

Adaptive Autonomous Decision Framework For Smart Grid Reliability Using A 4R Decision Model

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Abstract

This work presents an enhanced smart grid framework with predictive and self-healing capabilities validated through simulation results. Modern electrical distribution systems face increasing challenges due to grid instability, power quality disturbances, and unexpected faults in distribution networks. This study proposes an Adaptive Autonomous Decision Framework (AADF) designed to enhance the resilience, monitoring capability, and self-healing capacity of smart electrical networks. The proposed approach integrates real-time sensing, intelligent analytics, and automated control to support rapid and accurate operational decision-making in distributed power environments. Modern electrical distribution systems face increasing challenges due to grid instability, power quality disturbances, and unexpected faults in distribution networks. This document proposes an Adaptive Autonomous Decision Framework (AADF) to enhance resilience, monitoring capability, and self-healing capacity of smart electrical networks. The framework integrates real-time sensing, intelligent analytics, and automated control to support rapid and accurate decision making in distributed power environments.

The framework operates through three interconnected layers: Perception, Intelligence, and Response. In the perception layer, distributed sensors and smart meters continuously monitor voltage, current, harmonic distortion, and leakage currents across the network. These data streams are processed in the intelligence layer using adaptive signal analysis and predictive anomaly detection algorithms to identify disturbances such as harmonic distortion, insulation leakage, or grid instability before critical failure occurs. The response layer implements a microcontroller-driven decision engine capable of autonomously executing corrective actions including micro-grid islanding, harmonic filtering activation, and feeder reconfiguration.

For rural micro-grid scenarios, the system dynamically prioritizes essential loads such as healthcare facilities, water infrastructure, and communication networks using a hierarchical load-management algorithm. In laboratory or industrial environments, the framework performs high-resolution harmonic detection and applies adaptive filtering techniques to maintain waveform integrity and protect sensitive equipment. For underground distribution systems, the proposed architecture employs leakage-current trend analysis to enable pre-fault detection and automatic rerouting of electrical supply, thereby supporting self-healing grid functionality. The framework operates through three interconnected layers: Perception, Intelligence, and Response. Distributed sensors and smart meters continuously monitor voltage, current, harmonic distortion, and leakage currents across the network. These data streams are processed using adaptive signal analysis techniques such as FFT-based harmonic detection and predictive anomaly identification.

The decision engine evaluates disturbances and activates corrective actions including microgrid islanding, harmonic filtering, load prioritization, and automatic feeder rerouting. The architecture supports self-healing operation by detecting faults early and autonomously restoring stable grid conditions. The proposed framework improves power quality, reduces outage duration, and enhances operational reliability in modern smart grid infrastructures.

The decision-making model combines predictive diagnostics, priority-based control, and automated switching mechanisms, allowing the network to transition between normal, preventive, and emergency operating modes without human intervention. By integrating intelligent monitoring with autonomous corrective action, the proposed framework significantly improves grid reliability, reduces outage duration, and enhances operational efficiency.

The proposed Adaptive Autonomous Decision Framework demonstrates a scalable and robust approach for future smart grid infrastructures, enabling proactive management of electrical disturbances while ensuring uninterrupted and high-quality power delivery.

Date of Submission: 27-03-2026

Date of Acceptance: 07-04-2026

I. 4R Smart Grid Decision Model

Recognize – Detect disturbances using sensors and monitoring systems.

Reason – Analyze data using FFT analysis, anomaly detection, and predictive algorithms.

Respond – Implement corrective actions such as microgrid islanding, load prioritization, harmonic filtering, and feeder switching.

Recover – Restore and stabilize grid operation through automated self-healing control.

4R Decision Cycle

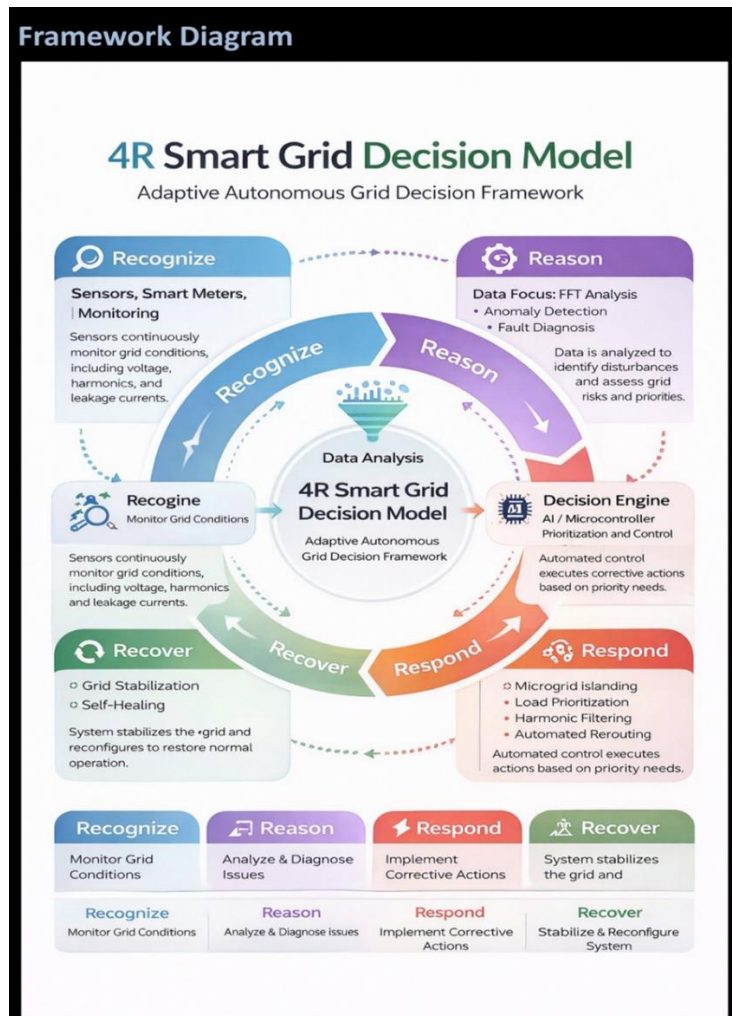


Three-Layer Smart Grid Architecture

Hardware Layer: Sensors, smart meters, current transformers, and leakage detectors collect real-time electrical data.

Intelligence Layer: Analytical algorithms and AI techniques process data to detect disturbances and evaluate system risks.

Control Layer: Smart relays and automated switches execute corrective actions and restore stable grid operation.



Smart Grid Challenges

- Grid instability and power outages
- Harmonic distortion affecting equipment
- Underground cable insulation faults
- Need for intelligent monitoring systems

Problem Statement

- Frequent rural grid outages
- Sensitive laboratory equipment affected by power quality
- Leakage currents leading to short circuits
- Traditional systems react only after faults occur

Proposed Solution

- Adaptive Autonomous Decision Framework (AADF)
- Real-time sensing and monitoring
- AI-based analysis and anomaly detection
- Automated corrective grid response

Monitoring and Data Analysis

- Continuous monitoring of voltage, current, harmonics
- FFT-based harmonic detection
- Predictive anomaly identification

Automated Grid Response

- Microgrid islanding during grid failure
- Load prioritization for critical infrastructure
- Harmonic filtering
- Automatic feeder rerouting

Future Innovation Concept

- Gravity-Based Nano Sensor Monitoring Concept
- Sensors detect electromagnetic or thermal anomalies
- Wireless data transmission
- Ultra-early fault prediction

Key Automation Components in Smart Grid



II. Simulation Results

Figure 1 shows THD improvement. Figure 2 shows faster recovery using AADF.

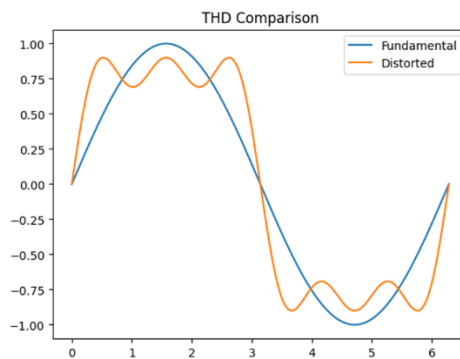


Fig 1: THD Comparison

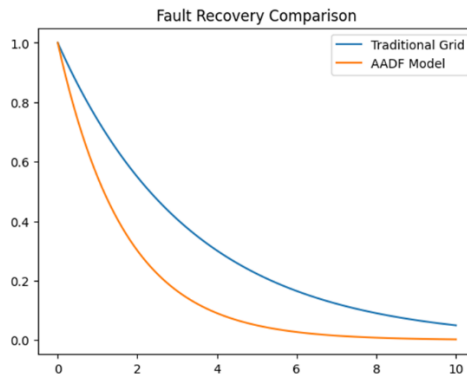


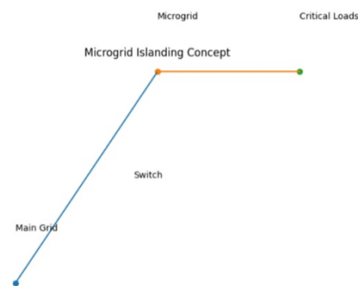
Fig 2: Fault Recovery Comparison

III. Conclusion

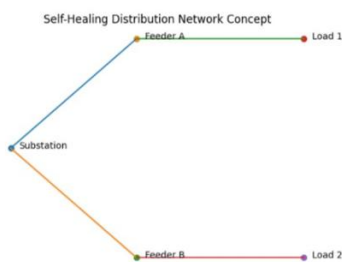
The framework significantly improves reliability and reduces recovery time. Thus; 4R model enables predictive and autonomous grids

- Improves reliability and power quality.
- Supports future intelligent energy infrastructure.

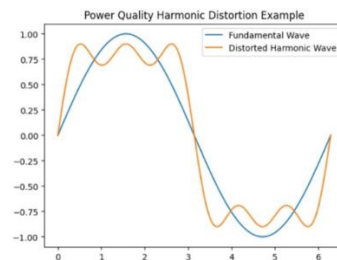
Microgrid Islanding Automation



Self-Healing Distribution Network



Power Quality Harmonic Analysis



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