Hybrid Model and Data Driven Fault Diagnosis and Self-Recovery Control of Integrated Energy Systems

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Abstract: In view of the common actuator faults, sensor faults and cyber attacks in the operation of integrated energy systems, this paper proposes a hybrid model and data driven fault diagnosis and self-recovery control method based on model-based fault observer and data-based deep learning technology, so as to improve the safety and reliability of integrated energy systems. This project will establish a fault testing model for a multi-energy complementary integrated energy system, applying the proposed hybrid model and data driven algorithm, researching robust and accurate diagnosis of multi-type complex faults and continuous fault-tolerant operation in integrated energy systems. The research results will provide new insights for the design of robust observers and the study of fault diagnosis and self-recovery control in complex systems.

Keywords: Integrated Energy Systems; Actuator Fault; Sensor Fault; Cyber Attacks; Fault Observer; Deep Learning.

1. Introduction

The advancement of human technology and industrial development has consumed vast amounts of fossil fuels such as coal and oil, leading to the gradual depletion of traditional fossil energy reserves on Earth. The combustion of fossil fuels releases massive emissions that pollute the environment and contribute to global warming. In the face of increasingly severe global energy crises and environmental pollution, the efficient development and utilization of new energy sources have become a crucial pathway for achieving sustainable energy and environmental strategies. Integrated energy systems that effectively harness primary energy sources like wind, solar, natural gas, biomass, and geothermal energy can provide diverse forms of electricity, heat, and cooling. These systems offer advantages such as low costs, high energy efficiency, and reduced emissions. By enabling complementary use of multiple energy sources, integrated systems optimize energy infrastructure structures, decrease traditional fossil fuel consumption, and enhance energy supply reliability—features that have garnered widespread global attention [1,2].

Based on energy transmission modes, integrated energy systems can be categorized into three components: heating networks, cooling networks, and power grids. Heating and cooling functions are achieved through combined heat and power (CHP) systems, which utilize various energy sources including electric water heaters, gas-fired boilers, electric chillers, and absorption chillers. From a control system perspective, all heating boilers and cooling units in CHP systems function as process control objects with characteristics of high inertia and long time scales. These systems require controllers to regulate critical parameters such as temperature, liquid levels, flow rates, and pressure. Actuators like valves and pumps in process control systems endure prolonged exposure to high temperatures, pressures, vibrations, and corrosive environments, making them prone to malfunctions including blockages, leaks, loosening, and warping. Sensor failures in these systems are inevitable due to external interference and component degradation, manifesting as complete failure, calibration deviations, drift errors, and reduced precision. As the two primary operational failures in CHP systems, actuator and sensor malfunctions not only degrade control performance but also damage equipment, potentially leading to system shutdowns and safety incidents.

The power grid in integrated energy systems receives electricity from wind and solar power generation to supply thermal hybrid systems. While the integration of physical power networks with information communication systems has advanced grid digitalization, it has also exposed critical cyber security vulnerabilities. A 2010 cyber attack on Iran's nuclear plant data monitoring system caused massive operational disruptions [3]. Similarly, a 2015 malware attack on Ukraine's power grid triggered widespread blackouts across multiple regions [4]. These cyber attacks have heightened concerns about cyber security in cyber-physical systems. From a control system perspective, power grids operate as networked platforms where local measurement data is transmitted to control centers via communication networks for real-time feedback. Control commands are then sent to regional generators through the same network, enabling stable operation of interconnected grids. However, these communication channels remain vulnerable to malicious attacks that could disrupt system functionality and jeopardize grid stability.

Fault diagnosis and self-recovery control serve as effective means to enhance system safety and reliability. Fault diagnosis involves detecting and identifying specific components where failures occur. Self-recovery control, based on diagnostic results, reconfigure the system to automatically transition from fault states back to fault-tolerant operation. Traditional model-based fault diagnosis and self-recovery control methods, developed over decades, have established comprehensive theoretical frameworks that account for system uncertainties during design, demonstrating strong robustness. However, as the number of faulty components increases and operating conditions become more complex, conventional model-based approaches struggle to achieve accurate fault detection and identification. Data-driven deep learning algorithms can address the recognition and classification of various complex faults, yet they are vulnerable to uncertain disturbances like parameter variations and model deviations, lack robustness, and cannot implement fault-based feedback control. Moreover, current fault diagnosis and self-recovery control methods are primarily applied in simple controlled processes, with limited research on integrated energy systems incorporating wind, solar, natural gas, and electrical energy sources, as well as communication network environments.

2. Fault Diagnosis and Self-recovery Control

2.1 Actuator Fault and Sensor Fault

Domestic and international researchers have conducted extensive studies on fault diagnosis of actuators and sensors in heat network heating boilers and cooling network refrigeration unit systems. Boilers convert energy sources such as electricity, gas, and solar power into thermal energy to provide users with hot water and heating. Refrigeration units transform electrical and thermal energy into cold energy to supply chilled water and air conditioning. Numerous studies design observers based on mathematical models of heating boilers and refrigeration units, calculating the residual signal between observer outputs and actual measurements. By comparing residual values with preset thresholds, normal operation shows zero residuals, while different fault types exhibit distinct non-zero residual characteristics, enabling detection of fault occurrence timing and identification of specific faulty components. Due to the complexity of model-based approaches, their sensitivity to operational variations, and inability to handle diverse complex faults, researchers have developed various data-driven fault diagnosis methods.

For heating boiler systems, literature [5] employs the classical Luenberger state observer for actuator fault diagnosis. Literature [6] proposes a high-gain observer-based fault detection method for boiler sensor failures. To address the noise sensitivity of both Luenberger and high-gain observers, literature [7,8] incorporated model random noise and developed multiple Kalman filters in parallel to detect sensor faults. Literature [9,10] considered modeling errors and external disturbances by designing robust residual generators using sliding mode observers for sensor fault detection. However, these conventional methods all rely on fixed thresholds, which may lead to erroneous diagnoses when operating parameters change. Consequently, literature [11,12] introduced adaptive threshold-based fault detection and identification techniques to enhance diagnostic accuracy and reduce computational load. Additionally, researchers have adopted data-driven approaches including artificial neural networks [13,14], fuzzy clustering, support vector machines, independent component analysis, and canonical correlation analysis for analyzing and detecting actuator and sensor faults in boiler systems.

Domestic and international researchers have achieved significant progress in addressing actuator and sensor failures in refrigeration unit control systems. These studies encompass both model-based approaches (including adaptive

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observers, nonlinear observers, extended Kalman filters, least squares estimators, and particle filters) and data-driven solutions (such as support vector machines, Bayesian networks, empirical mode decomposition, tree-structured learning, and margin information fusion learning). For self-recovery control of heating boilers and refrigeration units during failures, two primary approaches exist: hardware redundancy and software redundancy. The hardware approach involves installing additional sensors and actuators to replace faulty components when system failures occur. However, this method increases system complexity, raises costs, and risks component damage in harsh environments. Consequently, researchers have focused on developing cost-effective software-based recovery mechanisms. Current literature emphasizes using redundant estimation signals from observers. When faults occur, these signals are employed to reconfigure the control system based on fault diagnosis results, enabling automatic recovery. Key software-based recovery methods include second-order sliding-mode observers, fractional-order observers, and model predictors. These techniques ensure that heating boilers and refrigeration units can automatically reset and return to fault-tolerant operation modes during failures.

2.2 Cyber Attacks

Cyber-physical system integration in power networks has become a prominent research focus in recent years. As early as 2003, literature first introduced the concept of false data injection attacks targeting power system state estimation, which manipulates operational parameters by evading detection mechanisms, posing significant threats to grid stability. Subsequent studies by domestic and international researchers have developed multiple attack methods and effective detection techniques for state estimation, as comprehensively reviewed in [15]. The exploitation of automatic generation control systems in regional interconnected grids has emerged as another critical cyber threat, attracting substantial academic attention. Literature investigated four attack patterns, proportional, ramp, pulse, and random, targeting frequency measurement data in automatic generation control communication networks, analyzing their impacts on grid stability, and proposed distinct attack strategies focusing on risk assessment and temporal analysis respectively, demonstrated resonance-based attacks on automatic generation control load channels that rapidly induce frequency instability, developed unknown input observers within automatic generation control system models to detect various false data injection faults, employed multi-layer framework to identify fault data characteristics and diagnose fault types.

3. Analysis of Research Status

Based on the above literature, the current study has the following limitations:

(1) The heating boiler, refrigeration unit and regional interconnected power grid models are considered separately, without considering the embedding of random fluctuating energy such as wind and solar energy and the complementary utilization of multi-energy sources, and lack of a comprehensive energy system fault model including heat network, cold network and power grid from the perspective of system level.

(2) The fault types and operating conditions considered in the control system of heating boiler and refrigeration unit are limited, and the mutual influence between faults of different subsystems is ignored. In addition, the observer needs to be designed separately for actuator faults and sensor faults, which increases the complexity of fault diagnosis methods.

(3) The diagnosis methods for the automatic generation control system of the power grid ignore the influence of the communication network, and do not further implement self-recovery control under network attack based on the diagnosis results.

(4) Data-driven approaches suffer from inadequate fault feature extraction and pattern recognition capabilities. These methods require signal preprocessing to select fault-sensitive signals for feature extraction, which compromises information integrity. Moreover, their limited data processing capacity results in insufficient accuracy of final fault diagnosis outcomes. Additionally, data-driven methods are prone to model parameter variations, leading to poor robustness.

4. Research Meaning

The research meaning of fault diagnosis and self-recovery control of integrated energy systems are given as follows.

(1) Establish a comprehensive energy system

fault testing platform with multi-energy complementarity: Considering actuator failures, sensor malfunctions, and cyber attack scenarios, develop a standardized testing system integrating combined cooling, heating, and power systems with interconnected regional power grids. This system incorporates various fault types and operational conditions to provide sufficient diagnostic data, creating a standardized platform for evaluating fault diagnosis and self-healing control algorithms.

(2) Robust Fault Feature Extraction under Model and Communication Network Uncertainty: This research designs fault observers for actuator and sensor failures in combined cooling, heating, and power supply systems, while developing Kalman filters to counter cyber attacks in regional interconnected power grids. The output state estimates are utilized to generate residual signals, extract fault characteristics, and reset control systems. The observer and filter designs effectively address model uncertainties and communication network variations, demonstrating strong robustness against model errors and information loss.

(3) Proposing a model-data hybrid-driven fault diagnosis and self-recovery control method: A deep neural network is constructed using measurement signals, observer and filter estimated signals, as well as residual signals as training datasets. The network outputs a fault diagnosis and decision-making model for system reset and fault-tolerant operation under failures. The proposed fault diagnosis and self-recovery control algorithm inherits the advantages of robustness and software-based self-recovery control from model-based observer methods, while also incorporating the superior capabilities of data-driven deep neural networks in fault feature extraction and complex fault diagnosis.

5. Proposed Scheme

This paper takes the fault diagnosis and self-recovery control method of integrated energy system as the research subject, and the research objectives are as follows:

(1) Considering the dynamic characteristics of heating boilers and refrigeration units as well as the uncertainty of power system communication network, the integrated energy system model including heat network, cold network and power grid is established, and the fault test standard system of integrated energy system is established further considering the faults of actuators, sensors and network attacks;

This study investigates the complementary utilization of energy sources including wind, solar, natural gas, and electricity in heating and cooling systems, establishing an integrated energy system as shown in Figure 1. The system comprises two components: a combined heating and cooling system and a regional interconnected power grid. The combined heating and cooling system employs three-stage series-connected hot water boilers and refrigeration units to provide both heating and cooling. The regional interconnected power grid integrates wind and solar power generation, while a remote automatic power generation control system communicates via network to achieve stable multi-regional control. Detailed dynamic models are developed for solar water heaters, natural gas water heaters, electric water heaters, absorption refrigeration units, and electric refrigeration units, incorporating dynamic characteristics of actuators and sensors to design temperature controllers for heating boilers and refrigeration units. Additionally, a cyber-physical integrated model of the regional interconnected power grid is established to account for non-ideal communication networks and the impacts of wind and solar power generation.

Based on the established combined cooling, heating and power control system model, multiple types of actuator failures and sensor malfunctions are introduced into each heating and cooling subsystem. In a communication network environment, various types of false data are generated to conduct cyber attacks on the automatic generation control system of the regional interconnected power grid. Additionally, complex operational conditions such as wind speed variations, solar radiation fluctuations, load disturbances, measurement noise, and network information loss are simulated to establish a standardized test system for integrated energy system fault diagnosis and self-recovery control research. The study investigates the fault characteristics of different actuator failures, sensor malfunctions, and cyber attacks, as well as their impacts on the safe and stable operation of integrated energy systems.

(2) Leveraging model knowledge and data from integrated energy systems, this study explores a robust fault diagnosis and self-recovery control method. The approach demonstrates exceptional capability in feature extraction and pattern

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recognition while maintaining robustness against both model uncertainties and communication network anomalies. Furthermore, it enables controller software reset functionality, achieving reliable and accurate diagnosis of diverse complex faults in integrated energy systems alongside continuous fault-tolerant operation.

As shown in Figure 2, actuator failures and sensor failures are two primary types of malfunctions in the control systems of heating boilers and cooling units within combined heat and power systems. To address actuator and sensor failures in combined heat and power systems, robust fault observers are designed through parallel modeling of individual heating boilers and cooling units, accounting for parameter variations and modeling deviations. These observers estimate the operational status, actuator fault components, and sensor fault components of both heating and cooling subsystems. As depicted in Figure 3, communication networks between power grids and control centers are vulnerable to false data injection attacks that disrupt system operations. For such cyber attacks in interconnected regional power grids, observers are designed using grid models and communication network models, considering packet loss-induced network uncertainties. These observers accurately estimate the operational status and network attack-related fault components in each regional power grid.

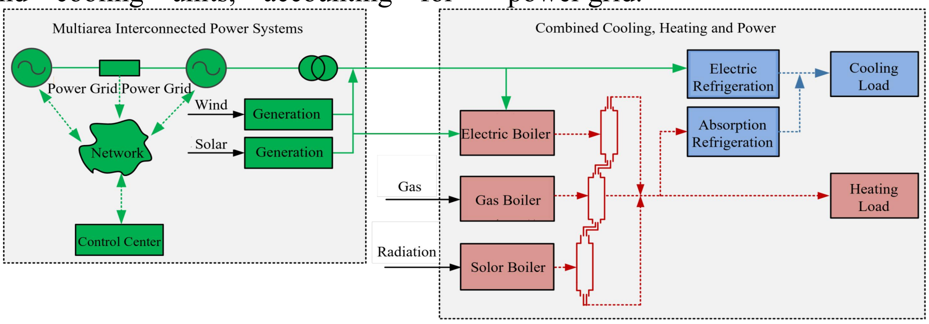

Figure 1. Integrated Energy System Structure

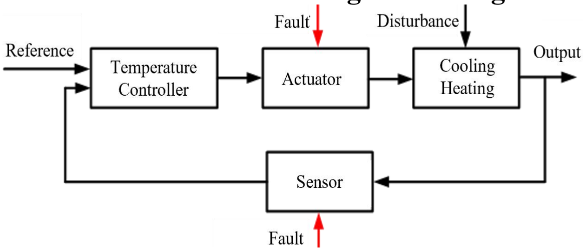

Figure 2. Fault of the Combined Cooling and Heating Supply Control System

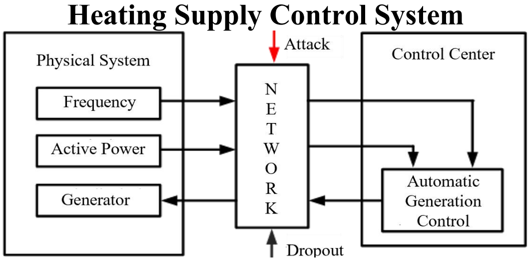

Figure 3. Network Attack on the Regional Interconnected Power Grid with Information and Physical Integration

By leveraging the robustness of model-driven observer methods and their fault-tolerant software implementation advantages, along with the data-driven deep neural networks 'strengths in feature learning and pattern recognition, this study explores a hybrid model-data driven approach for fault diagnosis and self-recovery control. The framework is illustrated in Figure 4. Building upon the fault observer designed in Research Content 2, we compute robust residual signals to characterize faults using state estimates from the observer and actual system measurements. This enables fault feature extraction and utilization through a robust observer mechanism. A deep neural network is constructed for complex fault diagnosis in integrated energy systems, with combined training and testing of the observer and network architectures. The output model then diagnoses and makes decisions for multi-type complex faults in the standard system outlined in Research Content 1. Finally, based on decision outcomes and the observer's fault component estimates, we develop fault compensation and self-recovery control strategies for integrated energy system controllers.

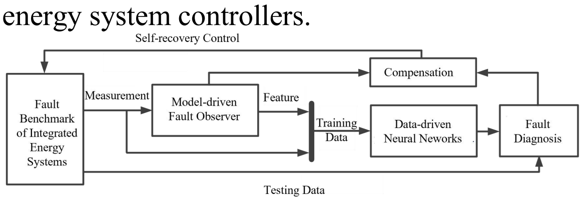

Figure 4. Structure of Fault Diagnosis and Self-recovery Control Method Driven by Model and Data Mixture

6. Conclusion

In conclusion, this research focuses on integrated energy systems, addressing actuator and sensor failures in heating and cooling network control systems, as well as cyber-attack vulnerabilities in power grid control networks. By integrating model-driven and data-driven approaches for fault diagnosis and self-recovery control, the study demonstrates significant practical value in enhancing system safety, reliability, and operational/maintenance efficiency. Furthermore, it provides innovative methodologies for condition monitoring, fault diagnosis, and self-recovery control in complex industrial processes and cyber-physical systems.

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