Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Construction of a Fault Analysis and Normal-State Database for Safety-Grade PLC Modules in Nuclear Power Plants

Gi Ho Cho [a*], Gang Min Park[a], Kwan Woo Yoo [a], Dong Hwa Yun [a], Dong Yeon Lee [a]
[a]SOOSAN ENS Co., Research Institute, 2F, Soosan Building, 13, Bamgogae-ro 5-gil, Gangnam-gu, Seoul, 06367
[*]*Corresponding author: nolnolii@soosan.co.kr*

Keywords : Fault Diagnosis, Safety-Grade PLC, Database, Reactor Protection System, Predictive Maintenance

1. Introduction

Since the 2000s, operational nuclear power plants constructed with digital instrumentation and control (I&C) technology have benefited from self-diagnostic functions and ease of maintenance. However, unlike analog components, digital components are prone to sudden failures*. Nuclear power plants implement regular preventive maintenance at fixed intervals to prevent failures and accidents. However, such maintenance is performed independently of actual component faults**, limiting its effectiveness in preventing sudden failures.

To address these challenges, recent research has concentrated on the development of AI-based condition monitoring and fault prediction technologies. Korea Hydro & Nuclear Power (KHNP) has been conducting pilot operations of an AI predictive diagnostic system utilizing big data [1, 2]. The foundation of these technologies lies in robust and reliable datasets, making the construction of robust databases crucial. Additionally, condition monitoring and fault prediction systems typically rely on normal-state data as a baseline for detecting anomalies, emphasizing the importance of establishing a comprehensive normal-state database.

This study presents a case study on fault analysis, the construction of a normal-state database for diagnosing faults and conditions of safety-grade Programmable Logic Controller (PLC) modules (POSAFE-Q), and key measurement examples using the database.

* Failure: The inability of a system or component to perform its required function within specified limits.

** Fault: A defect in a hardware component that has the potential to cause a failure.

2. Failure Analysis

2.1 Failure Classification and Causes by Occurrence Period

Failure can be classified into catastrophic faults and degradation faults. Additionally, based on the timing of occurrence, failure can be categorized as early failures, random failures, and wear-out failures. Furthermore, based on causative factors and severity, faults can be categorized as inherent faults, minor faults, and microscopic faults.

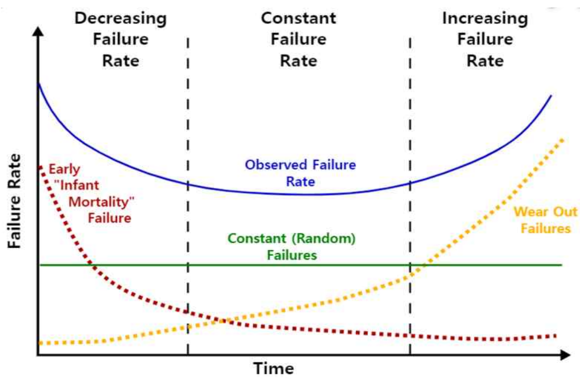

Fig. 1. Typical failure rate patterns over time.

The probability density function of a single component failure generally follows a normal distribution, with an increasing failure rate over time. In contrast, the failure probability density function of multiple components follows an exponential distribution, wherein the failure rate remains constant over time [3].

Table I: Time-Based Causes of Failure

Category	Cause of Occurrence
Early Failure	Failure due to Initial Stress, - Design Errors - Manufacturing Errors - Repair Errors - Improper Usage - Insufficient Debugging
Random Failure	Constant Failure Rate - Exceeding Design Limits - Vibration and Impact - Errors Undetected During Debugging - Overuse, User Errors - Failures Undetected by Previous Inspection Methods - Failures Uncontrollable Even with Preventive Maintenance (PM) - Natural Disasters
Wear Failure	Increasing Failure Rate - Characteristic Degradation - Shrinkage or Cracking

	- Insufficient Maintenance, Improper Maintenance

2.2 Causes and Types of Electronic Component faults

Most electronic component faults result from either inherent defect*** interacting with stress or independent stress factors. Among various stress factors, thermal stress is the predominant cause of failure. Stress categories include mechanical, thermal, electrical, and radiation stress. Alternatively, failures can be categorized into electrical and environmental stress, where environmental stress encompasses thermal, mechanical, and radiation stress [4].

*** Defect: A physical imperfection or flaw in a hardware component.

Table II. Types of Stress

Category	Detailed Classification
Physical	Thermal Shock, Thermal Cycle, Humidity
Mechanical	Vibration, Pressure, Impact, Friction Radiation Nuclear Radiation, Ionization
Electrical	Overvoltage, Overcurrent, Electrostatic Discharge (ESD), Surge & Spike, Electromagnetic Interference (EMI)

Fault modes of electronic components arise from the interaction of inherent potential defects with stress or from stress acting independently. Common fault modes in electronics include four types: short circuits, open circuits, parameter shifts, and electrical instability.
A short circuit occurs when a circuit is inadvertently connected, whereas an open circuit occurs when electrical continuity is lost. A parameter shift refers to a deviation from the expected operational range under normal input conditions, while electrical instability denotes fluctuating characteristics over time despite normal input signals [5].

3. Data Collection

3.1 Scope of Database Construction for PLC Condition Diagnosis

The database construction focuses on modules applied to the Reactor Protection System (RPS) of APR-1400 (Shin-Kori Units 5 and 6).

Table III. Reactor Protection System Modules

Type	Model
Power	NSPS-2Q
CPU	NCPU-2Q
NETWORK	NFD2-1Q, NFD1-5Q, NFD1-6Q
AI	NADF-1Q, NAD8-3Q
PI	NHSC-1Q
DI	NI-D23Q
DO	NQ-D23Q, NQ-A24Q

3.2 Types of PLC Condition Diagnosis Data

- Relay: Condition assessment through voltage and current waveform analysis following activation of the driving coil pulse power.
- Resistors, Inductors, Capacitors, Diodes: Condition assessment using current characteristics in response to input voltage.
- Operational Amplifiers (Opamps): Condition assessment through channel-wise gain (linear test) and IC saturation tests.
- Comparators: Condition assessment through IC saturation tests.
- Transistors / MOSFETs: Condition assessment using current characteristics in response to input voltage.
- Regulators: Condition assessment based on predefined input voltage and output voltage measurements.

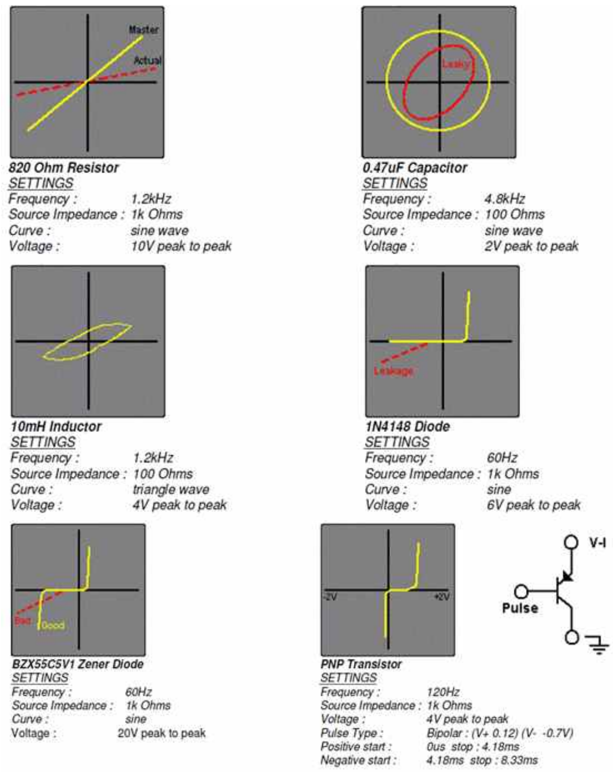

Fig. 2. Characteristic Curves of Components. (Yellow line: Master, Red line: Actual)

- Logic Devices: Condition assessment by verifying operational validity against the truth table provided in the datasheet.

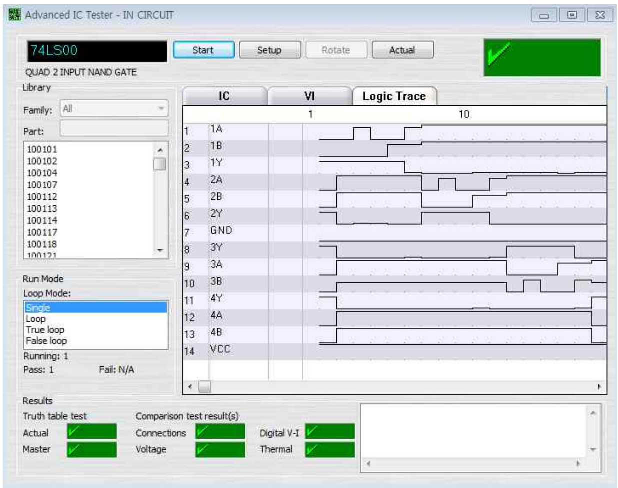

Fig. 3. Performance Evaluation of Logic Devices.

- Other IC Components: Condition assessment through current and voltage characteristics based on input voltage (or logic input).

3.3 Database Construction

The Reactor Protection System was classified into functional zones, and database construction was conducted by measuring and recording data from actual installed components within each functional zone.

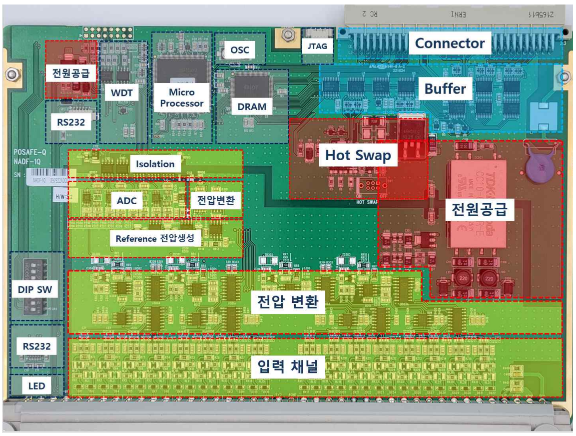

Fig. 4. Functional Block Analysis Example of NADF-1Q

The V-I Curve data for voltage and current characteristics is injected in the form of a sine wave at each measuring point, separated into 1024 measuring range voltages (e.g. -5 ~ 5V), and the current value is stored.

3.4 Database Utilization

The established database is utilized for evaluating the condition of suspected faulty or abnormal modules in nuclear power plants. Additionally, it is employed for fault injection testing (e.g., overvoltage and overcurrent conditions) and high-temperature environmental testing.

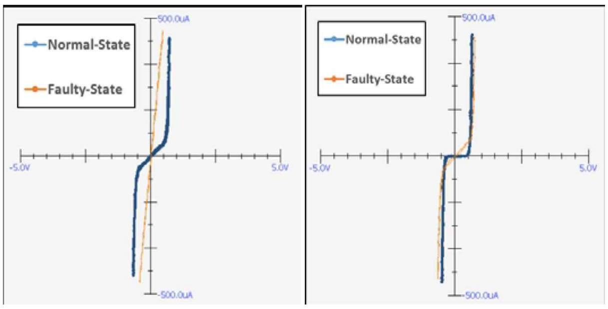

Fig. 5. Example of Fault Detection in NCPU-2Q [6]

4. Conclusions

This study systematically constructed a database for diagnosing the condition of safety-grade PLC modules comprising the APR-1400 Reactor Protection System. The database serves as a foundation for enhancing preventive maintenance and operational safety. Furthermore, this research highlights the potential for expanding its application to various nuclear power plant systems. Future studies will explore real-time evaluation methodologies based on the collected data.

5. Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) (No. RS-2022-00144239)

REFERENCES

[1] Korea Hydro & Nuclear Power Co., Ltd, KHNP Commercializes Automated Predictive Diagnostic Technology for Facilities, 2021.11.29, https://www.khnp.co.kr/main/selectBbsNttView.do?key=2289&bbsNo=71&nttNo=26175

[2] Korea Hydro & Nuclear Power Co., Ltd, KHNP Builds Big Data for Predictive Diagnostics of Key Nuclear Power Plant Equipment, 2018.01.11, https://www.khnp.co.kr/main/selectBbsNttView.do?key=2289&bbsNo=71&nttNo=25453

[3] Byeong Min Mun, A Reliability Analysis and Maintenance Optimization for Repairable Systems with Bathtub Shaped Intensity, hanyang university, 2017.

[4] Byeng Suk Song, Failure Analysis of Electronic Component, Journal of KWS, Vol 21 No. 3, 2003

[5] Chandler, G., W.K Denson, M.J. Rossi, R. Wanner, “Failure Mode & Mechanism Distribution”, RAC, 1991.

[6] Ka Ram Park, V-I Curve Analysis for Status Prediction of Nuclear Power Plant Safety-Grade PLC, Transactions of Korean Nuclear Society Spring Meeting, 2023