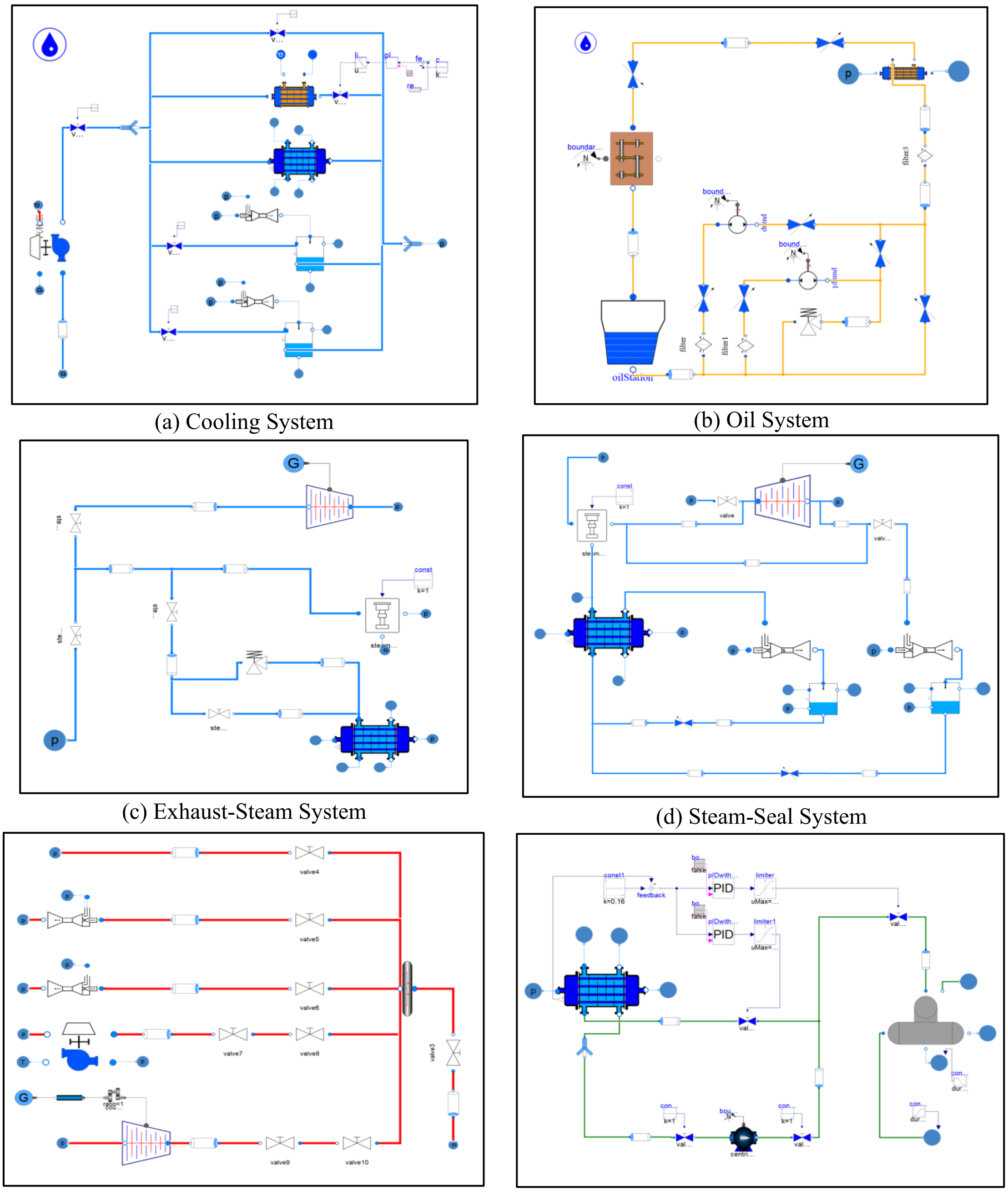

(a) Cooling System (b) Oil System

(c) Exhaust-Steam System (d) Steam-Seal System

(e) Steam Ststem (f) Condensate System

Figure 6 Simulation model of steam power system subsystem

After completing the construction of subsystem simulation models, they are connected according to the interface relationships between the subsystems of the steam power system based on its logical architecture. Finally, the steam power system simulation model is obtained (shown in Figure 7). The steam power system consists of a steam system, condensate system, low-pressure steam system, cooling water system, seal system and lubrication oil system. Its main equipment includes steam turbine, boiler feed pump, condenser, condensate pump, ejector, deaerator, lubricating oil cooler, lubricating oil pump, valves, and pipeline accessories. The control logic in the system includes condenser water level control and lubrication oil temperature control.

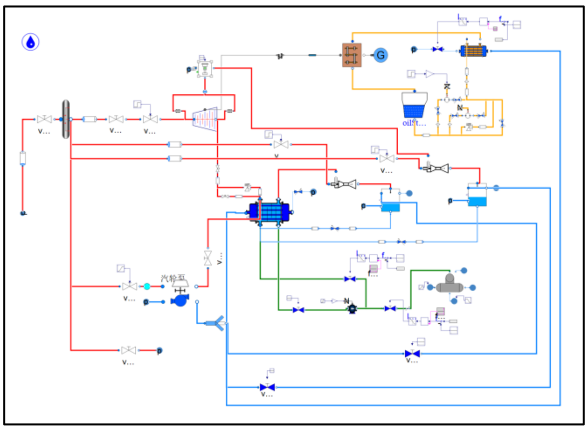

Figure 7 Simulation model of steam power system

3 System dynamic scene analysis and indicator validation

3.1 Dynamic scene analysis

In order to describe the dynamic scene of a steam power system, you can select the functional activity model in SysML language from the steam power system architecture design model library. By defining the dynamic operational scene of the steam power system, an activity diagram can be formed that can be used for simulation and verification. This achieves the integration of system architecture design and simulation verification.

In the activity diagram that describes the dynamic scene of the steam power system, functional activities are used to express the control behavior of the simulation model, such as the "start lubrication pump" functional activity. Based on the programming of the "start lubrication pump" behavior through architecture design software functionality, a design and simulation integrated script is defined, and a joint simulation interface for creating simulation models is established. Through UDP communication, the instruction signals for starting/stopping the "lubrication pump" device in the control simulation model are sent to the system simulation model, thus achieving dynamic verification of the steam power system operating scenario based on the simulation model. Figure 8 shows the activity diagram of the dynamic scene of the steam power system. In the activity diagram, functional activities for the steam power system are defined, including simulation preparation, system backup, start lubrication pump, start cooling water pump, start condensate pump, start air extractor, unit start-up test, lubrication temperature regulation, and test selection. The activities are connected by control flows according to the execution logic of the steam power system (represented by dashed lines with arrows in Figure 8), and the arrows indicate the sequence of activity execution.

Meanwhile, the steam power system simulation model needs to set corresponding control interfaces and

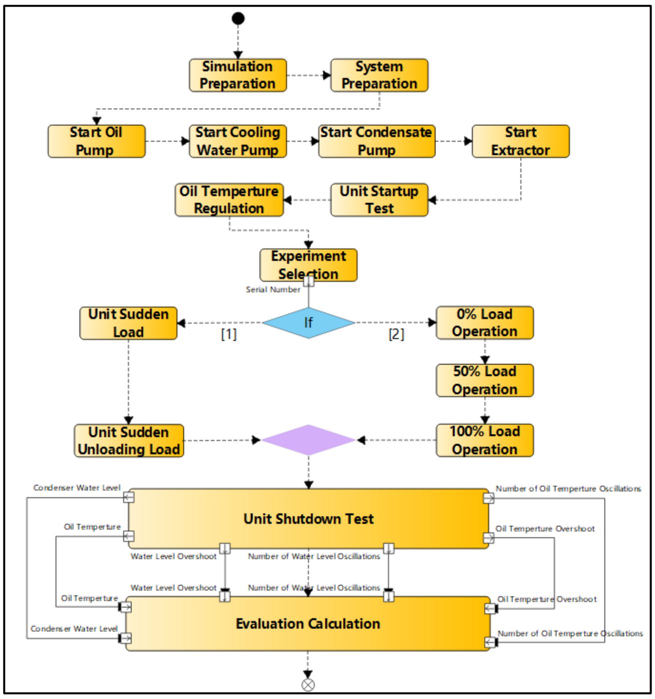

Figure 8 Steam Power System Dynamic Scene Activity Diagram

strategies to meet the evolving activity flow of the system's dynamic scene. Therefore, based on the previously constructed steam power system simulation model, a simulation model control module needs to be further established. The control instructions corresponding to different functional activities and the activity transition conditions are received and sent through the UDP communication component. When the activity diagram starts the simulation, the activity nodes execute according to the control flow of the activity diagram. Different activity nodes send different operation instructions to the simulation model. The simulation model feeds back the calculation results of the key parameters of the model to the activity diagram in real time. After the calculation parameters of the simulation model meet the transfer conditions of the corresponding activity, the activity diagram executes the next activity node. Figure 9 shows the communication component and control module of the system simulation model. The communication component is used to receive the control instructions in the activity diagram and the feedback signals of completed activities. The control module passes the control instructions received by the communication component to the corresponding component or device of the simulation model to achieve a dynamically simulated system based on the activity diagram.

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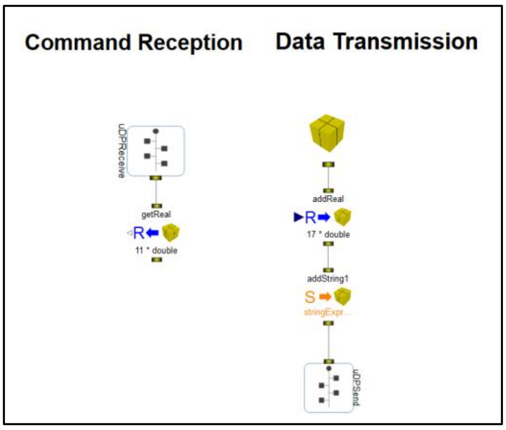
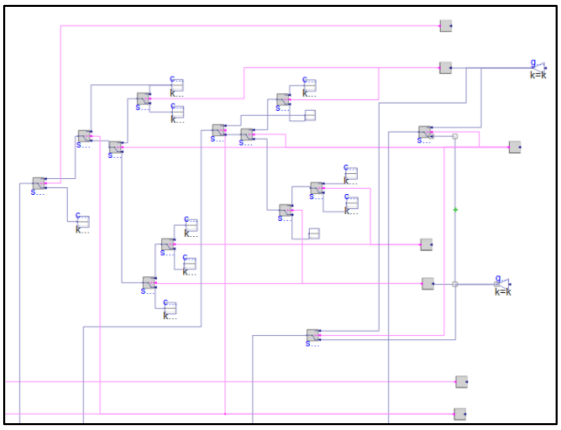


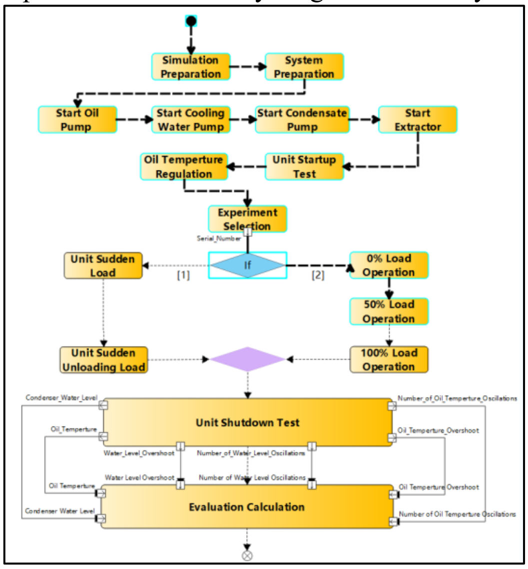
(a) Communication Components



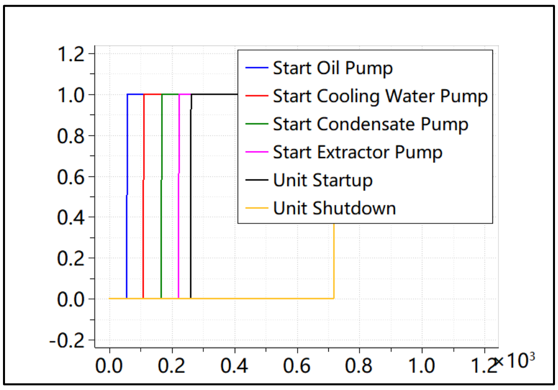
(b) Control Components

Figure 9 Communication component and control module of system simulation model

After debugging the communication and control module of the simulation model according to the execution logic of the system's dynamic scene activity diagram, the simulation calculation of the activity diagram can be performed. Figure 10 shows the schematic diagram of the activity execution status in the joint simulation process of the activity diagram and the system model, and the status of the system model instruction receiving. In the activity diagram, the current activity in the execution state is highlighted by the activity model. At the same time, when the corresponding control instructions are received by the system simulation model, the curve value of the corresponding instruction changes to 1.

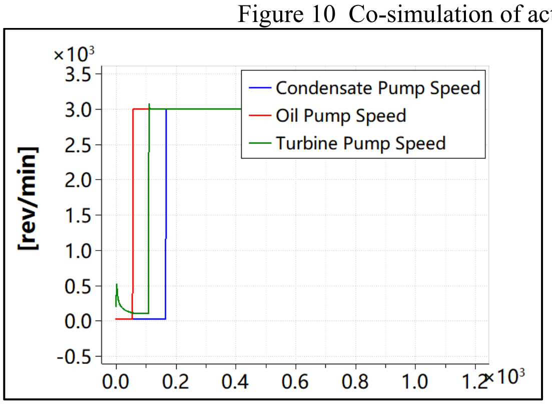


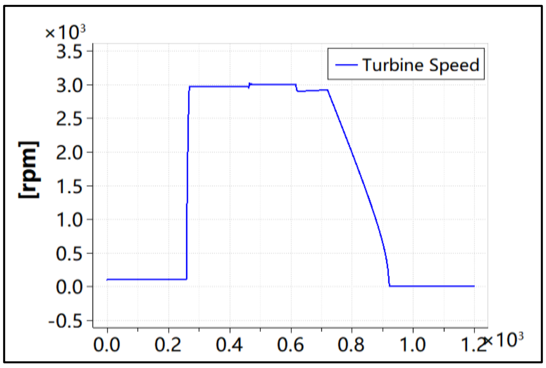
(a) Activity Diagram Simulation



(b) Command Reception

Figure 10 Co-simulation of activity diagram and system model





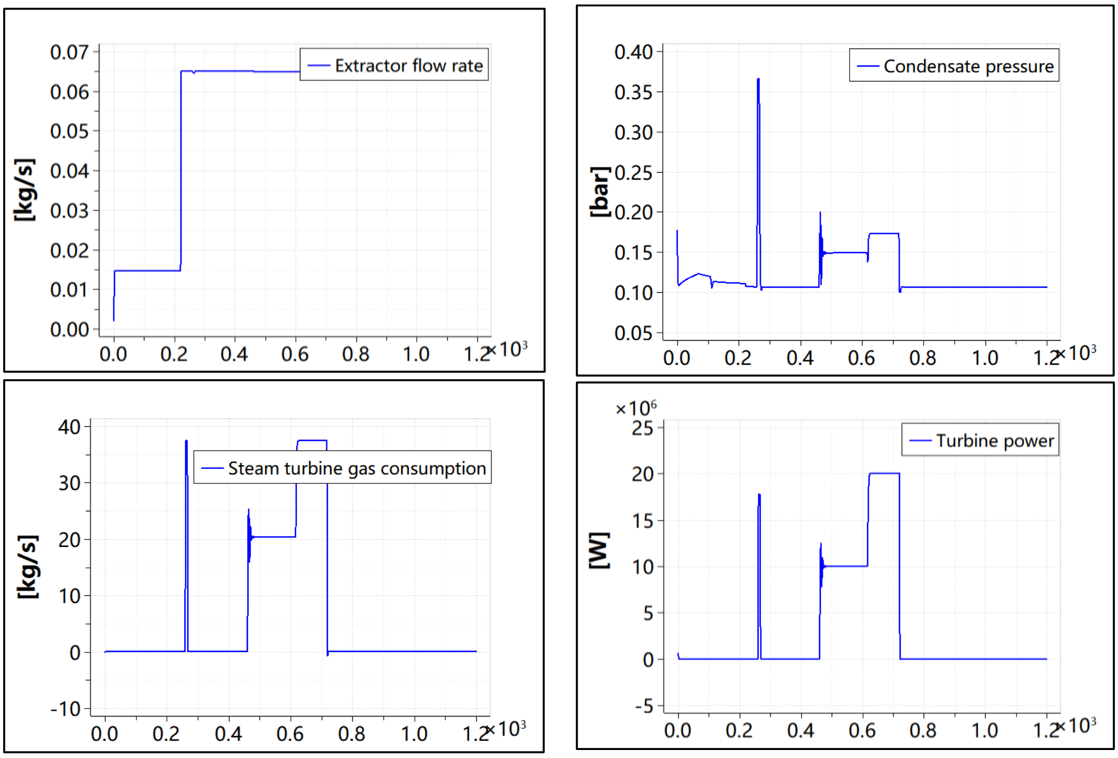


Figure 11 Key equipment parameters of the system simulation mode

Figure 11 shows the critical equipment parameter curves of the system simulation model, which primarily include the "lubricating oil pump speed," "condensate pump speed," "turbine circulation pump speed," "turbine speed," "exhauster extraction flow rate," and "condenser pressure." These curves are analyzed in comparison with the control command changes shown in Figure 10.

When the simulation model's "lubricating oil pump" receives the "start lubricating oil pump" command from the activity diagram, the lubricating oil pump speed rapidly increases to 3000 r/min. Similarly, at approximately 275 seconds, the "turbine unit" receives a "start-up" signal, causing the steam control valve to open and the steam flow to surge instantly. The turbine speed rapidly increases from a low standby speed to 3000 r/min. After the speed stabilizes, the valve is throttled to maintain 3000 r/min. During the start-up phase, the sudden increase in steam flow causes the condenser pressure to rise briefly before quickly decreasing.

At approximately 750 seconds, the "turbine unit" receives a "shut-down" signal, and the steam control valve closes. The steam flow into the condenser drops rapidly, leading to a decrease in condenser pressure. The turbine speed gradually decreases from the rated speed to 0 r/min.

3.2 System indicator validation

In the previous section, the steam power system simulation model executed dynamic calculations in sequence according to the activity diagram scenarios, accurately obtaining dynamic operating parameters for the system and equipment. These state parameters are fed back to the system architecture design software via UDP communication components, enabling comprehensive verification and validation of the system architecture design performance metrics.

This paper uses the verification of performance metrics for condenser water level and lubricating oil temperature control in the steam power system as an example. The steam system imposes strict performance requirements on water level control in the condensate system and lubricating oil temperature control in the lubricating oil system, specifically regarding overshoot and oscillation count. During dynamic operation, these parameters must meet the limits for overshoot and oscillation count. As shown in Figure 12, the overall performance metrics for the control system specify a maximum condenser pressure of 1 bar, with a maximum allowable oscillation count of 5 for water level; for lubricating oil temperature control, the maximum allowable overshoot is 0.3, and the maximum allowable oscillation count is also 5.

需求属性		
参数名称	值	单位
Maximum condenser pressure	1	bar
Maxmum_Number_of_Water_Level_Oscillations	5	1
Maxmum_Oil_Temperture_Overshoot	0.3	1
Maxmum_Number_of_Oil_Temperture_Oscillations	5	1

Figure 12 Control system performance indicators

As shown in Figure 13, the curves represent the computed performance metrics of the simulation model.

Figure 13(a-c) show the lubricating oil temperature variation curve, the oscillation count of lubricating oil temperature, and the overshoot of lubricating oil temperature. The oscillation count refers to the number of times the temperature crosses the target value under control regulation, totaling 2 times, while the overshoot is

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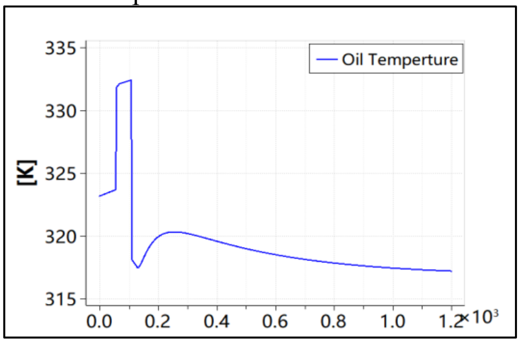
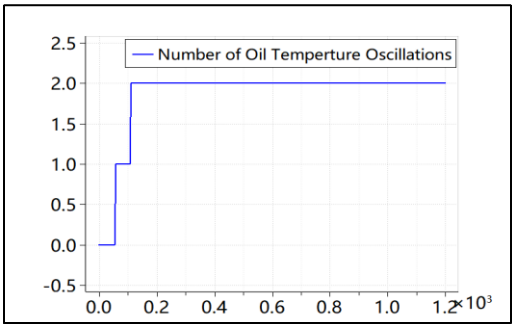
the percentage by which the maximum actual temperature exceeds the target, at 0.054%.

Figure 13(d-f) depict the oscillation count of the condenser water level, the condenser pressure, and the maximum condenser pressure. The oscillation count of the water level is the number of times it crosses the target value under control regulation, totaling 3 times.

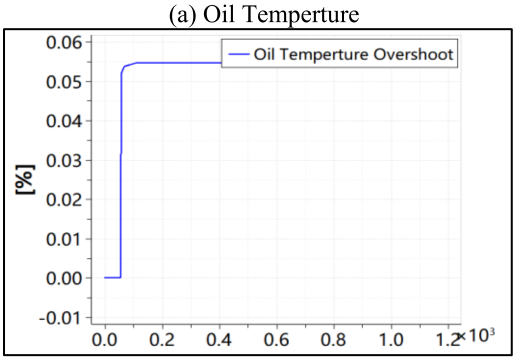
Figure 13(g) shows the state parameters received by the system architecture design software from the simulation model's feedback.



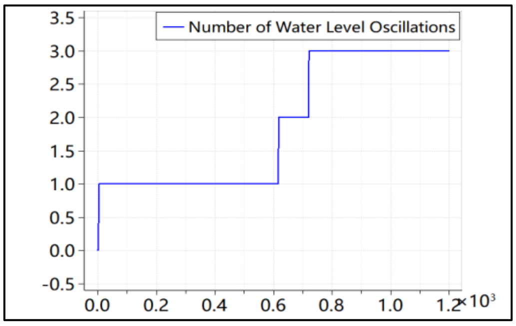
(a) Oil Temperture



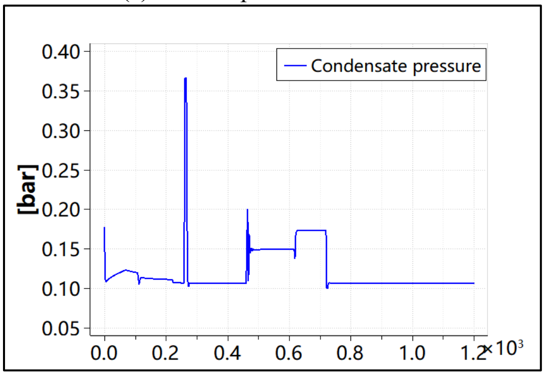
(b) Number of Oil Temperture Oscillations



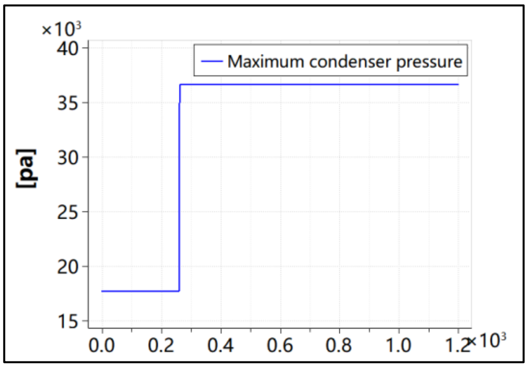
(c) Oil Temperture Overshoot



(d) Number of Water Level Oscillations



(e) Condensate pressure



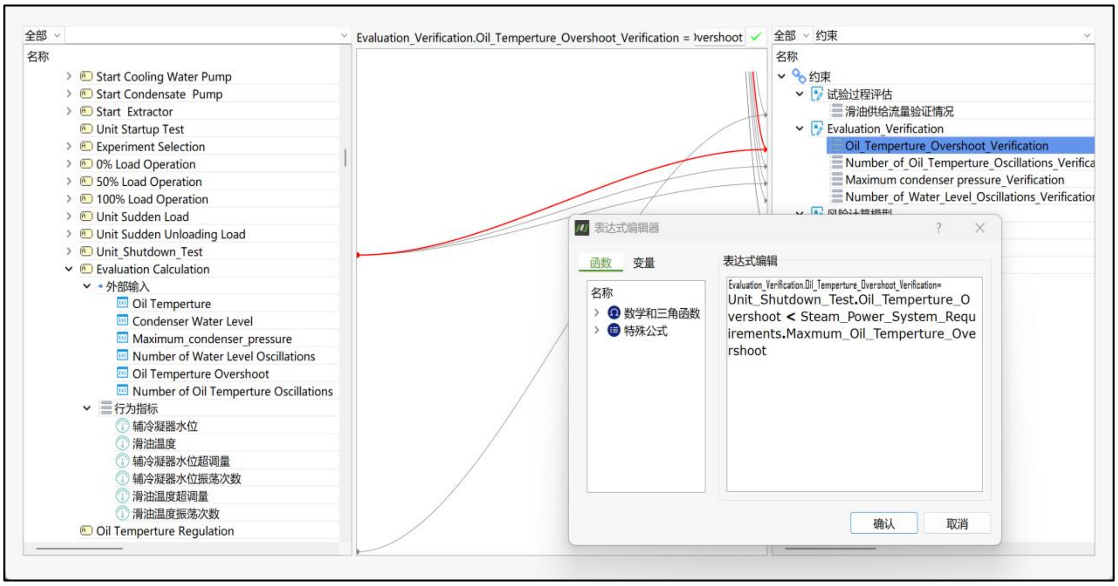
(f) Maximum_condenser_pressure

参数名称	值	单位
Condenser_Water_Level	0.384663	m
Oil_Temperture	313.148	K
Maximum_condenser_pressure	0.3662109	1
Number_of_Water_Level_Oscillations	3	1
Oil_Temperture_Overshoot	0.0551731	1
Number_of_Oil_Temperture_Oscillations	2	1

(g) Fedback Data of Simulation Model

Figure 13 Calculated parameters of the control system

To further validate whether the system performance metrics are met and determine the feasibility of the system architecture design, metric constraints can be established based on the overall performance metrics from the requirements model and the state parameters returned by the simulation calculations. Figure 14 illustrates the performance metric validation process. Figure 14(a) shows the constraint relationship between the performance metrics and the state parameters. Here, the actual maximum overshoot of the lubricating oil temperature is calculated and assigned to the constraint model value property. Figure 14(b) presents the results of all metric constraint validations. A metric constraint value of 1 indicates that the performance metric is satisfied. As shown in the figure, the actual maximum overshoot of the lubricating oil temperature (0.054%) is less than the metric value (30%), the actual oscillation count of the lubricating oil temperature (2 times) is less than the metric value (5 times), the actual maximum pressure of the condenser (0.366 bar) is less than the metric value (1 bar), and the actual oscillation count of the condenser water level (3 times) is less than the metric value (5 times). All performance metrics are thus satisfied.



(a) Constraint Relationship Construction

约束要求			
参数名称	值	约束要求	满足情况
Oil_Temperture_Overshoot_Verification	1	Unit_Shut...	满足
Number_of_Oil_Temperture_Oscillations_Verification	1	Steam_Po...	满足
Maximum condenser pressure_Verification	1	Steam_Po...	满足
Number_of_Water_Level_Oscillations_Verification	1	Steam_Po...	满足

(b) Verification Results

Figure 14 Performance indicator verification

4 Conclusion

Based on the model-based systems engineering approach, this paper has completed the architecture design and system simulation verification of a steam power system, realizing a closed-loop process of design-simulation-verification. The conclusions are as follows:

1) The paper innovatively proposes a closed-loop technical approach integrating steam power system design, simulation, and verification. This approach combines system design with simulation verification, overcoming the limitations of traditional separation and boosting design efficiency. Relying on Modelica's powerful functions for precise modeling and efficient simulation, it quickly identifies design issues, optimizes designs early, reduces iterations, cuts costs, and shortens development cycles, offering a new method for complex system design.

2) Based on the architectural model, this approach enables seamless transformation from system design architecture to system simulation architecture. By applying well-defined mapping rules, it accurately converts elements such as composition, interface, and connection relationships from SysML architectural models to Modelica simulation model architecture. This ensures consistency between design and simulation architectures in terms of interfaces and parameter passing. The process not only integrates design and simulation but also leverages Modelica's power in multi-domain physical system modeling, facilitating a smooth transition from conceptual design to performance verification.

3) Dynamic scenario simulation and verification of the steam power system are done via combined simulation of activity diagrams and system models. Using Modelica simulation technology with SysML-defined dynamic activity diagrams, it achieves precise dynamic simulation of the system's operation. This combined simulation not only reproduces the dynamic process but also provides reliable real-time state parameter feedback for performance metric verification, enhancing the closed-loop system of steam power system design, simulation, and verification.

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