Argonne NATIONAL LABORATORY

ANL R&D ACTIVITIES

A. DAVE, A. HEIFETZ, R. HUI, M. LI, T. NGUYEN, R. PONCIROLI, S. MOHANTY, R. VILIM, H. WANG, L. YACOUT
Nuclear Science and Engineering Division

Virtual presentation to NRC on AI/ML
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U.S. DEPARTMENT OF ENERGY
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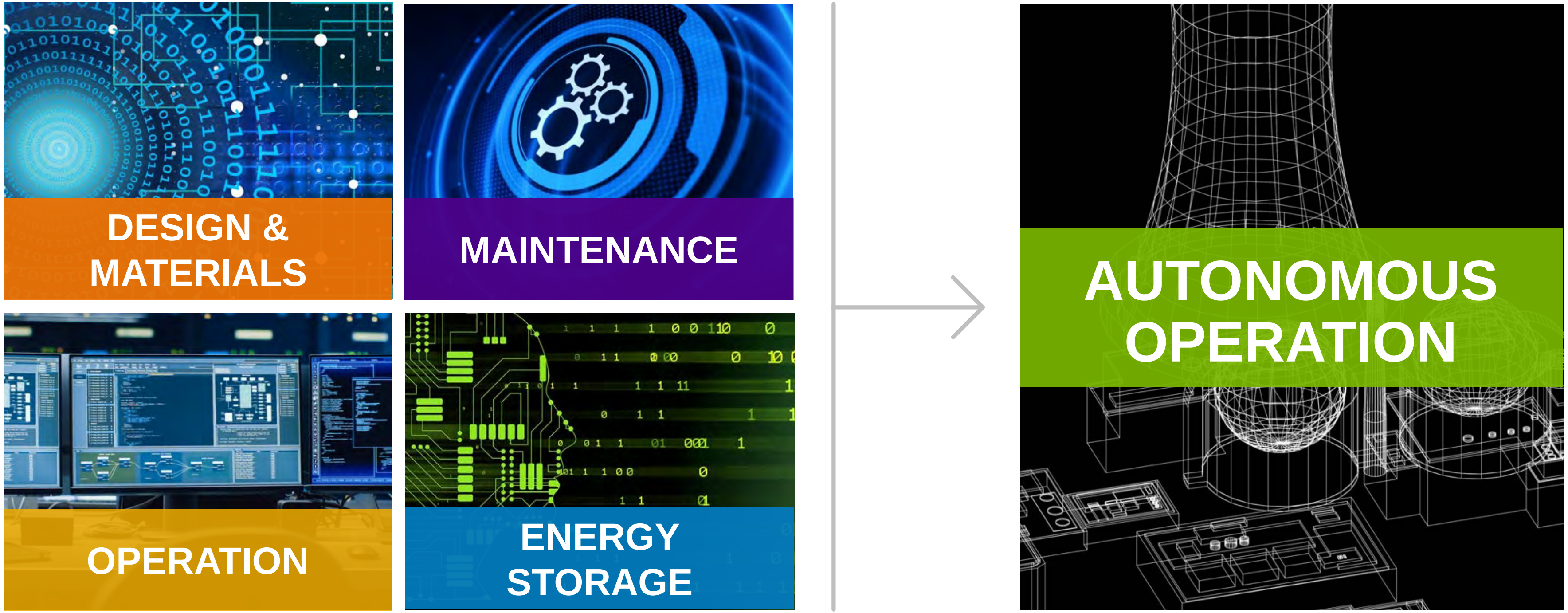
ANL AI/ML CAPABILITIES ENABLING FUTURE AUTONOMOUS OPERATION



DESIGN & MATERIALS

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AI FOR DESIGN SPACE CHARACTERIZATION

Design and Materials

1. NEED

Facilitate the development and deployment of advanced reactors by improving economics (through accurate safety margin predictions) and reducing the licensing burden (through improved uncertainty quantification).

2. CAPABILITY DEVELOPED

Method to develop ML-based closure models to capture complex spatial-temporal reactor transients, with uncertainty quantifications.

Integration of ML-based closure model into reactor system transient simulation tool SAM.

3. ACCOMPLISHMENTS

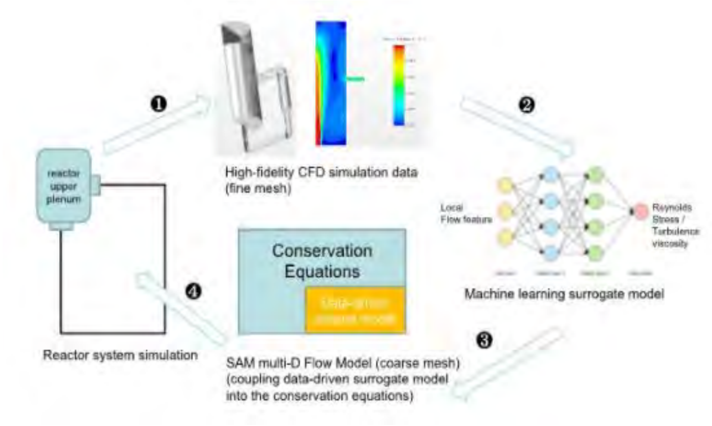
Development and application of data-driven turbulence closure model for thermal mixing and stratification modeling.

Developed a system approach on the optimization and uncertainty quantification of the data-driven ML models

4. FUTURE DEVELOPMENT

Incorporate more domain knowledge into machine learning-based closure for advanced reactor safety modeling;

Develop deep learning-based multi-physics online simulator to support autonomous operations in advanced reactors



Reduction of high dimensional data using ML to yield fast running low-order surrogate models

ML FOR MATERIALS DEVELOPMENT

Design and Materials

1. NEED

AI-enhanced radiation damage assessment to shorten material development and qualification cycle.

2. CAPABILITY DEVELOPED

Deep learning-based radiation defect analysis tools were developed for automated detection, tracking and analysis of voids and dislocation loops produced during in situ ion irradiation at Argonne's IVEM-Tandem Facility.

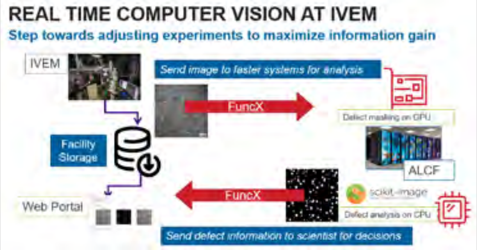
3. ACCOMPLISHMENTS

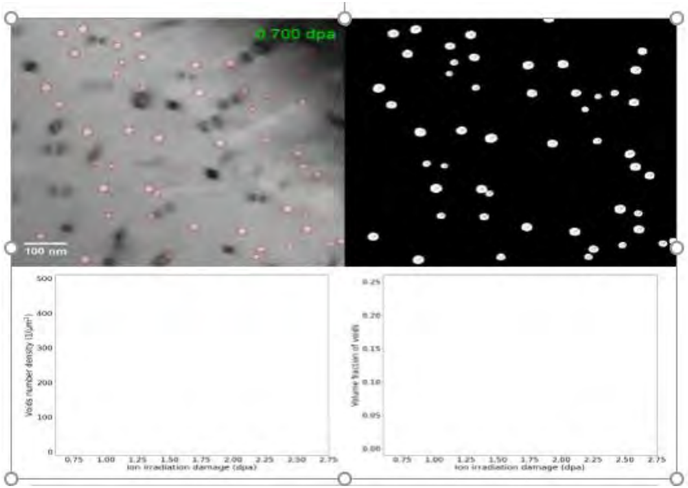
Developed multi-object tracking model to measure the lifetime of individual dislocation loops.

Developed an automated void detection and analysis tool using computer vision and deep learning.

Developed machine-learned dynamical equations.

4. FUTURE DEVELOPMENT





Processed a video recorded during in situ ion irradiation to measure the size and number of voids as a function of irradiation dose produced in pure Nickel irradiated with 1 MeV Kr ions at 600℃.

ML FOR MATERIALS INSPECTION

Design and Materials

1. NEED

Imaging of internal microscopic material defects in additively manufactured metallic structures (SS316 and IN718) for nuclear applications

2. CAPABILITY DEVELOPED

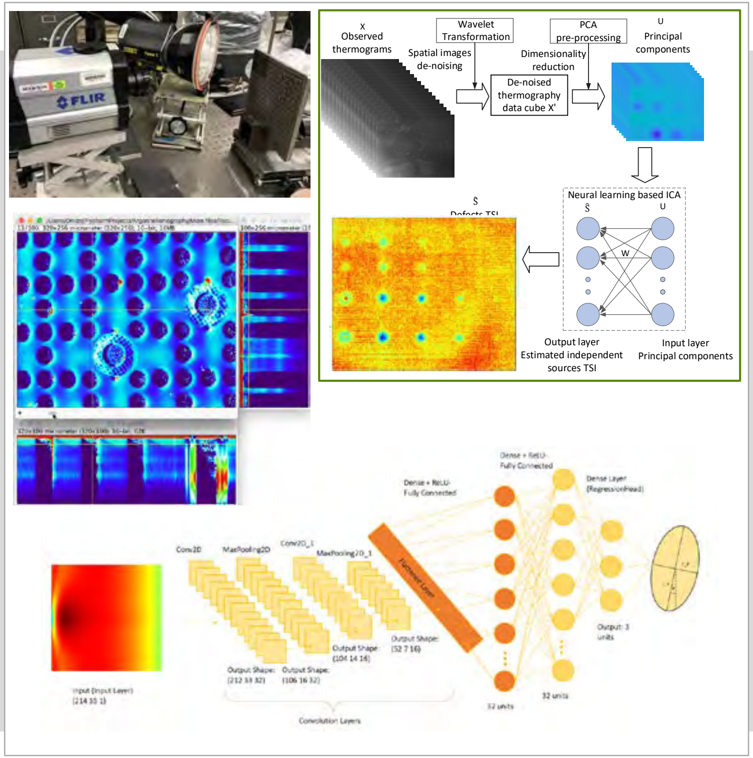
- Imaging hardware (FLIR X8501, flash lamp, optics)
- Machine learning image processing algorithms
- Thermal tomography depth reconstruction and defect classification algorithms

3. ACCOMPLISHMENTS

- Detection of calibrated subsurface microscopic defects in SS316 (down to 100µm size) with unsupervised learning of thermography images
- Classification of defects aspect ratio and orientation in thermal tomography images with convolutional neural network

4. FUTURE DEVELOPMENT

- Further reducing threshold of detected defect size (target 50µm)
- Rapid data processing for in-situ monitoring applications



OPERATION

HEALTH MONITORING: PHYSICS-BASED

Operation

1. NEED

Advanced heath monitoring of equipment for O&M

Inclusion of domain knowledge to deliver diagnoses with greater specificity and reliability

2. CAPABILITY DEVELOPED

Diagnoses both equipment and sensor faults within an engineered system

Requires no *a priori* values for equipment design parameters

Incorporates automated reasoning to facilitate ease of use by non-SMEs

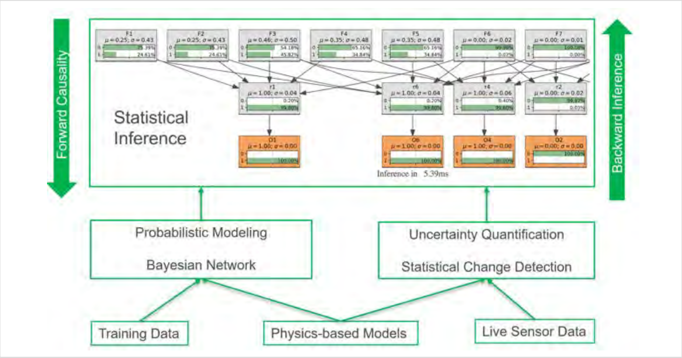
Derives real-time equipment performance from physics-based models

3. ACCOMPLISHMENTS

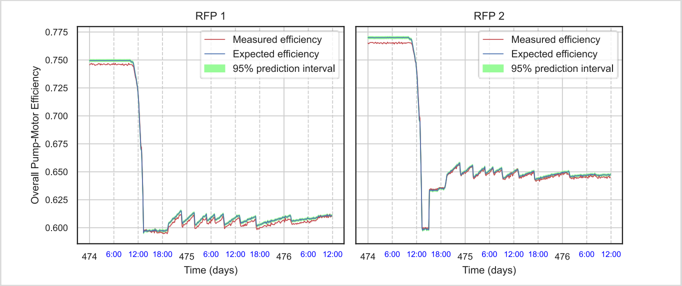
Blind detection and diagnosis of Monticello NPP reactor feed pump fault, North Anna NPP feedwater heater fault

4. FUTURE DEVELOPMENT

Subsume data-driven methods into the existing Bayesian setting for an integrated diagnostic tool utilities have deemed valuable



PRO-AID Code Architecture



PRO-AID Feed Pump Diagnosis: Efficiency Loss Attributed to Bearing Degradation

HEALTH PREDICTION: MECHANISTIC

Operation

1. NEED

High temperature operation can lead to material damage

Need real-time prediction of component health to reduce inspection cost

2. CAPABILITY DEVELOPED

System level structural mechanics model of the physical twin

Real time AI/ML nonlinear material damage prediction from sensors and structural state prediction

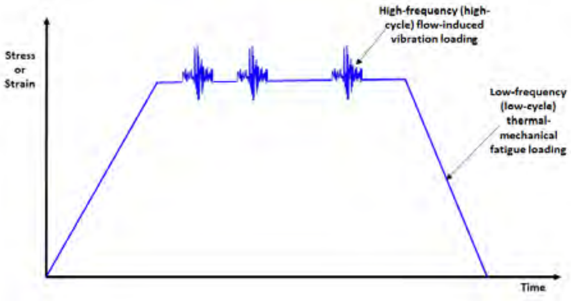
3. ACCOMPLISHMENTS

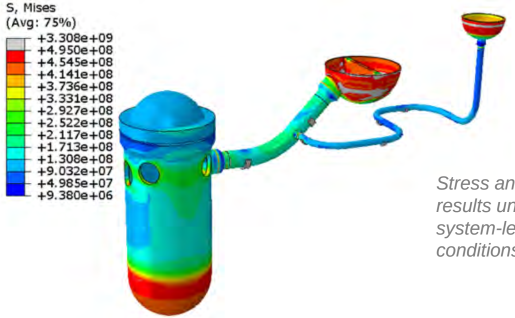
Prediction of component interior system-level stress analysis from AI/ML-digital-twin model during load following based on a few measurements

4. FUTURE DEVELOPMENT

Real-time benchmarking and concept validation using ANL METL or similar facility

Stress experienced over a fuel cycle





Stress analysis results under system-level conditions

PERFORMANCE OPTIMIZATION: OPEN-LOOP

Operation

1. NEED

A capability to learn complex relationships between sensed process variables and performance metrics, such as integrated thermal power and spatial peaking factors

2. CAPABILITY DEVELOPED

Machine learning models that can identify through physics and engineering principles the key process variables inputs

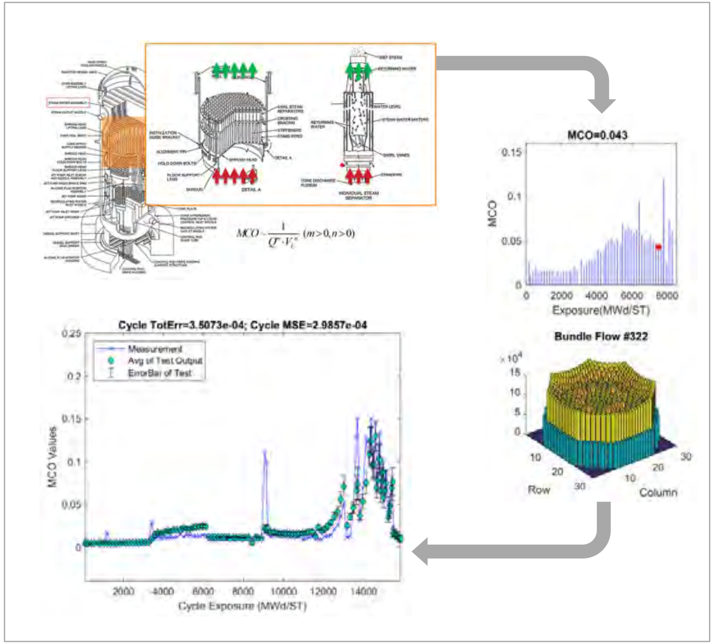
Supervised machine learning algorithms for predicting performance measures from sensor and digital twin virtual sensor inputs

3. ACCOMPLISHMENTS

IN-USE – A physics-informed neural network model developed for optimizing BWR reactor fuel loading and operation mid-cycle

4. FUTURE DEVELOPMENT

Identification and development of ML predictive models for estimation of important performance metrics for advanced reactors



Predictive model developed for a BWR from archived operating history – In use at a US utility

PERFORMANCE OPTIMIZATION: CLOSED-LOOP

Operation

1. NEED

Optimal control policies that avoid the *curse of dimensionality*

Ability to handle nonlinear phenomena (e.g., material degradation, dynamics during load-following)

2. CAPABILITY DEVELOPED

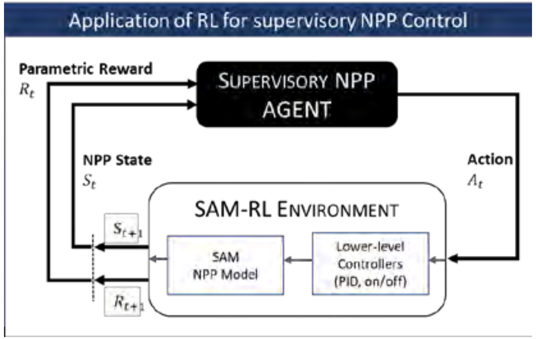
A reinforcement learning (RL) approach that is a data-driven having the potential to learn control policies whose performance surpasses that of humans.

RL agents that learn from a physics-constrained environment via the SAM code – a best-estimate system level code for advanced reactors

A design development framework that generates RL environments that is reactor design agnostic (MSRs, SFRs, HTGRs).

3. PROPOSED FUTURE DEVELOPMENTS

Numerical demonstration of RL-agent providing supervisory control for a Fluoride-cooled High-temperature Pebble-bed Reactor in FY22



Framework to train supervisory NPP agents using next-generation AR best-estimate system code SAM

MAINTENANCE

DECISION MAKING

Maintenance

1. NEED

Explainable diagnoses for decision making

Confirmatory diagnostic traceback via the conservation equations to an accountable set of sensors

2. CAPABILITY DEVELOPED

Physics-based fault symptoms from model residuals

Automated backward chaining reasoning

Fault diagnoses can be explained in the forward causality direction

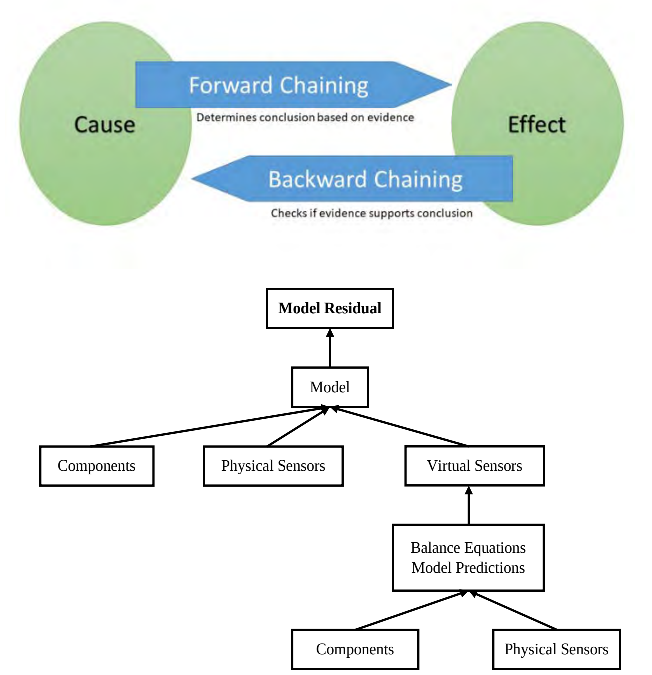
3. ACCOMPLISHMENTS

Conducted assessment tests with NPP operators on full scope simulator

Received confirmation of the utility and value of the approach

4. FUTURE DEVELOPMENT

Improve reasoning engine efficiency



Physics-Based Model Residual Generation: A Basis for Explainable Diagnoses

SCHEDULING

Maintenance

1. NEED

Cost optimization of O&M for increased economic competitiveness

2. CAPABILITY DEVELOPED

Sensor network design algorithm to provide for monitoring/diagnosing faults and component degradation over plant lifetime

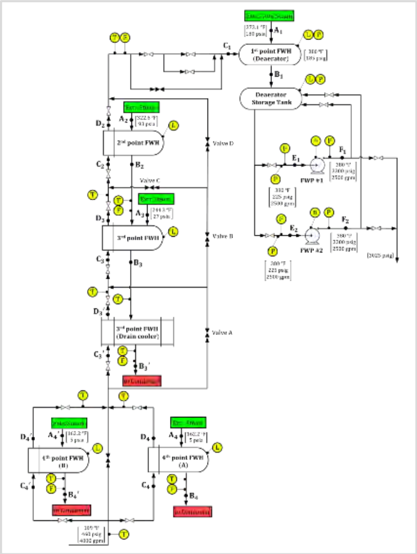
Maintenance and asset management approach that integrates online monitoring with plant risk profile

3. ACCOMPLISHMENTS

In-progress demonstration for the feedwater and condensate system of the MHTGR design

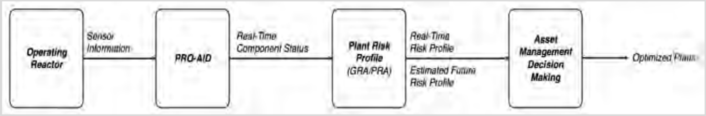
4. FUTURE DEVELOPMENT

Application of Markov Decision Process method for asset-management decision-making



P&ID of the feedwater system used as test-case

Overview of Operational Decision-Making Process



ENERGY STORAGE AND THE GRID

ENFORCING STORAGE CAPACITY CONSTRAINTS

Energy Storage and the Grid

1. NEED

Control strategies for improved regulation wrt to structure operating limits for margin recovery

2. CAPABILITY DEVELOPED

Algorithm for translating process variables constraints into power set-points limits

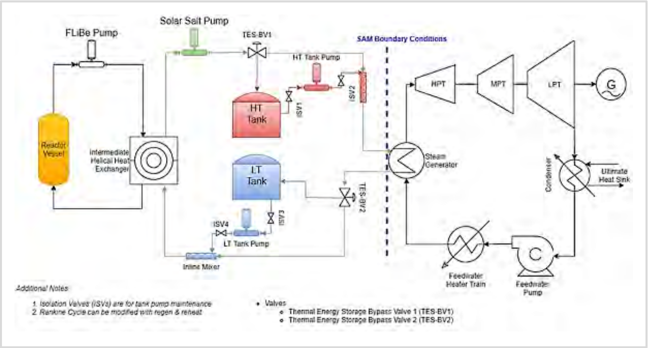
Satisfies n-dimensional envelope as set by constraints on important process variables

3. ACCOMPLISHMENTS

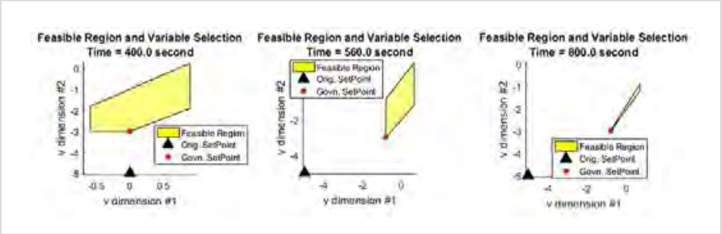
Preliminary implementation completed for representative integrated energy system

4. FUTURE DEVELOPMENT

Integrate with diagnostics and decision-making algorithms for semi-autonomous operation



Reactor with Thermal Storage



Time Evolution of Acceptable Region of Operation during a Transient

REDUCED ORDER ON-LINE LEARNING

Energy Storage and the Grid

1. NEED

Accurate mathematical representation of power systems at various power level and operational mode for efficient control

2. CAPABILITY DEVELOPED

Algorithm to update the state-space representation of power systems at various power level and mode using on-line simulation data

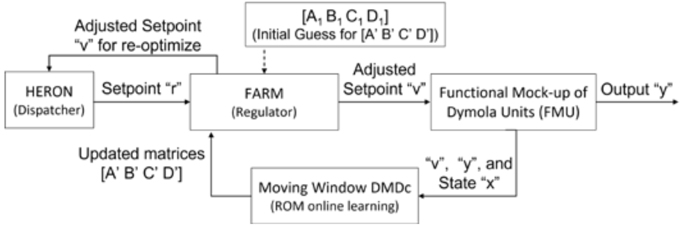
On-line updated mathematical models helped avoiding constraint violations, actuation oscillation and over-shooting

3. ACCOMPLISHMENTS

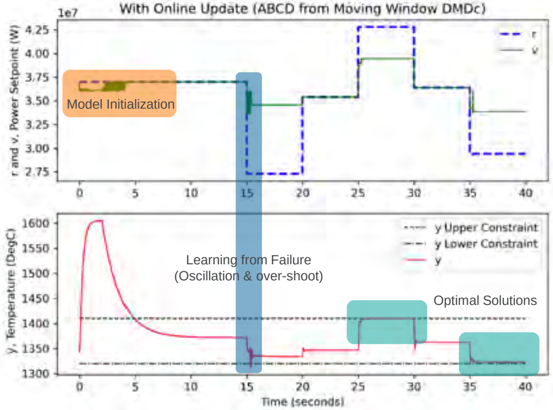
Preliminary implementation completed for representative power systems

4. FUTURE DEVELOPMENT

Improve the robustness of on-line learning algorithm to learn from noisy data



Block Diagram Schematic of Algorithms



On-line ROM learning and solution improvement example

AUTONOMOUS OPERATION

AUTONOMOUS OPERATION AS AN INTEGRATED PROCESS

Autonomous Operation

1. NEED

O&M cost reduction in deregulated markets through more efficient human resource allocation

2. CAPABILITY DEVELOPED

Diagnostics – Discrimination of sensor and component faults via PRO-AID algorithm

Control – Automation of constraint enforcement via Reference Governor algorithm

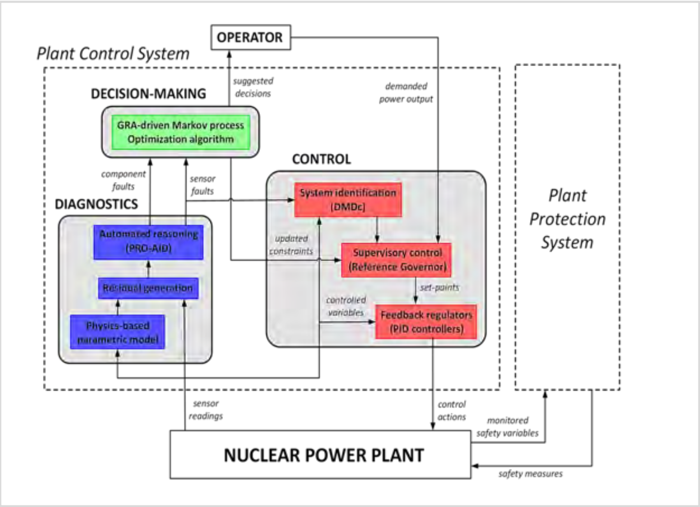
Decision-Making – Optimal operating and maintenance procedures via Markov process

3. ACCOMPLISHMENTS

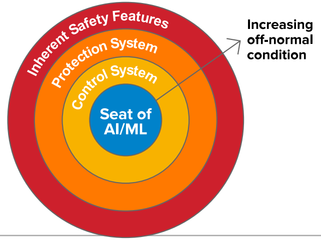
Developed a control-oriented simulator of KP-FHR coupled with thermal energy storage

4. FUTURE DEVELOPMENT

Integration of diagnostics, control, and decision-making for seamless autonomous operation



Advanced Reactor - Layers of Protection

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