Security Assessment of Integrated Energy Systems Considering Multi-Timescale Dynamics and Multiple Coupled Fault Types

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***Abstract*—Integrated energy systems (IESs) enable cascade utilization of energy and represent a future trajectory for energy development; however, their security is challenged by multi timescale behavior and multi energy flow coupling. In particular, water hammer arising from hydraulic transients in district heating networks can induce safety issues, and various coupled cascading events may be overlooked by conventional assessments. This paper develops a multi timescale hybrid safety assessment model that interleaves hydraulic-transient computations within the conventional workflow to achieve a more complete evaluation. We further classify coupled faults under multi energy flow coupling, expand the taxonomy of cascading events, and formulate a fault chain representation applicable across coupling types. Validation on a simplified case derived from a real system demonstrates that the proposed method more comprehensively captures coupled faults, thereby complementing traditional safety assessment.**

***Index Terms*—multi timescale, multi energy flow coupling, safety assessment, integrated energy systems**

I. Introduction

Efficient energy utilization is a hallmark of modern societal progress. Integrated energy systems (IESs), featuring electro thermal coupling as the primary mode of operation, represent the future trajectory of energy use [1], [2]. Compared with single carrier energy systems, IESs can fully leverage the complementary characteristics of diverse energy carriers, enhance overall economic performance, and enable cascade utilization of energy. Nevertheless, ensuring the secure and stable operation of IESs poses new technical challenges, with pronounced multi timescale characteristics and multi energy flow coupling being particularly salient [3].

Traditional safety assessments often overlook fluid dynamics in district heating networks. Sudden valve operations in near incompressible liquids induce sharp changes in velocity and pressure, imposing severe loads on pipelines; the resulting water hammer is a leading cause of ruptures [4]. The International Association for Hydraulics reports over USD 500 million in direct annual losses from water hammer related pipeline accidents worldwide. Because its characteristic timescale lies between those of the power grid and the heating network [5], water hammer is routinely omitted from conventional assessments. In integrated energy systems, multi energy coupling further renders cascading failures covert and far reaching: faults in energy conversion couplers spread across subsystems, and heating network controls (valves, circulating pumps) require secure power, so grid load shedding propagates disturbances from the control layer into the heating network. In 2020, icing in Jilin caused tower collapses and line breaks, constraining power transmission, limiting CHP output, and hindering heat supply.

Extensive studies have addressed safety assessment for integrated energy systems. Reference [6], using a combined heat and power (CHP) system as an example, focuses on the feasible operating region of CHP units and evaluates the impact of cascading failures, while [7], [8] propose event tree analysis to simulate cascading faults. Nevertheless, important gaps remain. 1): the fault types considered are often concentrated on components that directly perform energy conversion, with limited attention to coupling effects originating from the control layer [9]; 2): many existing studies model the power grid as the fast subsystem and the heating network as the slow subsystem, thereby overlooking hydraulic dynamics, even though water hammer can precipitate major system failures [10].

This paper addresses the above issues by proposing a safety assessment method for multi-energy systems that accounts for multiple time scales and diverse types of coupled faults. The method explicitly models hydraulic transients and the resulting water-hammer effect, captures chain-type failure propagation in multi-energy coupled systems, generalizes the N-1 contingency criterion to N-m cascading fault chains, and develops a multi-level classification taxonomy for coupled faults.

The remainder of the paper is organized as follows. Section 2 establishes a multi-timescale model describing hydraulic and thermal dynamics and develops the safety assessment framework for electro-thermal coupled systems. Section 3 elucidates the cascading failure mechanisms in multi-energy

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coupled systems. Section 4 presents case studies. Section 5 concludes the paper.

II. MULTI TIMESCALE MODEL

Safety issues triggered by a single fault in multi energy systems evolve across time scales. At short time scales, electromechanical and electromagnetic transients dominate, and mature power-system models exist, not detailed here. At intermediate time scales, pressure fluctuations from hydraulic dynamics impose loads on the pipeline network. At long time scales, models primarily capture temperature dynamics in district heating networks. This paper focuses on hydraulic transients and heating network dynamics.

A. Intermediate timescale model

For a pressurized pipeline, the flow must satisfy the momentum and continuity equations. Assuming constant pipe material, wall thickness, and inner diameter, the fundamental governing equations for the water hammer process can be expressed as:

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{f}{2D}V|V|=0 \quad (1)$$

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial V}{\partial x}+V\frac{\partial H}{\partial x}=0 \quad (2)$$

In the above equations, g denotes gravitational acceleration; H is the liquid pressure inside the pipe; V is the liquid flow velocity; f is the friction factor; and D is the inner diameter of the pipe.

Starting from the governing equations, we neglect frictional losses. With the pressure wave speed typically $a \approx 1000 m/s$ so that $a \gg V$, and since the abrupt changes in pressure and velocity are primarily temporal, the convective terms $V\frac{\partial V}{\partial x}$ and $V\frac{\partial H}{\partial x}$ are neglected, yielding a hyperbolic system of partial differential equations:

$$g\frac{\partial H}{\partial x}=\frac{\partial V}{\partial t} \quad (3)$$

$$\frac{\partial H}{\partial t}=\frac{a^2}{g}\frac{\partial V}{\partial x} \quad (4)$$

That is, the overpressure induced by water hammer can be represented as the superposition of a backward-traveling wave F and a forward-traveling wave f along the flow direction.

Taking the sudden closure of a terminal valve in a single pipeline as an illustrative case, the pipeline boundary conditions are prescribed such that pressure and velocity remain constant. Under this scenario, the full water-hammer response can be partitioned into four stages.

At t=0, the valve at A closes suddenly. During 0–dt_1, only the segment of length dx_1 near A changes: velocity drops from $V0$ to 0, pressure rises from $H0$ to $H_0+\Delta H$; fluid in dx_1 is compressed, allowing downstream flow to briefly continue at its original speed. After $t=L/a$, the whole pipe has $V=0$ and pressure $H_0+\Delta H$.

At $t=L/a$, imbalance at D drives a state change propagating from D to A. After another L/a, the velocity becomes

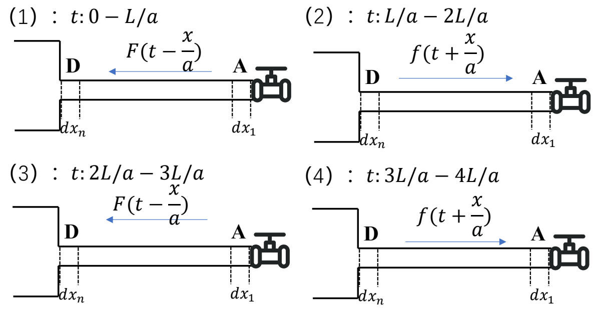

Fig. 1. Schematic of the water-hammer process

$-V0$ and the pressure returns to $H0$, i.e., a pressure-drop wave travels from D to A.

For $t=2L/a-3L/a$, a pressure-rise wave travels from A to D; after its passage, velocity is 0 and pressure is $H0-\Delta H$.

For $t=3L/a$–$4L/a$, a pressure-drop wave travels from D to A; after its passage, velocity and pressure return to their initial values. Define $T=4L/a$ as one period of the water hammer oscillation.

Because hydraulic friction is present in practice, these oscillations are damped and decay over time.

Based on valve-closure speed, water hammer is classified as direct or indirect. For direct water hammer, the maximum overpressure occurs at the instant of closure, before the reflected pressure-drop wave f reaches the valve; the overpressure thus depends only on the closure action, and from the general solution we obtain:

$$\Delta H=-\frac{g}{a}(V-V_0) \quad (5)$$

For a pipeline with initial velocity $V_0=4m/s$ and wave speed a=1000 m/s, rapid valve closure produces an overpressure of about $4MPa$, exceeding district-heating design limits and potentially causing pipeline rupture.

B. Long time scale model

At long time scales, the model captures temperature dynamics in district heating networks. The nodal method [11] avoids the substantial computational burden of finite-difference schemes while maintaining high accuracy. It first estimates the lossless outlet temperature by weighting the inlet-temperature history and then corrects it for heat losses. For a single pipeline, we have:

$$\tau_{b,t}^{\prime S,out}=\sum_{k=t-\phi_t}^{t-\gamma_t}K_{t,k}\tau_{b,k}^{S,in} \quad (6)$$

$$\tau_{b,t}^{\prime R,out}=\sum_{k=t-\phi_t}^{t-\gamma_t}K_{t,k}\tau_{b,k}^{R,in} \quad (7)$$

In the above, τ denotes the temperature without heat loss; S and R denote the supply and return networks; in and out indicate the pipe inlet and outlet; $K_(t,k)$,γ_t, and ϕ_t are coefficients computed from parameters such as flow rate, pipe

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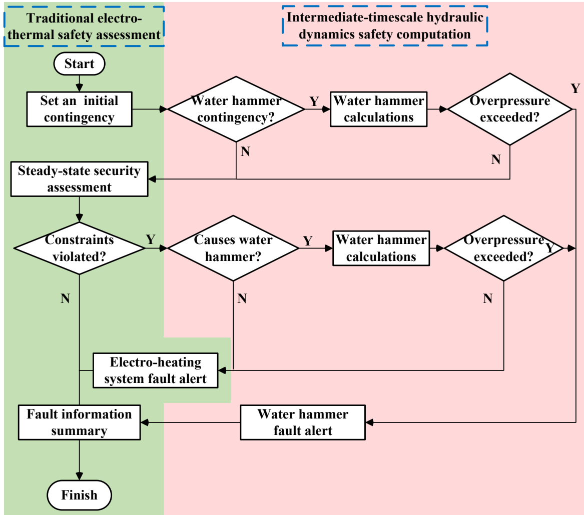

Fig. 2. Process diagram of the multi-timescale hybrid safety assessment

diameter, and length. The outlet temperature is then reduced to account for heat losses:

$$\tau_{b,t}^{S,out} = \tau_t^{am} + (\tau_{b,t}^{'S,out} - \tau_t^{am}) \cdot exp[-\frac{\lambda_b \Delta t}{A_b \rho c}(\gamma_{b,t} + \frac{1}{2} + \frac{S_{b,t} - R_{b,t}}{m_{b,t-\gamma_{b,t}} \Delta t})] \tag{8}$$

In the above, τ_t^{am} is the outdoor air temperature; λ_b is the heat transfer coefficient of pipe; A_b is the pipe area; ρ is the liquid density; and c is the liquid specific heat. The formulas for S and R are:

$$R_{b,t} = \sum_{k=0}^{\gamma_{b,t}} (m_{b,t-k} \Delta t) \tag{9}$$

$$S_{b,t} = \begin{cases} \sum_{k=0}^{\gamma_{b,t}} (m_{b,t-k} \cdot \Delta t) & \phi_{b,t} \geq \gamma_{b,t} + 1 \\ R_{b,t} & otherwise \end{cases} \tag{10}$$

S, R can be derived from the pipeline's historical flow rates. Using the above equations, this model computes the temperature dynamics of the district heating network.

C. Hybrid multi time scale safety assessment model

As discussed earlier, because integrated energy systems exhibit multi timescale behavior, the impacts of a disturbance or fault propagate across different time scales. Accordingly, we develop a multi-timescale hybrid safety assessment model. As shown in 2, it interleaves hydraulic transient computations into the conventional safety assessment workflow.

In most operating conditions of integrated energy systems, the conventional safety assessment (left branch) suffices. When severe consequences from water-hammer effects are possible, the workflow invokes the hydraulic-dynamics computation (right branch) to ensure a complete safety assessment.

III. Multi Energy Flow Coupled Fault Classification and Fault Chain Characterization

Faults may dynamically propagate across coupled energy networks; rigorously characterizing these couplings and delineating the full chain and propagation modes of cascading failures remains a central challenge in the safety assessment of integrated energy systems.

A. Coupled fault classification

As a complex system, an integrated energy system exhibits couplings not limited to couplers directly connecting the two networks. Using an electro-thermal IES as an example, we characterize these couplings across three layers: energy, logical, and geographic.

1) Energy layer coupled cascading events: The normal operation of multi-energy systems must satisfy safety constraints (e.g., branch power-transfer limits, district-heating node temperature bounds, and unit output limits). These constraints are not strictly instantaneous; for example, line tripping requires overload persistence beyond a dwell time. Accordingly, energy-layer faults can be viewed as cascades triggered when energy-related variables exceed thresholds for a specified duration. For such coupled faults, we express them as:

$$\int_{t_0}^{t_0+\Delta T} f(t)dt > M \tag{11}$$

$f(t)$ may represent physical quantities such as branch power flow, district-heating node temperature, or unit output.

2) Logical layer coupled cascading events: Couplings arise not only at the energy layer but also at the logical (control) layer, with material impacts on operation. In district heating systems, control devices in the hydraulic circulation network such as circulating pumps and valves govern hydraulic conditions and typically serve as electrical loads. Power system faults that trigger load shedding can disable these devices, inducing hydraulic imbalance and disrupting heat supply, thereby propagating faults from the power grid to the hydraulic network and onward to the heating network.

3) Geographic layer coupled cascading events: Geographic coupling refers to interactions arising from the spatial proximity of subsystems within an integrated energy system. For example, when district heating pipelines are close to power system assets, rupture and leakage of a hot water main may inundate nearby areas and fault adjacent electrical equipment; the ensuing power system failure can, in turn, trigger subsequent cascading contingencies, extending the fault chain. On October 29, 2015, a primary heating main burst in Zhengzhou, Henan, flooded a nearby construction site and caused trips in the adjacent $110kV$ grid. In constructing the cascading fault chain, geographically proximate components can be modeled via a proximity based triggering probability for the next stage event.

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B. Description of the chain

A single event cannot fully characterize faults in integrated energy systems; therefore, a cascade based fault chain description is required. Consider a multi energy system with n components. Using 1 and 0 to denote an element's in service and out of service states, respectively, the overall system state is represented by an n-dimensional vector s_i, where i indexes the position in the cascading fault chain. The initial state is s_0.

In a fault chain, three elements are considered: the faulted component, the fault occurrence time, and the fault transmission probability. For example, if at the initial instant the power grid suffers a load loss fault that supplies the CHP auxiliaries, the system is likely to exhibit a "CHP output limitation" event at the next step. We describe this event by the triplet $(p, type, time)$, where p, type, and time denote the fault propagation probability, fault type, and occurrence time, respectively. Accordingly, the cascading event is expressed as:

$$s_0 - (p_0, load_1, t = 0) - s_1 - (p = 1, CHP_1, t = 1) - s_2 \quad (12)$$

Any segment of propagation within the fault chain can be expressed as:

$$s_k - (p, type, time) - s_{k+1} \quad (13)$$

The three coupling event classes introduced above are likewise reflected in this representation: energy layer faults capture temporal accumulation through t; logical layer faults rely on prior knowledge and are relatively deterministic, encoded by a high probability p; geographic layer faults, which are difficult to represent in traditional models, can be specified via the propagation probability p within the $(p, type, time)$ triplet.

IV. Case Study

Case study validation is conducted on an electro-thermal system comprising the IEEE39 bus power grid and an 18 node district heating network, the latter being a simplified model derived from a northern Chinese city. The subsystems are energy-coupled via a single CHP unit. Moreover, three valves in the heating network are supplied by power system loads 26 and 29, establishing logical layer coupling. The case study shematic is shown as Fig.3.

We first conduct a conventional safety assessment of this case. The contingency set comprises power-system line outages, abrupt load changes, and unintended load shedding. Post-contingency impact is evaluated by three metrics, line overload severity, district heating supply temperature exceedance, and the amount of lost load and the corresponding indices are defined as:

$$\begin{aligned} Risk_{line} &= \sum P_r \cdot max(P - P_{max}, 0) \\ Risk_{tem} &= \sum P_r \cdot c \cdot m \cdot max(T - T_{max}, 0) \\ Risk_{load} &= \sum P_r \cdot P_{load} \end{aligned} \quad (14)$$

In (14), P_r denotes the occurrence probability of each contingency. For each of the three metrics above, we identify the postulated contingency with the highest value and greatest severity; details are given in TABLE.I.

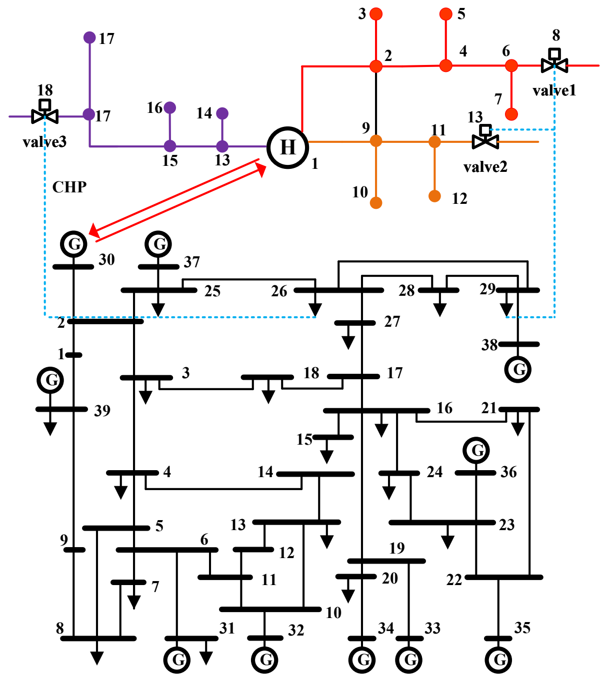

Fig. 3. Process diagram of the multi-timescale hybrid safety assessment

TABLE I
CONVENTIONAL SECURITY ASSESSMENT RESULTS

Fault name	$Risk_{line}$	$Risk_{tem}$	$Risk_{load}$	Fault source
Line1 outage	3.203	**1.938**	0	Electric
Line3 outage	11.49	0	**420.0**	Electric
Line35	**13.7216**	0.7908	329.0	Electric

According to the conventional safety assessment, system vulnerabilities lie on power system lines 1, 3, and 35; all weak points reside within the grid, while the district heating network exhibits greater robustness. Although loads 26 and 29 are not primary risk drivers, they supply critical control equipment in the heating network; their shedding can induce water hammer effects and generate significant overpressure in the pipelines.

Fig.4 shows nodal pressures in the district heating pipeline after shedding loads 26 and 29. Multiple nodes exhibit peak pressures exceeding allowable limits under water hammer, indicating a risk of pipeline rupture. This underscores the need to incorporate hydraulic dynamics into the safety assessment workflow and challenges the conventional conclusion that the heating network is inherently

n this case study, a loss of load on the power system precipitates a failure of the heating network control system, which in turn causes inadvertent valve closure, triggers water hammer, and generates over limit overpressure in district heating pipelines, thereby elevating the risk of rupture. To characterize this cross layer coupled cascading process, we

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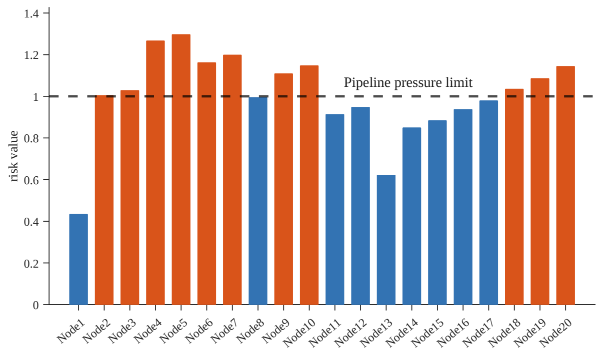

Fig. 4. Nodal pressures of the district heating network under hydraulic transients

adopt the previously introduced triplet based representation $(p, type, time)$, which jointly encodes the propagation probability, event type, and occurrence time. Concretely, the cascading fault chain is expressed as:

$$S_0 - (p_1, load\ loss, t_0) - S_1 - (p_2, heat\ leak, t_1) - S_2 \tag{15}$$

S_0, S_1 and S_2 denote the initial state, the load-shedding state, and the final fault state, respectively. In this process, p_1 is determined by the conventional safety assessment, whereas p_2 is informed by prior knowledge and should be close to 1, ensuring propagation of the fault chain to the final state with high pipeline rupture risk. This fault chain provides clear guidance for a comprehensive safety analysis; unlike conventional assessments that typically terminate at S_1, the proposed method identifies severe subsequent failure risks.

V. Conclusions

As electro-thermal coupled systems become more widely deployed within integrated energy systems, the importance of coupling security correspondingly increases. This paper evaluates the additional impacts of multi timescale behavior and multi energy flow coupling on system security. We first develop a multi timescale hybrid safety assessment model, with particular emphasis on overpressure induced by hydraulic transients (water hammer). We then classify cascading faults in IESs from the perspective of multi energy flow couplings, extend the propagation modes of fault chains, and provide a complete description that captures covert logical layer and geographic-layer cascades often overlooked by conventional assessments.

The proposed multi timescale model and multi energy coupling fault chain framework are validated through case studies, which reveal and accurately characterize cascading coupled events driven by hydraulic dynamics. The results confirm the effectiveness of the approach and provide actionable guidance for subsequent heating-network regulation and operation.

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References

[1] D. Xu, Q. Wu, B. Zhou, C. Li, L. Bai and S. Huang, "Distributed Multi-Energy Operation of Coupled Electricity, Heating, and Natural Gas Networks," *IEEE Trans. Sustain. Energy*, vol. 11, no. 4, pp. 2457-2469, Oct. 2020.

[2] S. Yao et al., "Dynamic Optimal Energy flow in the heat and Electricity Integrated Energy System," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 179–190, Jan. 2021.

[3] S. Zhang, W. Gu, S. Yao, S. Lu, S. Zhou and Z. Wu, "Partitional Decoupling Method for Fast Calculation of Energy Flow in a Large-Scale Heat and Electricity Integrated Energy System," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 501-513, Jan. 2021.

[4] G. Li, X. Wu, L. Li, W. Qiu, and W. Cui, "Research on water hammer protection for a long-distance water supply system of a deep well Pump Group," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 826, no. 1, p. 012047, Jul. 2021.

[5] M.S. Ghidaoui, M. Zhao, D.A. McInnis, D.H. Axworthy, A Review of Water Hammer Theory and Practice, Applied Mechanics Reviews 58 (1) (2005) 49–76.

[6] Y. Pan, F. Mei, C. Zhou, T. Shi and J. Zheng, "Analysis on Integrated Energy System Cascading Failures Considering Interaction of Coupled Heating and Power Networks," *IEEE Access*, vol. 7, pp. 89752-89765, 2019.

[7] Z. Liu, H. Li, K. Hou, X. Xu, H. Jia, L. Zhu et al., "Risk assessment and alleviation of Regional Integrated Energy System considering cross-system failures," *Appl. Energy*, vol. 350, p. 121714, Nov. 2023.

[8] R. Ma, S. Basumallik, and S. Eftekharnejad, "Controlled islanding resilience with high penetration of renewable energy resources," *IEEE Trans. Sustain. Energy*, vol. 14, no. 2, pp. 1312–1323, Apr. 2023.

[9] E. Guelpa and V. Verda, "Model for Optimal Malfunction Management in extended district heating networks," *Appl. Energy*, vol. 230, pp. 519–530, Nov. 2018.

[10] J. Tang, K. Xie, C. Li, H. Tai, C. Shao, B. Hu, "Load frequency control for integrated electrical-water system considering water hammer effect," *IEEE Trans. Smart Grid*, vol. 16, no. 5, pp. 3801–3816, Sep. 2025.

[11] Z. Li, W. Wu, M. Shahidehpour, J. Wang, and B. Zhang, "Combined Heat and Power Dispatch Considering Pipeline Energy Storage of District Heating Network," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp.12-22, Jan. 2016.