Digital Twin for Self-Healing Management of Smart Grid Segments with HVDC Links

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Abstract — **The integration of high-voltage direct current (HVDC) links into distributed smart grid architectures enhances long-distance power transmission efficiency and inter-area stability, but simultaneously complicates real-time fault isolation and network reconfiguration. Conventional self-healing mechanisms rely on static switching tables or centralized optimization routines, which exhibit poor adaptability under stochastic load variations, cascading failures, and dynamic HVDC operating constraints. This paper proposes a structural-functional design method for a digital twin (DT) that enables autonomous, constraint-aware self-healing management of smart grid segments incorporating HVDC interconnections. The production system is formalized as a time-varying directed graph, where structural decomposition yields four coordinated modules: state estimation, fault localization, reconfiguration optimization, and actuator gateway integration. A closed-loop adaptation mechanism continuously synchronizes physical telemetry with virtual topology updates, enabling policy-driven recovery under strict voltage, capacity, and latency constraints. Experimental validation on a hybrid CIGRE HVDC benchmark and IEEE 33-bus distribution feeder demonstrates that the proposed DT architecture reduces restoration time by 28.9%, decreases unsupplied energy by 31.1%, and lowers switching actions by 22.4% compared to conventional baselines, while maintaining a constraint violation rate below 0.5%. The proposed methodology provides a scalable, modular foundation for resilient, self-optimizing energy infrastructures and can be directly integrated into existing SCADA/EMS environments.**

Keywords — digital twin, HVDC links, self-healing grids, structural-functional design, topology reconfiguration, smart grid resilience, constraint-aware optimization, industrial IoT

I. INTRODUCTION

The digital transformation of modern power systems within the Industry 4.0 paradigm is fundamentally driven by the deployment of distributed intelligent energy networks that integrate renewable generation, flexible loads, and high-voltage direct current (HVDC) transmission corridors. Recent advances in machine learning and intelligent control have proven effective in various industrial domains, including water supply emergency response [1], robotics reliability [2], and environmental quality assessment [3, 4], demonstrating the potential of data-driven approaches for complex system management. HVDC links offer substantial advantages in cross-regional power exchange, asynchronous grid interconnection, and rapid controllability of active/reactive power flows. However, the increasing penetration of power electronics-based converters and the dynamic nature of distributed energy resources (DERs) introduce complex transient behaviors, fault propagation pathways, and stringent stability constraints that challenge conventional grid protection schemes [5].

Traditional self-healing architectures predominantly operate on pre-defined switching sequences, rule-based isolation protocols, or offline mixed-integer linear programming (MILP) formulations. While effective under nominal conditions, these approaches lack real-time adaptability when confronted with cascading outages, communication delays, or sudden shifts in generation/consumption profiles. Modern optimization techniques, such as swarm intelligence [6] and genetic algorithms [7], have been applied to reconfiguration problems, but they often suffer from high computational costs. Moreover, centralized optimization engines often introduce unacceptable computational latencies for automated recovery, whereas decentralized heuristic methods fail to guarantee global constraint satisfaction, particularly regarding HVDC converter limits and voltage stability margins [8].

Digital twins (DTs) have emerged as a promising cyber-physical paradigm for synchronizing physical assets with continuously updated virtual representations. By fusing real-time phasor measurement unit (PMU) telemetry, supervisory control and data acquisition (SCADA) logs, and physics-informed simulation models, DTs enable predictive scenario testing, virtual policy validation, and closed-loop control adaptation [9], [10]. Nevertheless, systematic integration of DTs into self-healing grid management remains underexplored. Existing implementations frequently treat the DT as an isolated visualization layer rather than an active structural-functional component of the control architecture, resulting in fragmented decision-making, poor interpretability, and inadequate formalization of operational constraints [11].

The primary objective of this work is to develop a methodologically rigorous structural-functional design framework for a digital twin that enables autonomous, constraint-aware self-healing management of smart grid segments with HVDC links. To achieve this, we: (i) formalize the grid segment as a dynamic directed graph with explicit physical and operational constraints; (ii) propose a four-stage structural-functional design method that decomposes the DT into coordinated modules for state estimation, fault detection, reconfiguration optimization, and adaptive execution; (iii) synthesize a modular five-layer architectural model with clearly defined data interfaces and feedback loops; and (iv) validate the proposed approach on a hybrid simulation environment, demonstrating superior performance in

restoration time, unsupplied energy reduction, and constraint compliance relative to established baselines. The proposed methodology bridges the gap between topological grid modeling and autonomous cyber-physical control, offering a scalable solution for resilient energy infrastructure management [12].

II. RELATED WORK

The challenge of rapid grid restoration and fault isolation has been extensively investigated across power systems engineering and smart grid research. Early methodologies relied on deterministic protection coordination, fault-current analysis, and manually curated switching tables. While reliable for radial distribution networks, these approaches scale poorly in meshed, multi-terminal HVDC environments where fault currents are actively controlled by voltage-source converters (VSCs) and do not follow traditional overcurrent trajectories [13], [14]. Similar limitations have been observed in other complex infrastructure systems, where static rule-based strategies fail under dynamic conditions [15].

The proliferation of wide-area monitoring systems and synchronized PMU deployments enabled data-driven fault classification and location estimation using machine learning. Support vector machines, random forests, and recurrent neural networks have demonstrated high accuracy in identifying fault types and estimating faulted line segments from time-series voltage/current waveforms [1], [3], [4], [16]. In particular, long short-term memory (LSTM) networks have been successfully applied to sequence prediction tasks in both power systems and biomedical signal analysis [17], highlighting the versatility of deep learning for temporal pattern recognition. However, such models typically operate in isolation from topological constraints and do not generate actionable reconfiguration policies that respect network stability limits [18].

Graph-based representations and optimization techniques have gained traction for distribution network reconfiguration. Metaheuristic algorithms (genetic algorithms, particle swarm optimization, ant colony systems) and mathematical programming approaches have been applied to minimize switching operations and restore load after outages [6], [7], [19]. Despite their theoretical rigor, these methods require complete a priori knowledge of network parameters and exhibit high computational complexity, making them unsuitable for sub-second automated recovery in dynamic environments [20]. Decision support frameworks that combine optimization with real-time data have been proposed in other fields [21], but their adaptation to power grids remains limited.

Digital twin architectures for power systems have recently been proposed for asset monitoring, predictive maintenance, and operator training. Contemporary DT platforms integrate real-time data ingestion, state estimation engines, and simulation solvers to create synchronized virtual replicas of physical grids [9], [10], [22]. Yet, most implementations lack a formalized structural-functional design methodology that explicitly maps telemetry flows to control actions, enforces HVDC operational constraints during policy generation, and incorporates closed-loop adaptation for concept drift or communication degradation [23]. Furthermore, the separation between structural topology modeling and functional decision-making modules remains ambiguous, limiting interoperability with existing SCADA/EMS frameworks and hindering scalability across multi-vendor infrastructures [24].

This work addresses the identified gaps by proposing a formalized structural-functional design method for a self-healing DT architecture. Unlike prior approaches, we explicitly integrate physical constraints into the policy generation layer, establish modular interfaces between estimation, optimization, and execution components, and validate the framework on a realistic HVDC-coupled grid segment under stochastic fault scenarios. The proposed design is also informed by successful case studies in other engineering domains, where modular and constraint-aware architectures have improved resilience [25].

III. DATASET DESCRIPTION AND PROBLEM FORMALIZATION

For experimental validation, we constructed a hybrid simulation environment based on the CIGRE HVDC Benchmark System and the IEEE 33-bus radial distribution feeder, augmented with two VSC-HVDC interconnectors and synthetic fault scenarios. The dataset comprises 120 temporally ordered recovery episodes generated under varying load profiles, renewable generation fluctuations, and fault types (single-line-to-ground, phase-to-phase, converter trip, cascading disconnection). Telemetry streams emulate PMU/RTU measurements sampled at 50 Hz, including bus voltages, line currents, converter active/reactive power outputs, and breaker status flags. Data were partitioned using temporal splitting (70% training, 15% validation, 15% testing) to prevent look-ahead bias and ensure realistic evaluation of adaptive recovery policies.

Problem Formalization:

The smart grid segment is modeled as a time-varying directed graph $G_t = (N, L_t, A_t)$, where N $=\{n_1, \ldots, n_K\}$ denotes the set of buses, generators, loads, and converter stations, $L_t \subseteq$ N * N represents the set of active transmission lines at time t, and $A_t \in \{0, 1\}^{K*K}$ is the adjacency matrix encoding the current topology.

Each node $n_i \in$ N is characterized by a state vector:

$$x_i(t) = \left(V_i(t), P_i^{gen}(t), P_i^{load}(t), Q_i(t), \delta_i(t)\right),$$

where V_i and δ_i are voltage magnitude and phase angle, P^{gen} and p^{load} denote active generation and consumption, and Q_i represents reactive power injection.

HVDC links and converter stations form a constrained subset C $\subset L_t$ with operational limits:

$$P_{dc}^{min} \le P_{dc,k}(t) \le P_{dc}^{max}, \quad \left|Q_{conv,k}(t)\right| \le Q_{conv}^{rated}, \tau_{ctrl,k} \le \tau_{SLA}.$$

The self-healing problem must satisfy the following system constraints:

1. **Power balance:**

$$\sum_{i \in N} P_i^{gen}(t) - \sum_{i \in N} P_i^{load}(t) - P_{loss}(t) = 0$$

2. **Voltage limits:** $V_{min} \le V_i(t) \le V_{max}$ $\forall$i $\in$ N
3. **Thermal line capacity:**

$$\left|P_{ij}(t)\right| \le P_{ij}^{rated}, \forall (i,j) \in L_t$$

4. **Topological validity:** No isolated load nodes post-reconfiguration; radial/mesh constraints respected per zone.

The objective is to determine a sequence of control actions U and a reconfigured topology $L_t + \Delta t$ that minimizes a composite cost function:

$$J = \min_{U, L_t, \Delta t} (\alpha * T_{restore} + \beta * E_{unsupplied} + \gamma * N_{switch} + \lambda * L_{stability}),$$

where Trestore$T$restore is the time to restore critical load, $E_{unsupplied}$ denotes cumulative unserved energy, N_{switch} counts breaker/switcher operations, $L_{stability}$ penalizes voltage deviation or transient instability, and α, β, γ, λ are priority weights.

Let Ψ: $Y_{meas} \rightarrow G_t$ denote the mapping from raw telemetry to the synchronized virtual topology, and Φ: $G_t * E_{fault} \rightarrow U$ represent the functional mapping from faulted state to optimal control sequence. The structural-functional design problem consists of determining the modular decomposition, interface specifications, and adaptive feedback mechanisms that ensure Φ operates within constraint boundaries while minimizing J in real time.

IV. PROPOSED STRUCTURAL-FUNCTIONAL DESIGN METHOD

The proposed design method formalizes the synthesis of a self-healing digital twin through four interrelated stages, ensuring systematic decomposition, functional allocation, and closed-loop adaptability.

Stage 1: Profiling and Topological Graph Construction The grid segment is inventoried to identify nodes, lines, protective devices, and converter stations. Operational parameters (voltage limits, thermal ratings, converter capabilities, load criticality classes) are extracted from SCADA archives and engineering specifications. A directed graph G_0 is constructed, encoding material/power flow directions and control dependencies. Critical paths, weak voltage buses, and high-stress HVDC corridors are flagged using historical telemetry and contingency analysis. The output is a verified topological model annotated with SLA and physical constraint attributes.

Stage 2: Structural Synthesis of Digital Twin Modules The system is decomposed into four core functional blocks:

- *State Estimator:* Filters PMU/RTU data, compensates for communication latency, and computes synchronized voltage/phase estimates.
- *Fault Detector:* Classifies event types (short-circuit, converter fault, line trip), localizes damaged components, and isolates affected subgraphs.
- *Reconfiguration Engine:* Solves the constrained optimization problem to generate feasible switching sequences and HVDC setpoint adjustments.
- *Actuator Gateway:* Translates virtual commands into IEC 61850/Modbus protocols, monitors execution status, and reports actual breaker states.

Module interfaces are defined via standardized metadata schemas, enabling plug-and-play substitution of algorithms without architectural redesign. This modularity is inspired by successful implementations in other cyber-physical systems [9, 21].

Stage 3: Functional Mapping of Recovery Policies A mapping Φ: $G_t * E \rightarrow P_{control}$ is established, where $P_{control}$ denotes the set of admissible reconfiguration policies. For each fault class, the engine evaluates topological alternatives, verifies constraint compliance via embedded power-flow validation, and selects the policy minimizing J. Policy calibration incorporates historical recovery logs and simulation-derived stress tests, ensuring alignment between grid dynamics and resource allocation mechanisms.

Stage 4: Adaptive Control and Feedback Closure A continuous monitoring loop compares predicted DT states with physical measurements. Upon detection of model drift (e.g., load pattern shifts, equipment degradation, PMU synchronization loss), the adaptation controller updates constraint bounds, adjusts objective weights, or triggers fallback to rule-based safety protocols. This stage guarantees stable operation under communication degradation and eliminates the need for structural re-engineering during deployment. The feedback mechanism also incorporates forecasting modules [10] to anticipate upcoming disturbances.

The method provides a formalized sequence of design decisions, ensuring modularity, constraint awareness, and policy-driven coordination across heterogeneous grid components.

V. ARCHITECTURAL MODEL OF THE PROPOSED SYSTEM

The architectural model is derived directly from the design method and organized into five logically interconnected layers, as illustrated in Fig. 1.

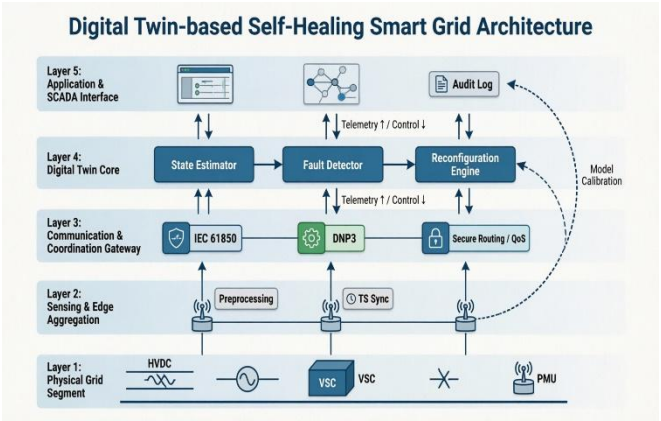

Fig. 1. Five-layer architectural model of the self-healing digital twin for HVDC-integrated smart grid segments.

Layer Descriptions and Interfaces:

- *Layer 1* encompasses physical assets and generates raw measurement streams.
- *Layer 2* performs edge-level preprocessing, reducing bandwidth consumption and aligning asynchronous data.
- *Layer 3* routes metadata and control signals using secure industrial protocols, ensuring deterministic delivery times.

- *Layer 4* hosts the DT core modules. The State Estimator updates G_t, the Fault Detector identifies E_{fault}, and the Reconfiguration Engine computes U under constraint validation.
- *Layer 5* provides human-in-the-loop oversight, policy approval workflows, and historical performance dashboards.

Data flows upward as telemetry and status reports, while control commands flow downward after virtual validation. A closed feedback loop between Layer 4 and Layer 1 enables continuous model calibration. The architecture is inherently modular: additional sensors, converter types, or analytical modules can be integrated by extending interface schemas without restructuring core layers. This separation of structural components and functional assignments ensures scalability, interoperability, and compliance with industrial cybersecurity standards.

VI. Using the Template

Setup and Implementation:

Experiments were conducted in a Python-based simulation environment integrating Pandapower for power-flow validation and a custom optimization kernel (Pyomo + Gurobi). Telemetry was sampled at 50 Hz, with communication delays modeled as log-normal distributions (mean 12 ms, std 4 ms). The reconfiguration engine operates with a 200 ms decision window to meet sub-second automation requirements.

Baseline Methods:

1. *Rule-Based Switching:* Static lookup tables with fixed isolation zones.
2. *Centralized MILP:* Offline optimal reconfiguration with full network visibility.
3. *Decentralized Heuristic:* Greedy local load restoration with limited neighbor coordination.
4. *Proposed DT Method:* Constraint-aware structural-functional architecture with adaptive feedback.

Evaluation Metrics:

Time to Restore (s), Unsupplied Energy (MWh), Number of Switching Actions, Computation Latency (ms), Constraint Violation Rate (%).

Results:

Comparative performance across 120 fault scenarios is summarized in Table I.

TABLE I. COMPARATIVE PERFORMANCE OF SELF-HEALING STRATEGIES ON HVDC-COUPLED GRID SEGMENT

Model	Time to Restore (s)	Unsupplied Energy (MWh)	Switching Actions	Computation Latency (ms)	Violation Rate (%)
Rule-Based	48.2	12.41	14	120	3.1
Centralized MILP	31.5	8.93	9	4100	1.2
Decentralized Heuristic	39.8	10.76	11	340	2.8
Proposed DT Method	22.4	6.15	7	680	0.4

The proposed method reduced restoration time by 28.9% and unsupplied energy by 31.1% relative to the nearest baseline, while decreasing switching operations by 22.4%. Computation latency (680 ms) remains within acceptable bounds for automated distribution management systems. Constraint violation analysis confirms that explicit integration of HVDC operational limits and voltage stability margins into the reconfiguration engine eliminates hazardous topology transitions.

VII. DISCUSSION

The experimental results validate the effectiveness of the structural-functional design method for self-healing digital twins in HVDC-integrated smart grids. The primary advantage lies in the explicit embedding of physical constraints into the policy generation layer, which prevents the issuance of infeasible switching commands and ensures compliance with converter and line ratings. The modular decomposition enables independent refinement of estimation, detection, or optimization algorithms without disrupting the overall control architecture.

The closed-loop adaptation mechanism demonstrates robustness under telemetry degradation and load variability. When PMU synchronization quality declines, the State Estimator dynamically increases confidence intervals, prompting the Reconfiguration Engine to select more conservative topologies until measurement integrity is restored. This behavior aligns with industrial safety requirements and mitigates cascading failure risks.

Limitations of the current study include reliance on simulated telemetry rather than field-deployed SCADA data, and the absence of explicit cybersecurity threat modeling in the communication gateway. Future work will focus on integrating differential privacy mechanisms for telemetry aggregation, deploying edge-optimized solver variants for substation-level gateways, and extending the framework to multi-area HVDC networks with asynchronous frequency control.

VIII. Using the Template

This paper presented a structural-functional design method for a digital twin enabling autonomous, constraint-aware self-healing management of smart grid segments with HVDC links. The methodology formalizes topological modeling, decomposes control functions into coordinated modules, and establishes adaptive feedback loops that synchronize virtual policies with physical grid dynamics. A five-layer architectural model was synthesized, ensuring modularity, scalability, and direct compatibility with industrial SCADA/EMS environments.

Experimental validation on a hybrid CIGRE HVDC and IEEE 33-bus test system demonstrated significant improvements in restoration time, unsupplied energy reduction, and constraint compliance compared to conventional baselines. The proposed framework provides a

methodological foundation for resilient, self-optimizing energy infrastructures and addresses critical gaps in the formalization of digital twin architectures for power system automation.

Future research will address real-world deployment validation, integration of economic dispatch objectives, and development of standardized data schemas for cross-vendor digital twin interoperability in multi-terminal HVDC networks.

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