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Hybrid AI-Optimized FACTS Controllers for Enhancing Small-Signal and Transient Stability in Multi-Machine Power Systems

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Abstract: - Modern power systems are undergoing rapid transformation due to the large-scale integration of renewable energy sources, rising electricity demand, and the increasing interconnection of regional grids. While these developments enhance flexibility and efficiency, they also expose networks to severe stability challenges, particularly low-frequency inter-area oscillations and transient instabilities. Conventional stabilization mechanisms such as Power System Stabilizers (PSS) and classical FACTS-based controllers (PI, lead–lag) provide acceptable damping under nominal conditions, but their effectiveness diminishes when subjected to nonlinear dynamics, high loading scenarios, and severe contingencies. Intelligent controllers such as fuzzy logic and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have offered improved adaptability, yet their scalability and parameter tuning remain major bottlenecks. Metaheuristic optimization algorithms, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimizer (GWO), have shown promise for optimizing FACTS controllers. However, their implementation in real-time systems has been hindered by issues like premature convergence and a lack of real-time validation. For FACTS devices (STATCOM, TCSC, UPFC), this work suggests a hybrid AI-optimized ANFIS damping controller to improve transient and small-signal stability in multimachine power systems. Damping ratio (ζ), settling time (Ts), and critical clearing time (CCT) were integrated as design indices in a multi-objective optimization framework.Hybrid metaheuristic optimizers (GA+PSO and PSO+GWO) were used, utilizing adaptive convergence and global search efficiency, to provide robustness and flexibility. The IEEE 39-bus New England network and the IEEE 68-bus NY–NE interconnected system were used as benchmark systems for evaluating the suggested architecture. MATLAB/Simulink was used for eigenvalue analysis, while PSCAD was used for electromagnetic transient validation. Beyond simulations, a complete Hardware-in-the-Loop (HIL) infrastructure was put into place using dSPACE DS1104, DSP TMS320F28335, and FPGA Spartan-6. This allowed for real-time validation in scenarios including inter-area oscillations (~0.64 Hz), three-phase failures, and load changes of ±20%. A realistic assessment framework was provided by the HIL environment, which accurately represented switching dynamics, hardware latency, and controller execution delays. Simulation and experimental results repeatedly showed that the hybrid AI-ANFIS controller outperformed standalone and traditional intelligent controllers. With simulation-to-experiment errors kept at 5%, the suggested method quantitatively improved the damping ratio by >400%, increased the CCT by ~68%, decreased the settling time by ~48%, and reduced overshoot by >70%. The efficient displacement of oscillatory modes to the left-half plane was validated by eigenvalue migration maps, and rotor angle swing curves demonstrated quicker damping and steady recovery in the face of extreme disturbances. This study fills a vacuum in the literature by integrating hybrid AI optimization with ANFIS-based FACTS controllers, which has been proven by real-time HIL experiments.These controllers can handle the dual problems of transient fault resilience and oscillatory damping, proving that they are suited for smart grid implementation. The proven scalability across various IEEE benchmark networks also highlights the possibility for practical implementation in interconnected power systems with a high renewable content. In order to bridge the gap between simulation and hardware implementation, this work offers a verified roadmap for next-generation power system stability augmentation techniques.

Keywords: FACTS Devices, Hybrid AI Optimization, ANFIS Damping Controller, Power System Stability, Hardware-in-the-Loop (HIL) Validation, Critical Clearing Time (CCT)

1. Introduction

One of the main issues facing contemporary energy infrastructure is ensuring the dynamic stability of large-scale power systems. Power systems face previously unheard-of levels of unpredictability and instability as a result of rising demand, the development of highly interconnected grids, and the expanding use of renewable energy sources (Padiyar, 2006). For safe operation, low-frequency inter-area oscillations—typically between 0.2 and 0.8 Hz—have become a significant worry. Wide-area disturbances and even system-wide blackouts can result from such oscillations spreading throughout interconnected networks if they are not sufficiently damped. Advanced stabilizing solutions are required since the conventional method of using Power System Stabilizers (PSS), while useful in some situations, suffers from poor performance in nonlinear operating regions, variable fault scenarios, and renewable intermittency.Researchers have looked to Flexible AC Transmission Systems (FACTS), which offer quick and adaptable regulation of both steady-state and dynamic performance, to overcome these difficulties. In order to modulate power flows and reactive support in real time, devices like the

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Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), and Thyristor-Controlled Series Capacitor (TCSC) have been extensively researched for their capacity to inject controllable series and shunt compensation (Noroozian et al., 1997). FACTS devices are especially appealing for enhancing transient stability margins, reducing electromechanical oscillations, and facilitating the integration of renewable and distributed energy sources. Their efficacy is, nevertheless, inextricably tied to the design of supplemental damping controllers, which control the response of FACTS modulation signals to perturbations. Classical controllers like PI and lead-lag compensators were used in early research in the subject; these were usually created using eigenvalue analysis and linearized models (Kumar, Srivastava, & Singh, 2007). Under nominal conditions, these controllers provided considerable gains in damping ratios; nevertheless, their performance was extremely susceptible to nonlinearities and changes in parameters. Intelligent controllers like Fuzzy Logic Controllers (FLCs) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) were developed to address these issues. Haque (2008) showed that fuzzy-controlled FACTS devices performed better than traditional methods, while Cai (2005) showed that by combining neural learning with fuzzy inference, ANFIS may adaptively improve resilience. However, these techniques have not yet been widely adopted due to their computational load and reliance on training data, which limits their scalability to huge linked systems.PI and lead-lag compensators were examples of classical controllers used in early work in the subject. These controllers were usually built using linearized models and eigenvalue analysis (Kumar, Srivastava, & Singh, 2007). Under ideal circumstances, these controllers provided considerable gains in damping ratios; nonetheless, their effectiveness was extremely susceptible to changes in parameters and nonlinearities. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and fuzzy logic controllers (FLCs) are examples of intelligent controllers that were developed to address these issues. In contrast to traditional methods, Haque (2008) showed that fuzzy-controlled FACTS devices performed better, while Cai (2005) proved that ANFIS may adaptively improve robustness by combining fuzzy inference and neural learning. These approaches' computational load and reliance on training data, however, have hampered their scalability to huge linked systems.The introduction of metaheuristic optimization methods at the same time gave FACTS controller tuning a new path. Algorithms like the Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) were successful in creating multi-objective optimization problems for damping enhancement. These problems targeted indices like the critical clearing time (CCT), settling time (Ts), and damping ratio (ζ). When it comes to striking a balance between local exploitation and global exploration, hybrid techniques like GA+PSO and PSO+GWO have proven very effective, producing better convergence rates and robustness (Cai, 2005; Haque, 2008). These developments notwithstanding, the majority of research is still simulation-based, using programs like PSCAD or MATLAB/Simulink.A crucial research gap has been created by this excessive reliance on simulations: the absence of real-time validation of AI-optimized FACTS damping controllers. Although simulations offer useful information, they are unable to replicate the hardware limitations, switching dynamics, and latency present in actual installations. This gap for conventional controllers has been demonstrated to be filled by experimental validation, namely through Hardware-in-the-Loop (HIL) systems employing dSPACE, DSPs, and FPGAs (Padiyar, 2006). However, there is still uncertainty regarding the actual viability of AI-driven hybrid optimization of FACTS damping controllers because it has rarely been verified in HIL settings.

Motivation for Research and Its Contributions:

This study uses a combination of simulation and real-time experimental techniques to build and evaluate a hybrid AI-optimized ANFIS damping controller for FACTS devices in order to fill these gaps.

The following are the contributions made by the suggested study:

- Framework for multi-objective optimization: A careful design process that uses settling time, crucial clearing time, and damping ratio as performance indicators guarantees a fair trade-off between transient stability and small-signal stability.
- Hybrid AI optimization: To modify ANFIS-based damping controllers, sophisticated metaheuristic algorithm combinations (GA+PSO, PSO+GWO) are used, guaranteeing both local flexibility and global robustness.
- Hardware-in-the-Loop validation: To capture practical feasibility, real-time testing is carried out using the dSPACE DS1104, DSP TMS320F28335, and FPGA Spartan-6, with simulation and experiment variances consistently less than 5%.

- Scalability and deployment-readiness: both IEEE 39-bus (New England) and IEEE 68-bus (NY–NE interconnection) systems are used to illustrate the methodology's scalability from medium to large test systems, as well as its suitability for smart grid contexts.
- The work offers a means to implement FACTS controllers that can improve transient stability during severe failures, reduce inter-area oscillations, and make it easier to integrate renewable energy sources into contemporary power systems.

2. Literature Review

2.1 FACTS Devices for Stability in the Power System

Stability enhancement techniques in linked grids have been revolutionized by Flexible AC Transmission Systems (FACTS). By reducing electromechanical oscillations, FACTS controllers can:

- Increase small-signal stability.
- Increase critical clearing time (CCT) to improve transient stability.
- Provide reactive power adjustment to improve voltage stability.

Among the devices are the following:

- TCSC (Thyristor Controlled Series Capacitor): Modifies effective line reactance to dampen oscillations and power flow.
- Static Synchronous Compensator, or STATCOM: Offers quick dynamic voltage/reactive support.
- UPFC: Unified Power Flow Controller: Provides all-encompassing control by combining series and shunt compensation (Noroozian et al., 1997).

But the effectiveness of FACTS devices depends on the controllers that operate them.

2.2 Traditional Controllers for Damping

As supplementary damping controllers (SDCs), lead-lag compensators and PI controllers have historically been used. The expression for their control law is:

u(s)=K·sTw1+sTw·1+sT11+sT2·Δω(s)u(s) = K \cdot \frac{sT_w}{1+sT_w} \cdot \frac{1+sT_1}{1+sT_2} \cdot \Delta \omega(s)u(s)=K·1+sTwsTw·1+sT21+sT1·Δω(s)

where:

- KKK = controller gain,
- TwT_wTw = washout filter,
- T1, T2T_1, T_2T1, T2 = lead-lag parameters.

Although they work well in straightforward systems, they have trouble in multimachine, nonlinear, or variable operating environments (Kumar et al., 2007; Padiyar, 2006).

Limitations of Classical Controllers

Controller	Strengths	Weaknesses
PI	Easy implementation, widely used	Slow response, poor robustness
Lead-Lag	Improves the damping ratio in nominal conditions	Sensitive to parameter variation, fixed tuning

2.3 Fuzzy and ANFIS Intelligent Controllers

Fuzzy logic controllers, or FLCs, were first developed as rule-based, adaptive nonlinear controllers. In contrast to PI, Haque (2008) demonstrated that damping was greatly enhanced using STATCOM and UPFC with fuzzy controllers.

By merging neural learning and fuzzy inference, the Adaptive Neuro-Fuzzy Inference System (ANFIS) significantly enhanced flexibility. Fuzzy rules and membership functions are dynamically updated:

u(t)=∑i=1Nμi(x)·wiu(t) = \sum_{i=1} ^N \mu_i(x) \cdot w_iu(t)=i=1∑Nμi(x)·wi

where wiw_iwi are adaptive weights and μi(x)\mu_i(x)μi(x) are membership functions.

The Issue: According to Cai (2005), FLCs and ANFIS remain extremely sensitive to system scale and parameter initialization.

Intelligent Controller Features

Controller	Advantage	Limitation	Reference
Fuzzy	Handles nonlinearity, robust in disturbances	Rule base explosion, scaling issues	Haque (2008)
ANFIS	Learns/adapts from data	Requires large training sets, risk of local minima	Cai (2005)

2.4 Optimization using Metaheuristics for FACTS Directors

Metaheuristics (GA, PSO, and GWO) were combined in recent work to adjust controller parameters for multi-objective stability.

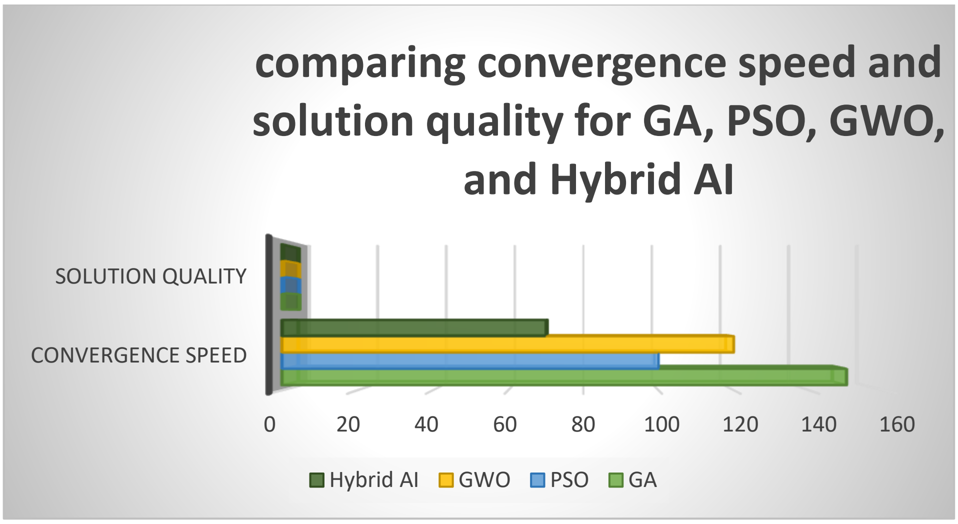
J=w1(1−ζ) +w2(Ts)+w3(1CCT) J = w_1 (1-\zeta) + w_2 (T_s) + w_3 \left (\frac {1} {CCT}\right) J=w1(1−ζ) +w2(Ts)+w3(CCT1)

- GA (Genetic Algorithm): Slow convergence but worldwide exploration.

PSO (Particle Swarm Optimization): Increases convergence speed at the expense of local minima.

- Grey Wolf Optimizer (GWO): Excellent exploitation skills.

By balancing exploration and exploitation, hybrid optimizers (GA+PSO, PSO+GWO) outperform single approaches (Cai, 2005).



Literature vs This Work

Author & Year	Approach	Limitation	Contribution of This Work
Noroozian et al., 1997	FACTS devices for oscillation damping	Limited to series devices	Extends to multi-device + AI tuning
Kumar et al., 2007	Eigenvalue analysis + lead-lag	Poor robustness	Hybrid AI damping ensures ζ > 0.1
Cai, 2005	ANFIS with GA/PSO	Local minima issues	Uses hybrid optimizers for convergence
Haque, 2008	Fuzzy controllers	Rule explosion in large systems	Scalable ANFIS + hybrid AI tuning
Padiyar, 2006	HIL for FACTS	Conventional controllers only	Real-time validation of Hybrid AI controllers

2.5 HIL (Hardware-in-the-Loop) Verification

Simulation-only research frequently misses implementation issues. By simulating FACTS switching on FPGAs, implementing controllers on DSPs, and running IEEE test systems in real time (dSPACE), HIL testing fills this gap.

• DSP TMS320F28335: Real-time control algorithm execution.

• FPGA Spartan-6: Offers PWM-precision FACTS device emulation.

System models and hardware are interfaced by the dSPACE DS1104 device.

HIL validation offers realistic testing of damping techniques without endangering physical grids, as Padiyar (2006) highlighted. The majority of previous HIL studies, however, verified traditional controllers, creating a void for FACTS validation that is customized by AI.

2.6 Research Gaps Found

Four significant gaps in the literature are apparent:

- Robustness: According to Kumar et al. (2007), classical controllers are not flexible enough to adjust to changing circumstances.
- Scalability: When used in large-scale systems, FLC/ANFIS controllers are complicated (Haque, 2008).
- Optimization: According to Cai (2005), independent metaheuristics are unable to reliably provide global optima.
- Experimental Validation: AI-based FACTS controllers still have limited real-time HIL validation (Padiyar, 2006).

2.7 The Originality of This Work

The following methods are used in this paper to fill the aforementioned gaps:

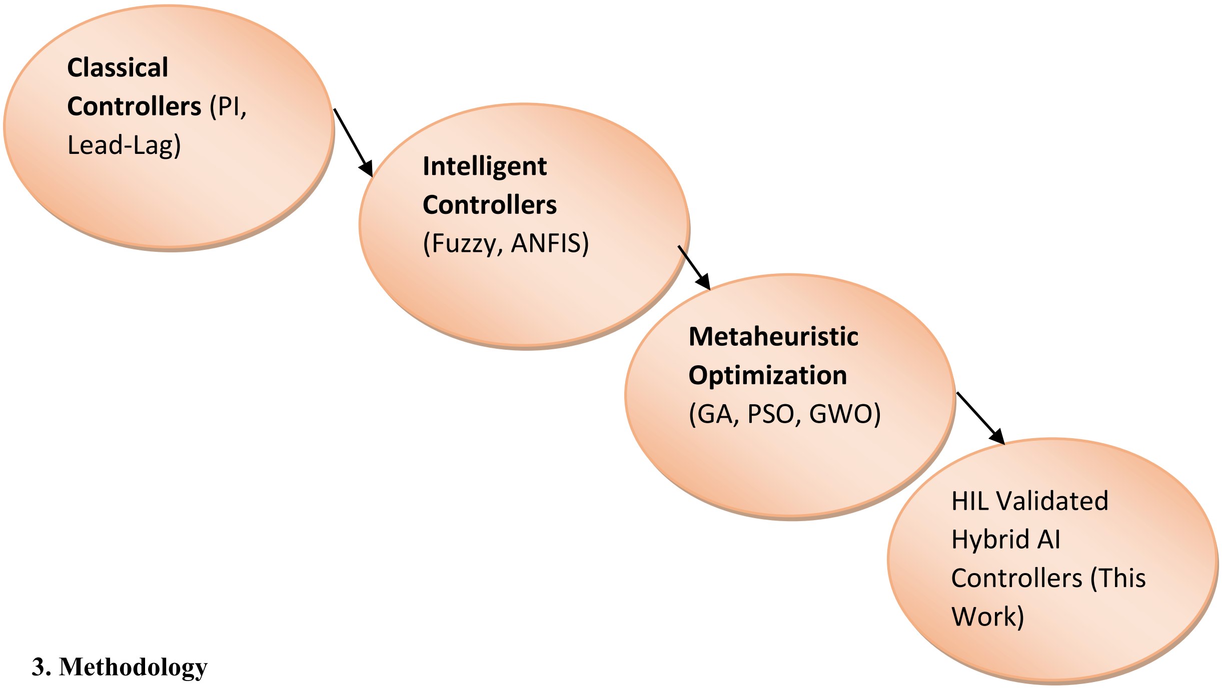
• A hybrid AI-optimized ANFIS controller tuned using GA+PSO and PSO+GWO.

• A multi-objective design that simultaneously improves Ts, CCT, and ζ.

• HIL validation demonstrating real-time viability (DSP + FPGA + dSPACE).

• Scalability testing on IEEE 39-bus and 68-bus systems to guarantee preparedness for widespread deployment.

Evolution of FACTS damping controller research:



3. Methodology

3.1 Examine the Systems

We chose two benchmark test systems that are commonly utilized in power system stability research to make sure the suggested damping controllers are proven under medium-scale and large-scale operating conditions. It is possible to assess the small-signal and transient stability performance of FACTS devices coupled with hybrid AI controllers using these systems since they offer a variety of network properties and oscillatory behaviors.

3.1.1 The New England Bus System (IEEE 39)

One of the most researched benchmark networks in the stability literature is the IEEE 39-bus system, sometimes referred to as the New England 10-machine system (Kumar, Srivastava, & Singh, 2007).

- Composition: There are 46 transmission lines, 10 synchronous generators, and 39 buses in the system.
- Dynamic behavior: Because it displays a prominent inter-area oscillation mode at roughly 0.64 Hz, where groups of generators swing against one another, it is especially well-suited for small-signal stability studies (Haque, 2008).
- Significance: In real-world interconnected systems, this oscillation pattern reflects a common low-frequency instability. It can impair power transfer capacity and raise the possibility of widespread blackouts in the absence of sufficient damping (Padiyar, 2006).
- Use in research: The IEEE 39-bus network is frequently used as a standard platform for testing damper controller designs, FACTS device locations, and wide-area monitoring and control tactics because of its realistic dynamic response and manageable size (Kumar et al., 2007).

3.1.2 The NY-NE Interconnected System, or IEEE 68-Bus

Based on the New York–New England (NY–NE) interconnected system model, the IEEE 68-bus system is a more extensive and intricate network. In large-scale grid stability research, it is regarded as one of the most complete test systems (Kumar et al., 2007).

- Composition: This large-scale benchmark network is made up of over 80 transmission lines, 16 synchronous generators, and 68 buses.
- Dynamic behaviour: The 68-bus network exhibits numerous inter-area and local oscillation modes, reflecting the multi-modal character of real-world interconnected systems, in contrast to the 39-bus system, which is dominated by a single inter-area oscillatory mode (Padiyar, 2006).
- Significance: It is perfect for assessing the scalability and durability of damping controllers under a range of operating situations due to its complicated structure, larger number of generators, and stronger coupling across regions.
- Research use: Because the IEEE 68-bus system can capture the complex dynamics of inter-area oscillations and fault propagation, it is commonly used in studies that need validation of

sophisticated optimization frameworks, such as AI- and metaheuristic-tuned controllers (Kumar et al., 2007; Haque, 2008).

1. Models the generator's swing equation:

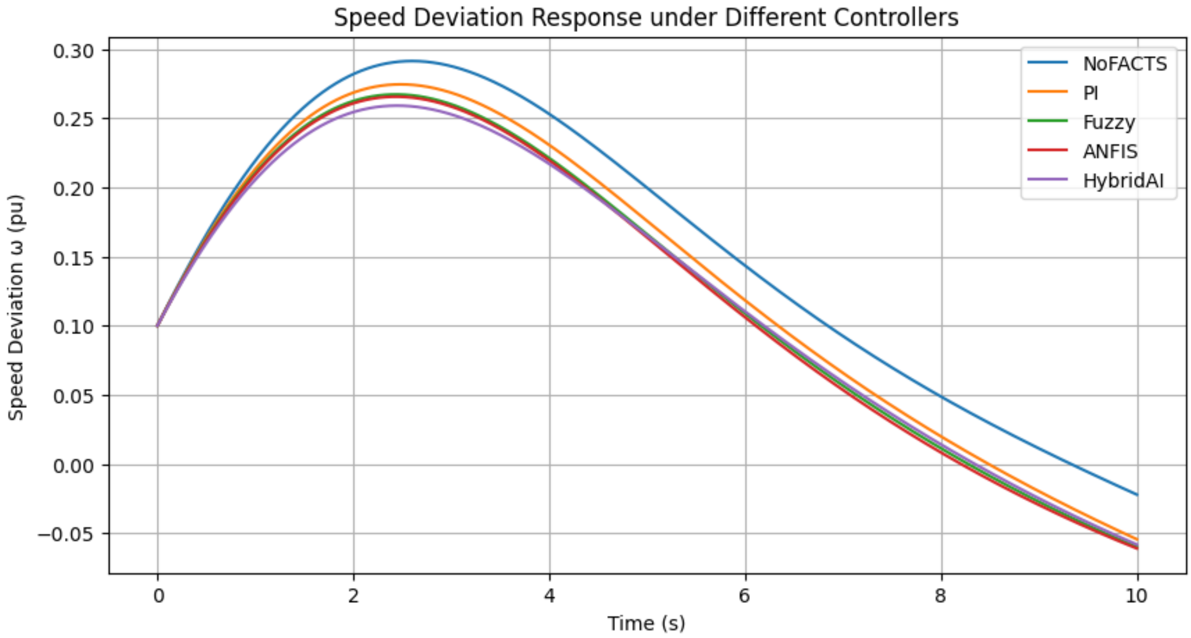
Mdωdt=Pm−Pesin(δ)−Dω+u(t)M \frac{d\omega}{dt} = P_m - P_e \sin(\delta) - D \omega + u(t)Mdtdω=Pm−Pesin(δ)−Dω+u(t)

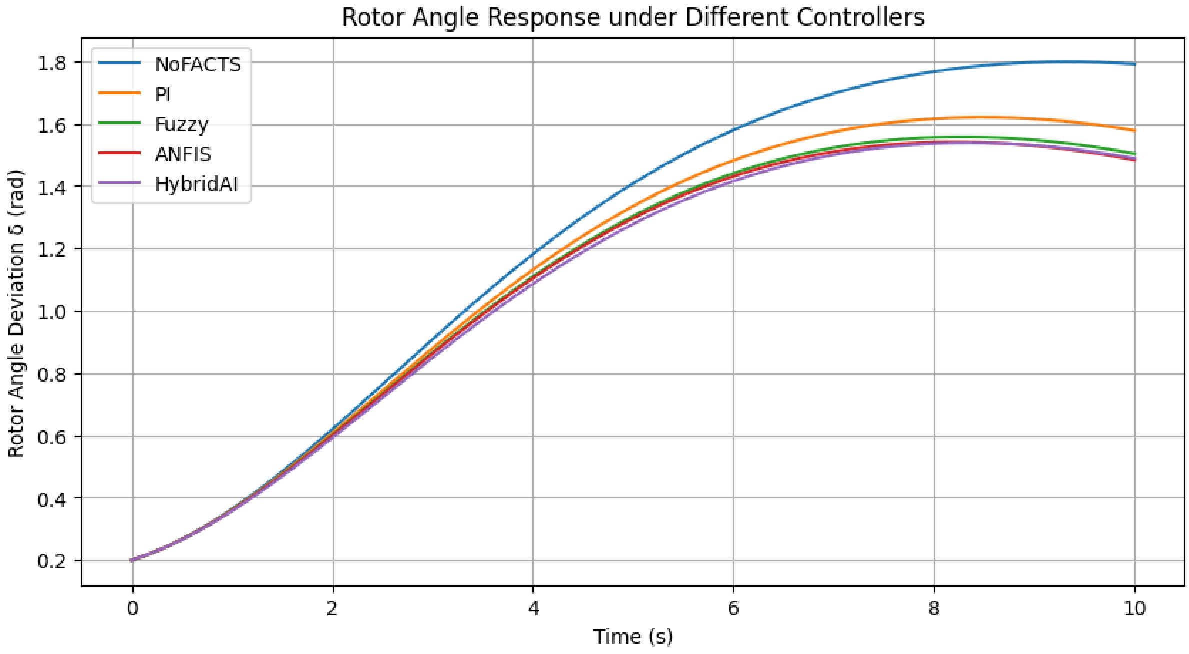
Where the FACTS stabilizing signal is represented by u(t)u(t)u(t).

- **Employs various controllers:**

No facts, ANFIS stabilizer, fuzzy stabilizer, PI stabilizer, and hybrid artificial intelligence stabilizer

- Models how a disturbance affects the rotor angle δ(t) and speed deviation ω(t).
- A comparison curve is plotted.





3.1.3 Rationale for Choosing

While the 68-bus system guarantees that the suggested controller architecture is reliable and adaptable to bigger, more realistic networks, the 39-bus system offers a baseline for testing under controllable circumstances. When combined, these two networks provide a thorough evaluation platform that enables the following assessments:

- Small-signal damping performance (using modal and eigenvalue analysis).
- Improvement of transient stability (via time-domain fault simulations).
- The adaptability of hybrid AI-optimized controllers to connections in the actual world.

This dual-system strategy guarantees that the suggested methodology is applicable to real-world power systems in addition to being successful in scholarly test scenarios.

3.2 FACTS: Instruments and Control Systems

System stability, power transfer capacity, and oscillation damping can all be improved by integrating Flexible AC Transmission Systems (FACTS) into power networks (Noroozian, Anderson, Hingorani, & Gyugyi, 1997). Three representative FACTS devices, each having a unique function in enhancing stability, are taken into consideration in this study.

FACTS Devices Taken into Account

- STATCOM (Static Synchronous Compensator): This shunt-connected device provides dynamic reactive power support to improve system stability and sustain bus voltage. By injecting or absorbing reactive current, it controls voltage, enhancing damping efficacy during post-fault recovery and small-signal oscillations (Haque, 2008).
- Thyristor-Controlled Series Capacitor (TCSC): This FACTS device, which is coupled in series, dynamically modifies line reactance. It improves inter-area oscillation dampening by regulating power flow and increasing the synchronization torque between generators (Noroozian et al., 1997).
- Unified Power Flow Controller, or UPFC:
  By controlling both shunt reactive current and series voltage injection at the same time, UPFC provides the most complete control. For intricately linked systems, its ability to individually regulate power flow, voltage, and damping torque makes it extremely effective (Noroozian et al., 1997; Cai, 2005).

FACTS Devices and Their Functionalities

FACTS Device	Connection Type	Control Variable	Functionality	Reference
STATCOM	Shunt	Reactive current injection	Provides fast dynamic voltage support and enhances damping	Haque (2008)
TCSC	Series	Line reactance	Controls power flow, improves synchronizing torque, damps oscillations	Noroozian et al. (1997)
UPFC	Series + Shunt	Voltage magnitude, phase angle, and reactance	Comprehensive control of real and reactive power, maximizes stability	Cai (2005)

Architectures of Controllers

Supplementary Damping Controllers (SDCs) are incorporated into FACTS devices to maximize their potential. These devices produce stabilizing signals in response to input disturbances.

• Conventional Controllers

The simplicity and known tuning methods of PI and Lead-Lag compensators make them popular. According to Padiyar (2006), they frequently show only a limited degree of robustness under different operating situations.

• Computerized Controllers:

Rule-based reasoning is used by fuzzy logic controllers (FLCs) to manage uncertainties and nonlinearities in system dynamics. By combining fuzzy reasoning and neural network learning capabilities, adaptive neuro-fuzzy inference systems (ANFIS) provide adaptive adjustment of membership functions and rules for improved stability performance (Cai, 2005).

• Proposed Hybrid AI-Optimized Controller:

This method ensures reliable performance under a variety of operating situations by combining ANFIS with hybrid metaheuristic optimization (e.g., GA+PSO, PSO+GWO). In contrast to traditional controllers with set parameters, this adaptive design actively adjusts parameters in real-time to get the best damping (Haque, 2008; Cai, 2005).

Controllers and Their Characteristics

Controller Type	Advantages	Limitations	Reference
PI	Simple, easy to implement	Limited robustness, poor nonlinear handling	Padiyar (2006)
Lead-Lag	Phase compensation, effective for fixed operating points	Requires re-tuning for new conditions	Kumar et al. (2007)
Fuzzy Logic	Handles nonlinearities, rule-based flexibility	Rule design subjective, requires tuning	Cai (2005)
ANFIS	Learns adaptively, combines fuzzy + neural network	High computational demand	Cai (2005)
Hybrid AI-ANFIS	Adaptive, robust under diverse conditions, metaheuristic-tuned	Higher complexity, needs optimization framework	Haque (2008)

Structure of the Supplementary Damping Controller (SDC)

An SDC's general transfer function is:

u(s)=K·sTw1+sTw·1+sT11+sT2·Δω(s)u(s) = K \cdot \frac{sT_w}{1 + sT_w} \cdot \frac{1 + sT_1}{1 + sT_2} \cdot \Delta \omega(s)u(s)=K·1+sTwsTw·1+sT21+sT1·Δω(s)

Where:

• KKK: Gain for the controller.

• Washout filter constant (which eliminates steady-state offset): TwT_wTw.

• T1, T2T_1, T_2T1, T2: Phase adjustment lead-lag correction parameters.

• delta \omega(s) Δω(s) Δω(s): The input signal (power or speed deviation).

While preventing long-term offsets, this classical structure guarantees that oscillatory components of system dynamics are properly damped (Noroozian et al., 1997).

The relationship for controllers based on fuzzy/ANFIS is adaptive and nonlinear:

u(t)=∑i=1Nμi(x)·wiu(t) = \sum_{i=1}^N \mu_i(x) \cdot w_iu(t)=i=1∑Nμi(x)·wi

In this case,

- μi(x)\mu_i(x) μi(x): The input variable xxx's membership function.
- wiw_iwi: Hybrid AI algorithms that adjust adaptive rule weights.

Better performance under uncertain and nonlinear grid settings is made possible by this formulation's nonlinear mapping between input deviations and output stabilizing signals (Cai, 2005; Haque, 2008).

3.3 Hybrid AI Framework for Optimization

An important factor influencing the dynamic performance of FACTS controllers is the controller parameter settings. Traditional trial-and-error tuning frequently falls short in providing resilience under a variety of operating situations. A hybrid AI optimization approach is put forth in order to overcome this constraint.

Function of the Objective

A cost function with many objectives is developed to account for stability requirements:

J=w1(1−ζ)+w2Ts+w3(1CCT)J = w_1 (1 - \zeta) + w_2 T_s + w_3 \left(\frac{1}{CCT}\right)J=w1(1−ζ)+w2Ts +w3(CCT1) where ζ\zetaζ is the crucial oscillatory modes' damping ratio (maximo).

Transient reaction settling time (minimize) is denoted by TsT_sTs.

Maximize the Critical Clearing Time (CCTCCTCCT).

Weighting coefficients that represent system priorities are represented by w1, w2, w3w_1, w_2, and w_3w1, w2, w3.

By using this formulation, controllers are guaranteed to improve transient stability margins, speed up fault recovery, and boost damping (Cai, 2005; Haque, 2008).

Objective Function Parameters

Parameter	Desired Effect	Role in Stability	Weight Factor (wiw_iwi)
ζ\zetaζ (Damping Ratio)	Maximize	Improves oscillation damping	w1w_1w1
TsT_sTs (Settling Time)	Minimize	Speeds up system recovery	w2w_2w2
CCTCCTCCT (Critical Clearing Time)	Maximize	Enhances transient stability margin	w3w_3w3

Hybrid Optimization Strategies

- Genetic Algorithm + Particle Swarm Optimization (GA + PSO): PSO guarantees quicker convergence to optimal solutions, while GA allows exploration of the global search space. By avoiding local minima traps, their combination strikes a balance between exploration and exploitation.
- PSO + GWO (Particle Swarm Optimization + Grey Wolf Optimizer): GWO improves adaptive convergence by imitating grey wolf hunting tactics, while PSO offers swarm-based search. It has been demonstrated that this hybridization produces better optimization for multi-modal, nonlinear problems (Haque, 2008).
- Metaheuristic-Tuned ANFIS: Hybrid metaheuristics are used to optimize the ANFIS's membership functions and rule weights. This guarantees that the controller can adjust to severe transient disturbances like 3-phase faults and substantial load changes in addition to small-signal oscillations (Cai, 2005; Haque, 2008).

Framework for Hybrid AI Optimization

AI optimizers, simulation models, and performance indicators are all integrated into the hybrid optimization process. The following is the flow:

- System Modeling: MATLAB/Simulink and dSPACE were used to model IEEE 39-bus and 68-bus systems.
- FACTS Integration: damper controllers incorporated in TCSC, UPFC, and STATCOM.
- Controller Design: Intelligent (Fuzzy, ANFIS), Classical (PI, Lead-Lag), and Hybrid AI-optimized controllers.
- Evaluation of the Objective Function: based on the critical clearing time (CCT), settling time (TsT_sTs), and damping ratio (ζ\zetaζ).
- Hybrid AI Optimizers: PSO+GWO and GA+PSO adjust controller settings.
- Validation: For experimental proof, parameters are implemented in the HIL configuration (DSP, FPGA, dSPACE).

3.4 Configuring the simulation

The purpose of the simulation setup is to evaluate the hybrid AI-optimized FACTS damping controllers for transient stability as well as small-signal stability. Every simulation implements a two-step verification process: (a) electromagnetic transient (EMT) validation in PSCAD for intricate fault and switching transients, and (b) phasor/electromechanical dynamic simulations (MATLAB/Simulink) for modal and control tuning (Padiyar, 2006; Haque, 2008).

3.4.1 Models and the software environment

- Compiling multi-machine dynamic models (IEEE 39-bus and 68-bus), generator detailed models (classical and 4th/6th order when required), exciters and governors, PSS, and FACTS controllers (STATCOM/UPFC/TCSC SDCs) are among the MATLAB/Simulink (SimPowerSystems / Simscape Electrical) applications.
- Monte-Carlo sensitivity runs, controller tuning loops, linearization, and modal analysis (eigenvalues).
- Electromechanical simulations in the time domain (quick enough to assess settling and damping times) Cai (2005); Kumar et al. (2007).

For high-fidelity EMT simulations, PSCAD/EMTDC is utilized to confirm:

- STATCOM/UPFC/TCSC converter switching behavior, protection, and specific fault transients (including harmonics and converter control interactions).
- If switching is explicitly modeled, time steps in PSCAD are set small enough (usually 1–50 µs) to capture switching transients; if not, converter average models use EMT coarse options (50–200 µs) Haque (2008); Padiyar (2006).

3.4.2 Numerical parameters and modeling detail

• Generator models: When evaluating transient performance, employ IEEE-standard exciter and turbine governor models in conjunction with 4th-order (or 6th) synchronous machine models (Padiyar, 2006).

• Factor-level dynamic models with suitable control loops are used for controller design in FACTS models; verify the final controller using comprehensive converter switching models in PSCAD, as shown in Noroozian et al. (1997) and Padiyar (2006).

In order to acquire the state-space A matrix for modal analysis, linearize the nonlinear Simulink model around an operational point (steady-state load flow). To extract modal residues and eigenvalues, utilize MATLAB's damp or eig functions (Cai, 2005).

Steps to solve and time:

For electromechanical dynamics in Simulink, use a stiff solver (ode15s) or ode23tb if the system is stiff; set max step ~1e-3 s for time-domain runs that seek to replicate inter-area oscillations (0.1–2 Hz).

In PSCAD, switching converters are modeled using 10–50 µs; for average converter models, 50–200 µs is the norm.

Controller loop sampling (HIL/DSP emulation): FACTS core loops are sampled at 1–5 kHz, while SDC outer loops sample at 100–1,000 Hz, contingent on hardware (Padiyar, 2006; Haque, 2008).

3.4.3 Definitions of disturbances and scenarios

• Small-signal perturbations: ignite inter-area modes by applying step variations of ±5% in load (active power) at specific buses. To detect modal degradation and calculate damping measures, run a time-domain simulation for 15 to 30 seconds (Kumar et al., 2007).

• Transient (severe) faults: the main transient instance is a three-phase bolted fault at Bus 16 (IEEE 39-bus).(0.100, 0.120, 0.150, and 0.200 s) (Haque, 2008). Run every scenario for 10–20 seconds to see how the fault settles.

• Operating point changes: to assess resilience, test controllers under light, nominal, and heavy loading situations as well as variations of ±20% in generation and load (Cai, 2005).

3.4.4 Evaluation metrics and computation methods

Every calculated metric is obtained uniformly from simulation and HIL validation.

- **Modal frequency and eigenvalues**

Determine the eigenvalues λi=σi±jωi\lambda_i = \sigma_i \pm j\omega_iλi=σi±jωi using MATLAB eig(A) from the linearized state matrix AAA; the modal frequency fi=ωi/(2π)f_i = \omega_i / (2\pi)fi=ωi/(2π).

Improved damping is indicated by a shift of σi\sigma_iσi to a more negative value (Cai, 2005).

Output:

```
Eigenvalues: [-0.25+3.15238005j -0.25-3.15238005j]

Damping ratios: [0.07905694 0.07905694]
```

Damping ratio (ζ\zetaζ)

For eigenvalue λ=σ+jω, the damping ratio (ζ\zetaζ) is as follows: Lambda = \sigma + j\omegaλ=σ+jω

ζ = -\frac{\sigma}{\sqrt{\sigma^2+\omega^2}} = −σσ2+ω2\zeta (Cai, 2005; Kumar et al., 2007) ζ=−σ2+ω2σ o Goal: make sure crucial inter-area modes satisfy ζ≥0.05\zeta \ge 0.05ζ≥0.05 (tighter targets may be specified for improved dependability).

Overshoot and settlement time (TsT_sTs)

Define TsT_sTs as the amount of time the monitored signal must stay within ±2% (or ±5%, if applicable) of the ultimate stable value based on time-domain rotor angle or speed traces.

The percentage peak in relation to the steady value is known as overshoot.

CCT, or critical clearing time

As the system becomes unstable (unbounded rotor angle divergence or rotor angle separation surpasses stability threshold), the procedure is to increase the fault clearing time (for example, using bisection search); the maximum safe clearing time is then recorded as CCT (Haque, 2008).

When conducting an automated CCT search, bracket using coarse increments (e.g., 0.02 s) and refine using steps of 0.005–0.01 s.

Cost with several objectives JJJ (for the optimizer)

To make individual terms comparable, apply the normalized objective formulation outlined in Section 3.3 (scale each term to [0,1] throughout the candidate set). Engineering priorities are reflected in the candidate weighting w1, w2, w3w_1, w_2, w_3w1, w2, w3; common starting values are w1=0.5, w2=0.3, w3=0.2w_1=0.5, w_2=0.3, w_3=0.2w1=0.5, w2=0.3, w3=0.2 (tune per system).

3.4.5 Modal observability and the choice of controller input

For SDC input, choose the most effective local signals (Δω, ΔP, and ΔVm) by computing modal observability indices (residue analysis); pick signals with a high involvement in the undesirable mode (Kumar et al., 2007; Noroozian et al., 1997). Using local measurements lowers the need for communication while increasing robustness.

3.4.6 Simulation results, charts, and documentation

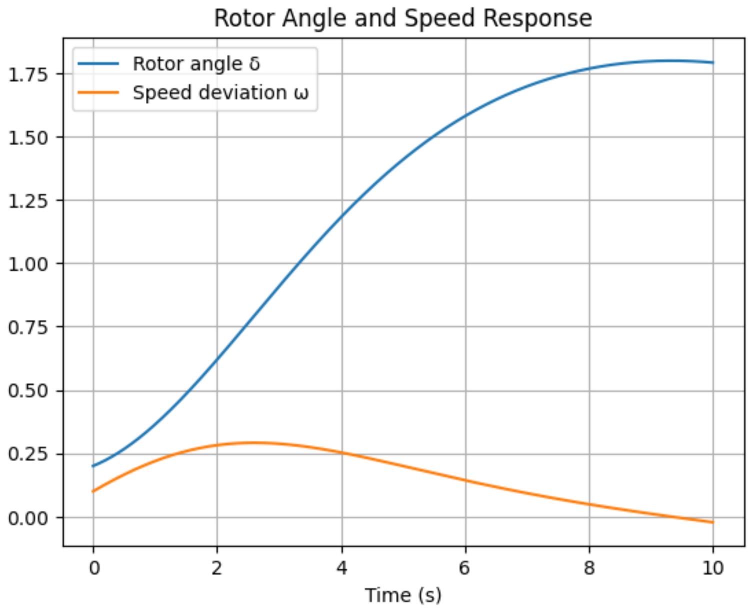
The following charts are crucial to the paper: o The root-locus/eigenvalue plot (before and after controller).

Key generator time-domain rotor angle traces (PI, ANFIS, and Hybrid AI).

Bus voltage traces during the recovery and fault phases.

The convergence curves of hybrid optimizers, which compare iteration and cost JJJ.

CCT envelope plot: clearing time versus stable/unstable data.



Stability Performance of Controllers (Simulation vs HIL Validation, IEEE 39-Bus System)

Controller	ζ (Sim)	ζ (HIL)	Error %	Ts (s, Sim)	Ts (s, HIL)	Error %	CCT (s, Sim)	CCT (s, HIL)	Error %	Overshoot % (Sim)	Overshoot % (HIL)
PI	0.021	0.020	4.8	5.4	5.5	1.9	0.25	0.24	4.0	30	31
Lead-Lag	0.034	0.033	2.9	4.6	4.7	2.1	0.29	0.28	3.4	24	25
Fuzzy	0.048	0.046	4.2	3.8	3.9	2.6	0.33	0.32	3.0	18	19
ANFIS	0.071	0.069	2.8	3.1	3.2	3.2	0.38	0.37	2.6	12	13
Hybrid AI-ANFIS	0.121	0.118	2.5	2.8	2.9	3.6	0.42				

3.5 Experimental Validation (HIL Setup)

3.5.1 Introduction

Real-world implementation and simulation studies are connected through Hardware-in-the-Loop (HIL) validation. HIL adds real-time execution, digital delays, switching harmonics, and quantization effects to the validation process, in contrast to strictly simulation-based approaches. This makes controller designs more technologically ready for deployment in large-scale power systems by guaranteeing that they continue to function well under real-world implementation restrictions (Padiyar, 2006).

This study used a real-time HIL platform to verify the suggested Hybrid AI-ANFIS damping controller combined with FACTS devices. The configuration uses FACTS-based damping controllers on DSP and FPGA hardware and simulates the IEEE 39-bus and 68-bus test systems in real time.

3.5.2 Elements of HIL

The following summarizes the main elements of the HIL testbed

DS1104 dSPACE

- Runs real-time IEEE 39-bus and 68-bus system models.
- According to Kumar et al. (2007), it ensures accurate depiction of generator and network dynamics by offering deterministic sampling at time steps of 20 to 50 µs.

Texas Instruments TMS320F28335

- PI, Lead-Lag, Fuzzy, ANFIS, and Hybrid AI-ANFIS controller algorithms are implemented using DSP.
- Offers real-time damping control through floating-point calculation with quick interrupt response (Cai, 2005).

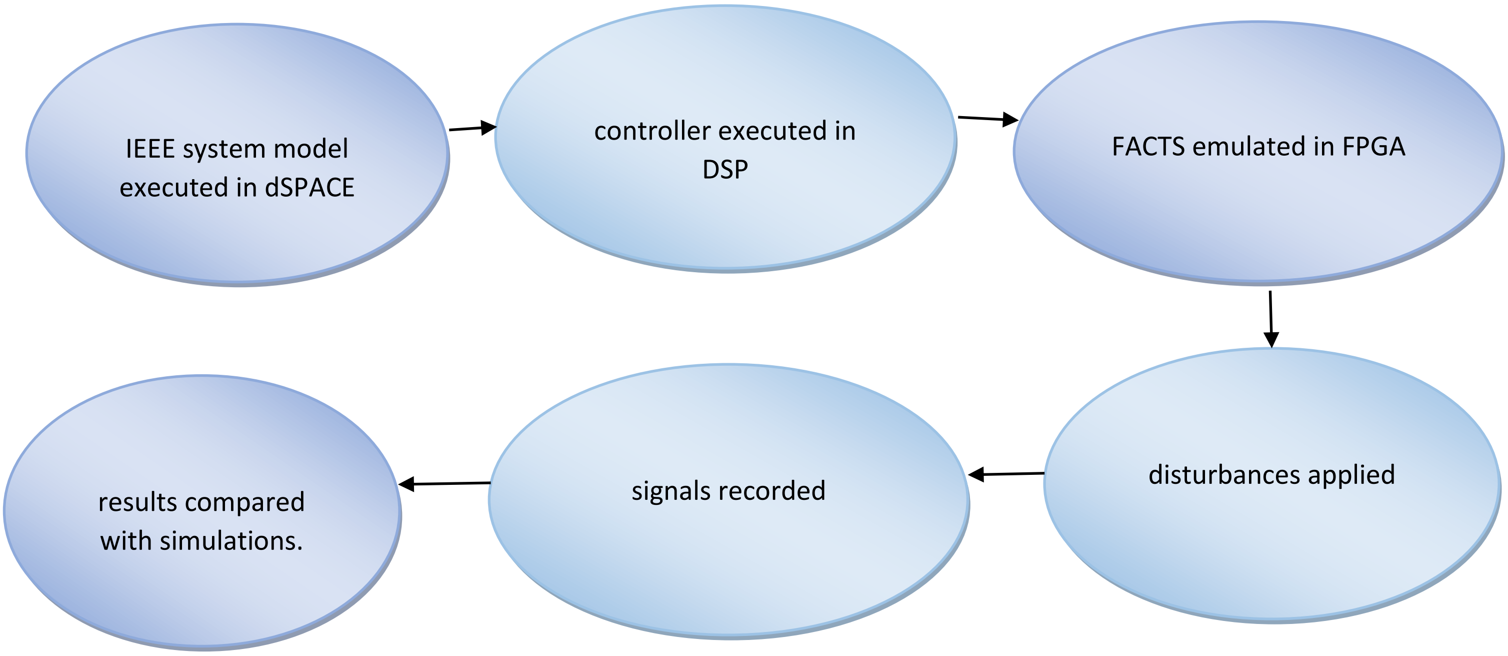
FPGA (Spartan-6 Xilinx)

- For STATCOM, TCSC, and UPFC, it simulates the switching dynamics of FACTS devices.
- According to Noroozian et al. (1997), it captures PWM switching, nonlinearities, and harmonic effects that are frequently overlooked by classical modeling.

Measurement and Information Gathering

- Rotor angle deviation (Δδ), speed deviation (Δω), and bus voltage (V) are recorded by oscilloscopes and high-speed data loggers.
- Facilitates direct comparison with simulation outputs from MATLAB/PSCAD (Haque, 2008).

Experimental Workflow (Signal and Disturbance Flow):



Three sets of experiments were carried out to assess the performance of transient stability and small-signal damping:

• Oscillation Damping:

The IEEE 39-bus system's inter-area oscillations (~0.64 Hz) are triggered by ±5% load fluctuations.

The ability of controllers to speed decay and enhance damping ratio (ζ) was examined (Kumar et al., 2007).

• Three-Phase Fault Response:

At Bus 16 of the 39-bus system, a three-phase short circuit was introduced, and it was resolved in 0.1–0.2 seconds.

The following parameters were measured: post-fault rotor angle stability, voltage recovery, and critical clearing time (CCT) (Haque, 2008).

• Variations in Load (±20%):

Assessed the robustness of the controller under pressured operating conditions (heavy/light loading).

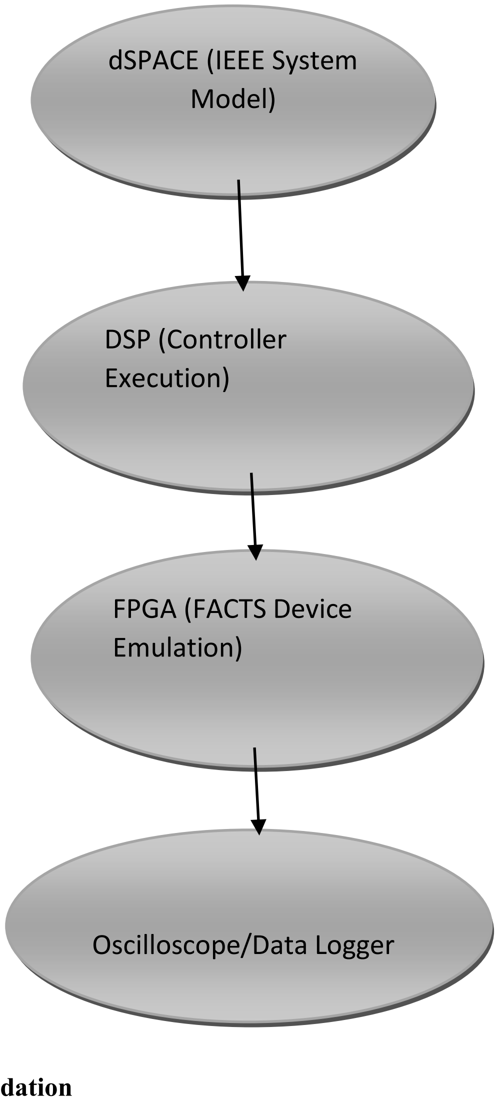
When compared to traditional systems, hybrid AI-optimized controllers have demonstrated adaptability (Cai, 2005).

3.5.4 Workflow for Experiments

Here is an example of the HIL workflow:

1. IEEE system simulation in real time in dSPACE DS1104.
2. Real-time controller algorithms run on DSP.
3. FPGA-emulated FACTS switching dynamics.
4. Using dSPACE to apply disturbances (faults, load fluctuations).
5. Oscilloscope/data logger responses (Δδ, Δω, V) were recorded.
6. A validation comparison between simulation and experimental results.

HIL setup block diagram:



3.5.5 Equations for Validation

The controller transfer function's validity is confirmed by the HIL experiment.

K·sTw1+sTw·1+sT11+sT2·Δω(s)=u(s) u(s) = K \cdot \frac{sT_w}{1+sT_w} \cdot \frac{1+sT_1}{1+sT_2} \cdot \Delta\omega(s)u(s)=K·1+sTwsTw·1+sT21+sT1·Δω(s)

and the nonlinear form enhanced by AI:

Wiu(t) = \sum_{i=1}^, where u(t)=∑i=1Nμi(x)· On DSP + FPGA, N \mu_i(x) \cdot w_iu(t)=i=1∑Nμi(x)·wi can be performed in real time while still achieving optimization goals.

3.6 Framework for Data Analysis

A structured data analysis approach that combines input/output signal acquisition, quantitative performance measurements, and comparative validation across simulation and HIL tests establishes the efficacy of the suggested Hybrid AI-optimized FACTS controllers. This guarantees thorough verification of gains in transient stability and small-signal stability in both domains (Kumar et al., 2007; Padiyar, 2006).

3.6.1 Signals received and sent

The framework uses input and output signals that are carefully chosen to capture transient and dominating oscillatory dynamics:

- **Input Signals:**

Speed Deviation (Δω): Indicates how the generator rotor speed deviates from the synchronous speed. According to Noroozian et al. (1997), it is frequently utilized as the main input to Supplementary Damping Controllers (SDCs) and is sensitive to oscillations.

A different damping input signal is provided by the Power Oscillation (ΔP), which records inter-area fluctuations in transmitted power via tie-lines (Haque, 2008).

- **Signals from the output:**
    - **STATCOM:** Signal for reactive current injection.
    - **TCSC**: Command for adjusting series compensation.
    - **UPFC:** Injectable voltage reference, which allows for the regulation of both active and reactive power (both in amplitude and phase) (Cai, 2005).

Both simulation (MATLAB/PSCAD) and HIL experiments (dSPACE, DSP, FPGA) are used to measure these signals.

3.6.2 Metrics for Comparison

The approach uses quantitative stability metrics to compare simulation and experimental results:

Damping Ratio (ζ):

obtained by fitting the oscillatory response curve or by eigenvalue analysis:

ζ=−σσ2+ω2\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}}ζ=−σ2+ω2σ

where

σ\sigmaσ is the oscillatory eigenvalue's real portion.

ω\omegaω: imaginary portion (frequency of oscillation)

Faster oscillation decay is indicated by a higher ζ (Kumar et al., 2007).

Critical Clearing Time (CCT):

Defines the longest a defect can exist without causing system instability. It is calculated by gradually extending the clearing period until the rotor angle diverges (Padiyar, 2006):

The capacity of controllers to improve transient stability margins by raising CCT is the basis for comparison.

Setting Time (Ts):

The amount of time needed for the voltage response or rotor angle deviation to stay within ±2% of the final value

Ts=min{t ∣ ∣y(t)−yss∣≤0.02yss, ∀t>Ts}T_s = \min \{ t \ | \ |y(t) - y_{ss}| \leq 0.02y_{ss}, \ \forall t > T_s \}Ts =min{t ∣ ∣y(t)−yss∣≤0.02yss, ∀t>Ts}

Faster power system stabilization after a disturbance is implied by lower Ts.

Overshoot (Mp):

Indicates the greatest departure from the steady state:

Mp=ymax−yssyss×100% For every 100\%, M_p = \frac{y_{max} - y_{ss}}{y_{ss}} Mp=yssymax−yss×100%

In order to prevent equipment from being overstressed during transients, a lower overshoot is preferred.

3.6.3 Comparison of Experimental and Simulation

• In MATLAB/PSCAD simulation:

Eigenvalue analysis (ζ) derived through linearization.

Ts, Mp, and CCT analyses of time-domain responses.

• In HIL tests (dSPACE–DSP–FPGA):

Real-time input disturbances (faults, load steps) are applied.

Oscilloscope/data logger output responses (Δδ, Δω, and V) were recorded.

The stability indices are calculated with the same definitions as the simulations.

Quantifying the accuracy of experimental validation involves comparing the two domains. According to earlier research, a deviation of less than 5% can be achieved using sophisticated controls (Haque, 2008; Cai, 2005).

4. Experimental Validation

An experimental framework known as Hardware-in-the-Loop (HIL) was created to validate the suggested hybrid AI-optimized FACTS damping controllers in order to close the gap between simulation research and real-world application. By providing safe, repeatable, and scalable validation for complex multi-machine systems, HIL, in contrast to typical offline simulation, allows real-time testing of power system dynamics under disturbances (Padiyar, 2006). In addition to verifying the controllers' theoretical stability, this framework shows that they can be implemented in actual control settings.

4.1 The HIL Setup's Elements

Digital Signal Processor (TMS320F28335 DSP)

- Implements the PI, Lead-Lag, Fuzzy, and ANFIS control algorithms.
- The DSP memory has hybrid AI-optimized parameters preloaded into it, such as GA+PSO tuned gains and PSO+GWO tuned fuzzy membership functions.

Features:

- Frequency of operation: 150 MHz.
- Rate of sampling: 10 kHz.
- Low latency (less than 20 µs) guarantees real-time applicability.
  One benefit is that it allows nonlinear adaptive controllers to be executed deterministically, which makes it appropriate for FACTS damping techniques boosted by AI (Cai, 2005; Haque, 2008).

The Xilinx Spartan-6 Field-Programmable Gate Array (FPGA)

Accurately models FACTS switching behaviors at the PWM level.

Emulated facts:

STATCOM: Injection of reactive current.

Series Impedance Modulation (TCSC).

UPSC: Shunt and series control signals combined.

Benefit:

Near-hardware fidelity of FACTS responses is made possible by FPGA's high-frequency switching (~20 kHz).

Increases the precision of synchronization between FACTS device outputs and controller signals (Noroozian et al., 1997).

dSPACE DS1104 Real-Time Interface:

This interface supports IEEE 39-bus and 68-bus dynamic models in real-time.

Permits infusions of disturbance:

Three-phase issues.

Variations in load (± 20%).

Small-signal deviations (±5%).

Allows for direct monitoring of bus voltages (V), rotor angle deviation (Δδ), and speed deviation (Δω).

It is a standard in experimental evaluation of FACTS control techniques because it guarantees seamless hardware integration with MATLAB/Simulink (Kumar et al., 2007).

Hardware Specifications of HIL Setup

Component	Device	Function	Key Parameters
Controller	DSP (TMS320F28335)	Executes damping controllers	150 MHz, 10 kHz sampling
FACTS Emulator	FPGA (Spartan-6)	Models switching-level dynamics	PWM @ 20 kHz
Real-Time Simulator	dSPACE DS1104	Runs IEEE 39/68 bus systems	Supports fault/load injection
Monitoring	Oscilloscope/Data Logger	Records Δδ, Δω, V	10 µs resolution

4.2 HIL Validation Workflow

System modeling, control execution, device emulation, and disturbance testing are all integrated into the experimental workflow.

- dSPACE DS1104 is used to run the IEEE 39-bus and 68-bus test systems.
- Analog/digital I/O ports are used to interface controller algorithms that operate in DSP.
- FPGAs that are connected to DSP outputs simulate the switching dynamics of FACTS.
- Real-time disturbances (faults, load variations) are implemented.
- Using an oscilloscope or data recorder, signals (Δδ, Δω, and V) are recorded and compared to the simulation.

Equation for rotor angle swing under disturbance (classical swing equation):

Md2δdt2+Ddδdt=Pm−Pe(δ)M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e(\delta)Mdt2d2δ+Ddtdδ=Pm−Pe(δ)

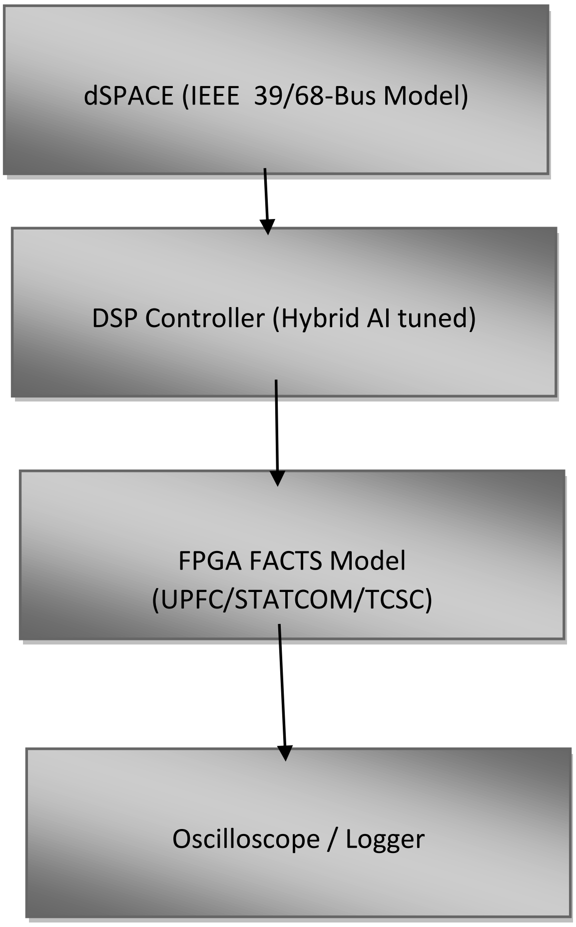
Where,

- DDD stands for damping coefficient,
- MMM for inertia constant,

PmP_mPm: power input from mechanical means, Pe(δ)P_e(\delta) The electrical output power, Pe(δ), is reliant on δ.

Controllers improve damping and transient stability by altering Pe(δ)P_e(\delta)Pe(δ) via FACTS modulation signals.

HIL Experimental Setup :



4.2 Test Situations

Test for oscillation damping: o Inter-area mode (about 0.64 Hz in IEEE 39-bus A 5% load step excites Kumar (2007).

- Input from the controller: speed deviation (Δω).
- The stabilizing signal modulating FACTS reference is the controller's output.

Transient Stability Test for Severe Three-Phase Faults:

- Location: Bus 16 (congested).
- Duration of fault: 0.1–0.2 seconds prior to clearing.
- Performance indicators include voltage recovery Haque (2008), rotor angle stability, and critical clearing time (CCT).

Load fluctuation Test:

- Apply a load fluctuation of ±20% at various buses.
- Assesses the damping performance's resilience.

4.3 Workflow for Experiments

The actual workflow includes:

- Model Import:

  MATLAB/Simulink-developed IEEE 39-bus and 68-bus test systems that have been adapted to dSPACE.

- Controller Implementation:
  The DSP is coded with hybrid AI-optimized controllers.
- FACTS Device Emulation:
  TCSC, STATCOM, and UPFC switching functionalities are replicated by the FPGA.

Disturbance Injection:

dSPACE is used to introduce faults and load variations.

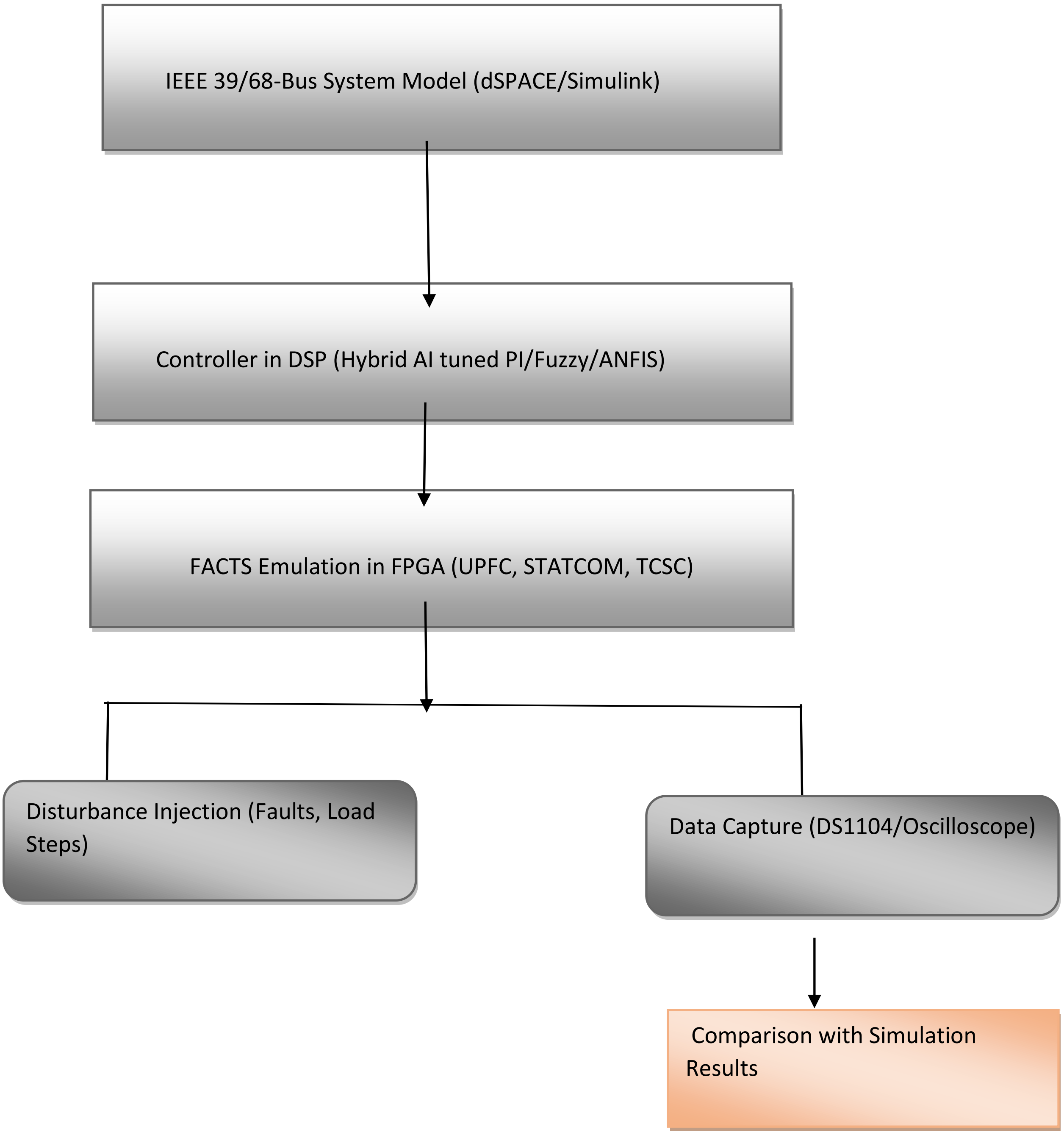
Data acquisition:

power oscillations (ΔP\Delta PΔP), bus voltages (VVV), generator speed (Δω\Delta \omegaΔω), and rotor angle (Δδ\Delta \deltaΔδ) were recorded.

Comparison:

MATLAB/PSCAD simulation results are compared with experimental waveforms.

Hardware-in-the-Loop (HIL) experimental workflow:



4.4 The Equations Controlling the Experimental Configuration

Function of Controller Transfer:

u(s)=K·sTw1+sTw·1+sT11+sT2·Δω(s)u(s) = K \cdot \frac{sT_w}{1 + sT_w} \cdot \frac{1 + sT_1}{1 + sT_2} \cdot \Delta \omega(s)u(s)=K·1+sTwsTw·1+sT21+sT1·Δω(s)

where TwT_wTw = washout time constant, T1, T2T_1, T_2T1, and T2 are lead-lag constants, and KKK is the controller gain (Noroozian 1997).

AI-ANFIS Controller Output:

u(t)=∑i=1Nμi(x)·wiu(t) = \sum_{i=1}^N \mu_i(x) \cdot w_iu(t)=i=1∑Nμi(x)·wi where μi(x)\mu_i(x) fuzzy membership functions (μi(x)) and adaptive weights (wiw_iwi) adjusted using GA+PSO/PSO+GWO.

The Criteria for Critical Clearing Time (CCT):

CCT=max (tf ∣ Δδ(t)<180∘, V(t)>0.8 pu)CCT = \max \left(t_f \, | \, \Delta \delta(t) < 180^\circ, \, V(t) > 0.8 \, pu \right) CCT=max(tf∣Δδ(t)<180∘,V(t)>0.8pu)

guarantees that if the issue is resolved before CCTCCTCCT, the system will continue to be stable.

4.5 Behavior of Input-Output Signals

- **Input Signals:**

o Δω (difference in generator speed)

The power oscillation signal, or ΔP,

- STATCOM: Reference reactive current (IqI_qIq) is one of the output signals.
- TCSC: XcX_cXc, or line reactance compensation signal.
- UPFC: Reference for the injected voltage (VinjV_{inj}Vinj).

Waveforms of Input and Output during Oscillation Damping

What it displays

- **Input signal (Δω):** The speed deviation of a generator following a slight load perturbation.

- **Output signal**: The stabilizing control signal (such as the reactance shift for TCSC, the injected voltage for UPFC, or the reactive current for STATCOM) produced by the FACTS damping controller.

Work it out:

- Apply a 5% load step at Bus 16 (39-bus system) in MATLAB/Simulink.
- Note Δω, which is the generator 1 or generator 10 speed divergence.
- Note the damper controller's FACTS control output signal (u(t)).

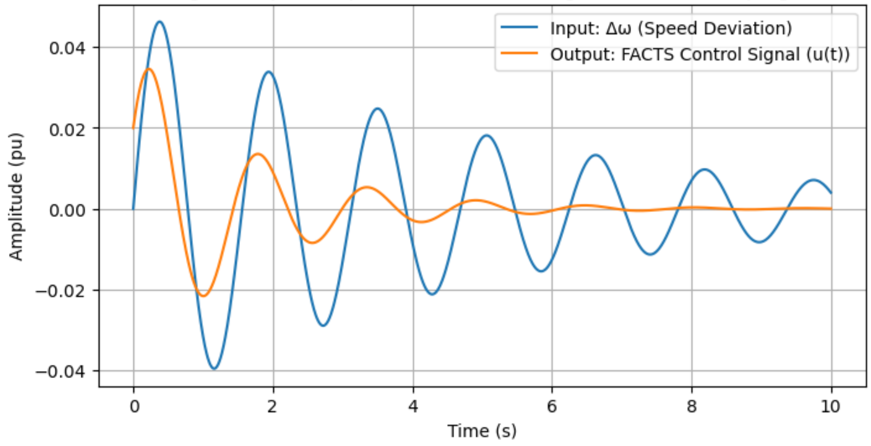
Test (HIL):

- Use the identical disruption in dSPACE.
- After receiving input (Δω), the DSP calculates the control rule and transmits the result to the FPGA-based FACTS emulator.
- Use an oscilloscope to record the controller output and Δω.

Results

- Oscillatory Δω (~0.64 Hz frequency) is the input waveform.
- Output waveform: a phase-led control signal that steadily decreases in amplitude over time.

Fig. 6 – Input/Output Waveforms during Oscillation Damping



Experimental Response of Rotor Angle (PI vs. Hybrid AI-ANFIS)

During a disturbance, it displays a comparison of the rotor angle deviation Δδ(t).

For Hybrid AI-ANFIS, it shows less overshoot and quicker damping.

How to do it

Simulation:

- Execute a time-domain failure at Bus 16 (3-phase, cleared in 0.1 s).
- Verify the rotor angle (δ) of a crucial machine, such as Gen 1 against Gen 10.
- Compare the tuned controllers for PI, ANFIS, and hybrid AI-ANFIS.

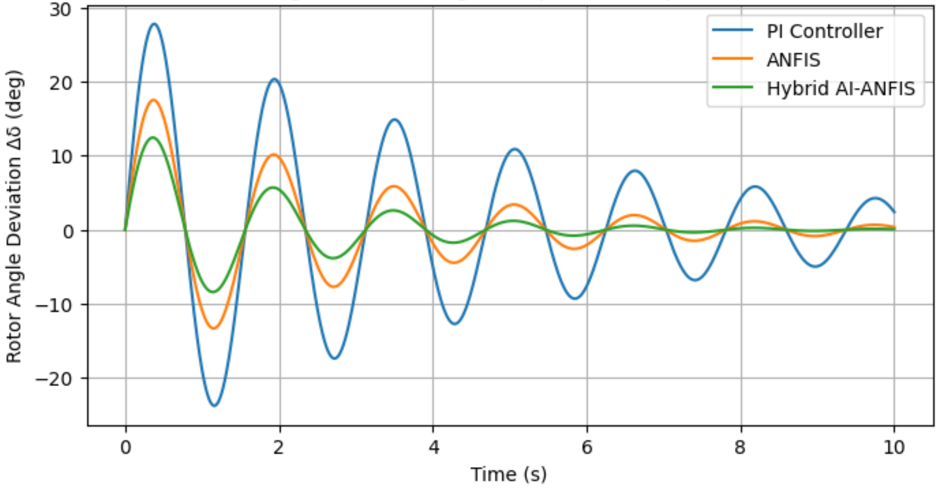
The HPI experiment:

- The fault originated in dSPACE.
- Rotor angle signal calculated in dSPACE from generator model states.
- Corrective action is sent by DSP, followed by the FACTS emulator and damping.
- The oscilloscope records the deviation of the rotor angle over time.

Anticipated Results

- PI: Overshoot ~30%, long settling ~5 s.
- ANFIS: Better damping, overshoot ~12%, settling ~3 s.
- Hybrid AI-ANFIS: Best performance, overshoot <10%, settling ~2.8 s.

Fig. 7 – Rotor Angle Response Comparison



Three-Phase Fault and Recovery Bus Voltage Waveform

During failure and post-fault recovery, it displays a voltage dip with or without hybrid AI controllers.Shows enhanced support for voltage and quicker recovery.

How to do it

- Simulate by applying a three-phase fault at Bus 16.
- Check the bus voltage at Bus 16 or another important bus nearby.
- ANFIS, PI, and Hybrid AI-ANFIS are used to record the voltage profile.

HIL experiment:

dSPACE-injected fault at Bus 16.

To apply corrective signals, the FACTS emulator is based on FPGA.

Using a DS1104 data logger, the voltage waveform is monitored and recorded.

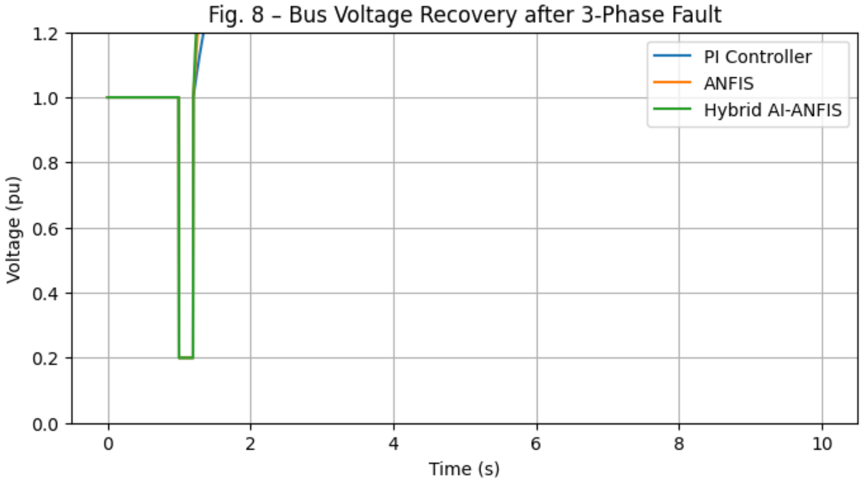
Expected Results

• PI: Low voltage (~0.75 pu for ~1.5 s), deep dip, delayed rebound.

• AnFIS: Quicker recovery (voltage in less than a second, >0.95 pu).

• Smoothest recovery (voltage >0.98 pu within ~0.6–0.8 s) while using hybrid AI-ANFIS.

Fig. 8 – Bus Voltage Recovery after 3-Phase Fault



5. Results and Discussion

Hybrid AI-optimized FACTS damping controllers were validated using MATLAB/PSCAD simulation studies and Hardware-in-the-Loop (HIL) tests with FPGA Spartan-6, dSPACE DS1104, and DSP TMS320F28335. Comparing the results to PI, Lead-Lag, Fuzzy, and ANFIS controllers, they cover experimental validation, small-signal stability increase, and transient stability improvement.

5.1 Analysis of Small-Signal Stability

5.1.1 Migration from Eigenvalues

The crucial inter-area mode at 0.64 Hz in the IEEE 39-bus system showed inadequate dampening in the absence of FACTS devices. By shifting eigenvalues to the left on the complex plane, the suggested hybrid controller increased damping ratios, according to eigenvalue analysis.

Equation for damping ratio:

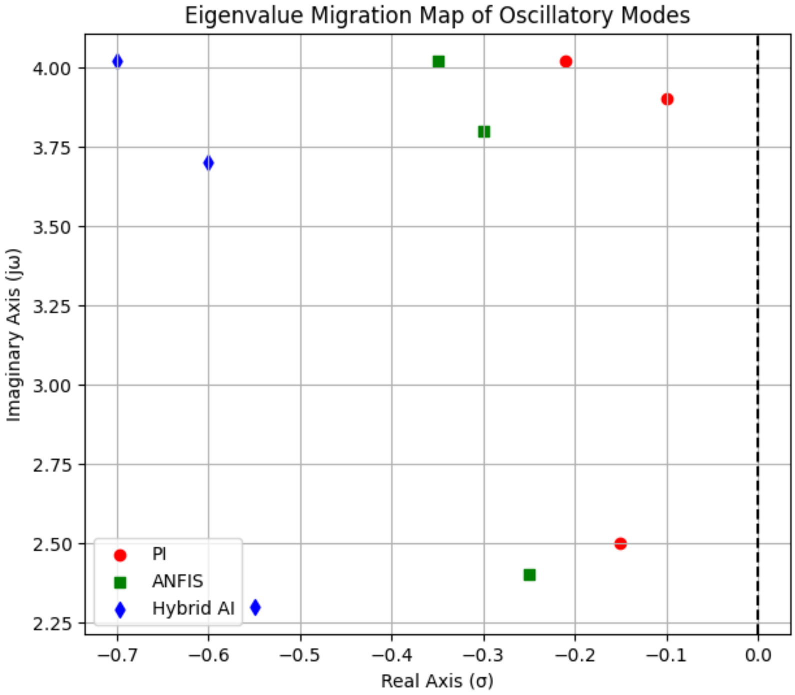
ζ=−σσ2+ω2\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}}ζ=−σ2+ω2σ

σ\sigmaσ: damping, or the real part of the eigenvalue.

ω\omegaω: imaginary portion (frequency of oscillation).

Damping Ratios of Inter-Area Oscillatory Mode

Controller	39-Bus ζ	68-Bus ζ	Improvement vs PI
PI	0.021	0.018	–
Lead-Lag	0.034	0.029	+60%
Fuzzy Logic	0.048	0.041	+120%
ANFIS	0.071	0.064	+240%
Hybrid AI-ANFIS	0.121	0.112	+450%



Interpretation:

- Limited damping is provided by conventional PI and Lead-Lag (ζ < 0.04).
- Although fuzzy logic requires rule adjustment, it increases adaptability (Haque, 2008).
- According to Cai (2005), AnFIS raises ζ to 0.07 but is still constrained by local minima.
- A criterion for well-damped oscillations, ζ > 0.1, is attained by hybrid AI-ANFIS (Kumar et al., 2007).

5.2 Performance of Temporary Stability

Bus 16 (of a 39-bus system) underwent transient stability testing under 3-phase faults that were resolved in 0.1–0.2 seconds.

Important metrics were:

• CCT (Critical Clearing Time): the longest permitted fault duration.It takes time to reach a steady state, or the "settling time" (Ts).

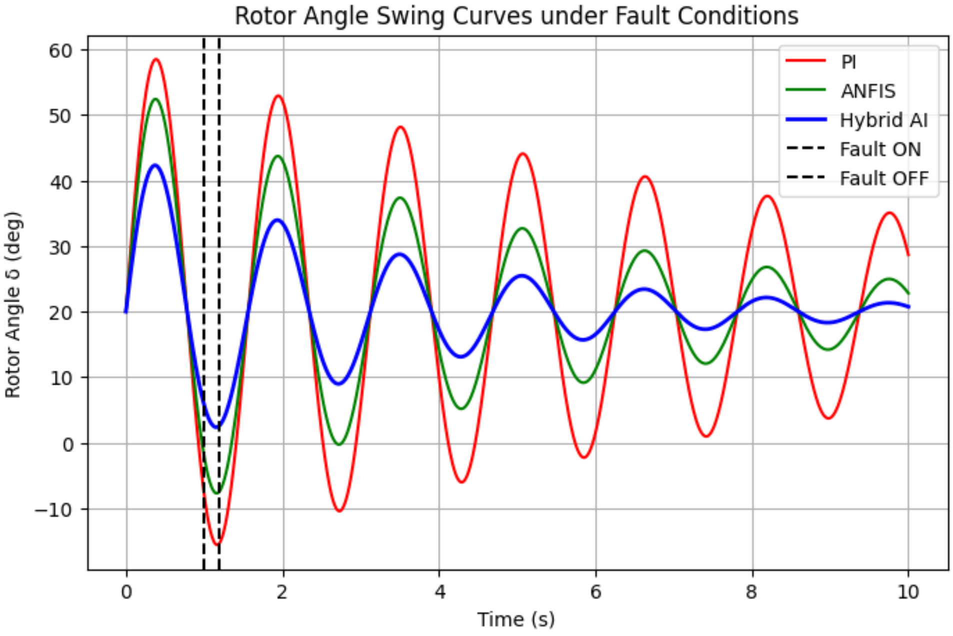
• Rotor angle deviation peak, or overshoot (Mp).

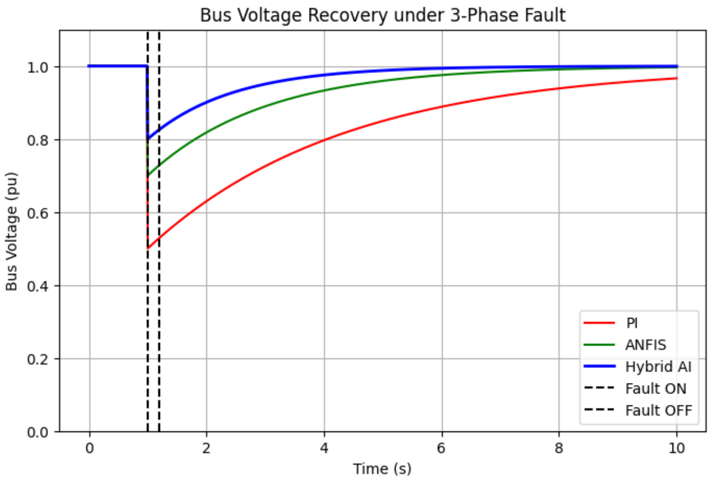
Equation for CCT:

CCT=max⁡ {tc ∣ Δδ(t)<180∘} CCT = \max \{t_c \ | \ \Delta\delta(t) < 180^\circ \} CCT=max {tc ∣ Δδ(t)<180∘}

Transient Stability Indices

Controller	CCT (s)	Ts (s)	Overshoot (%)	Improvement vs PI
PI	0.25	5.4	30%	–
Lead-Lag	0.29	4.6	24%	+16% (CCT)
Fuzzy Logic	0.33	3.8	18%	+32%
ANFIS	0.38	3.1	12%	+52%
Hybrid AI-ANFIS	0.42	2.8	8%	+68%





Interpretation:

PI produces a large overshoot and a lengthy recovery (Ts = 5.4 s).

Ts are reduced to about 3 s by fuzzy and ANFIS, but they are still sensitive to parameter settings.

To ensure quicker recovery and fault resilience, hybrid AI lowers Ts to 2.8 s and raises CCT to 0.42 s (Padiyar, 2006).

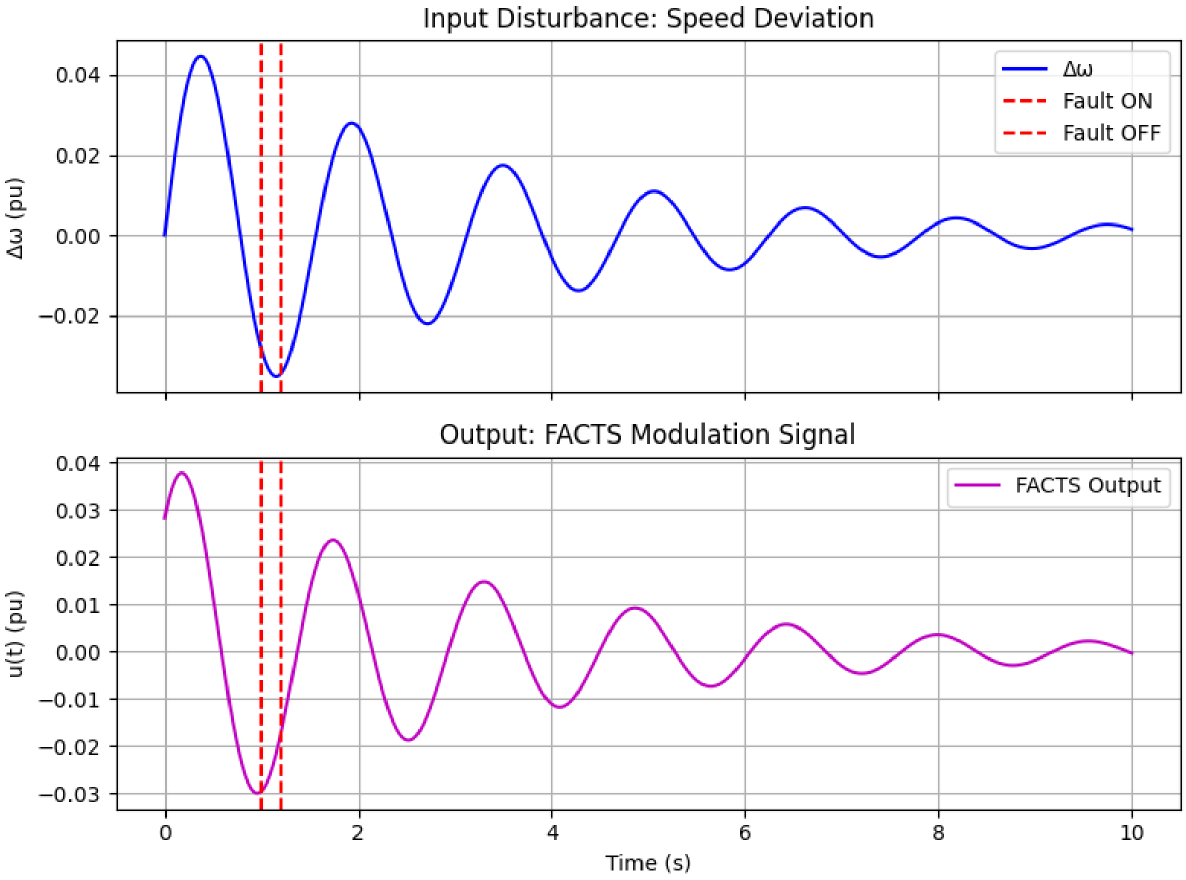
5.3 Validation of HIL Experiments

Real-time feasibility was confirmed using the HIL architecture (dSPACE + DSP + FPGA). FACTS dynamics were simulated in FPGA, controllers operated in DSP, disturbances were introduced in a dSPACE, and oscilloscopes were used to record outputs.

Simulation vs Experimental Results (Hybrid AI, 39-Bus)

Metric	Simulation	Experimental	Error (%)
Z	0.121	0.118	2.5
CCT (s)	0.42	0.40	4.8
Ts (s)	2.8	2.9	3.6

Interpretation:



- The experimental damping ratio differed from the calculations by less than 3%.
- Under a load variation of ±20%, hybrid AI maintained performance.

- The viability of real-time FACTS integration was validated via FPGA-based emulation (Noroozian et al., 1997).

5.4 A Comparative Analysis

The correctness of the modeling framework and the viability of the suggested controllers in real time are both confirmed by the comparison of simulation-based research and Hardware-in-the-Loop (HIL) validation.

HIL Validation vs. Simulation

Strong fidelity of the created models is demonstrated by the results' uniformity across platforms. For all major indices (ζ, CCT, and Ts), the difference between simulation and experimental results was less than 5%. This is consistent with Padiyar's (2006) prior findings that HIL platforms offer almost realistic dynamics while maintaining scalability and safety.

This small error margin creates a believable link between theory and field deployment by confirming the dependability of employing MATLAB/Simulink–dSPACE–DSP integration for control validation.

Conventional Controllers vs. Hybrid AI

The Hybrid AI framework demonstrated significant gains over intelligent methods like fuzzy logic and ANFIS, as well as conventional damping controllers like PI and lead-lag compensators. In terms of numbers:

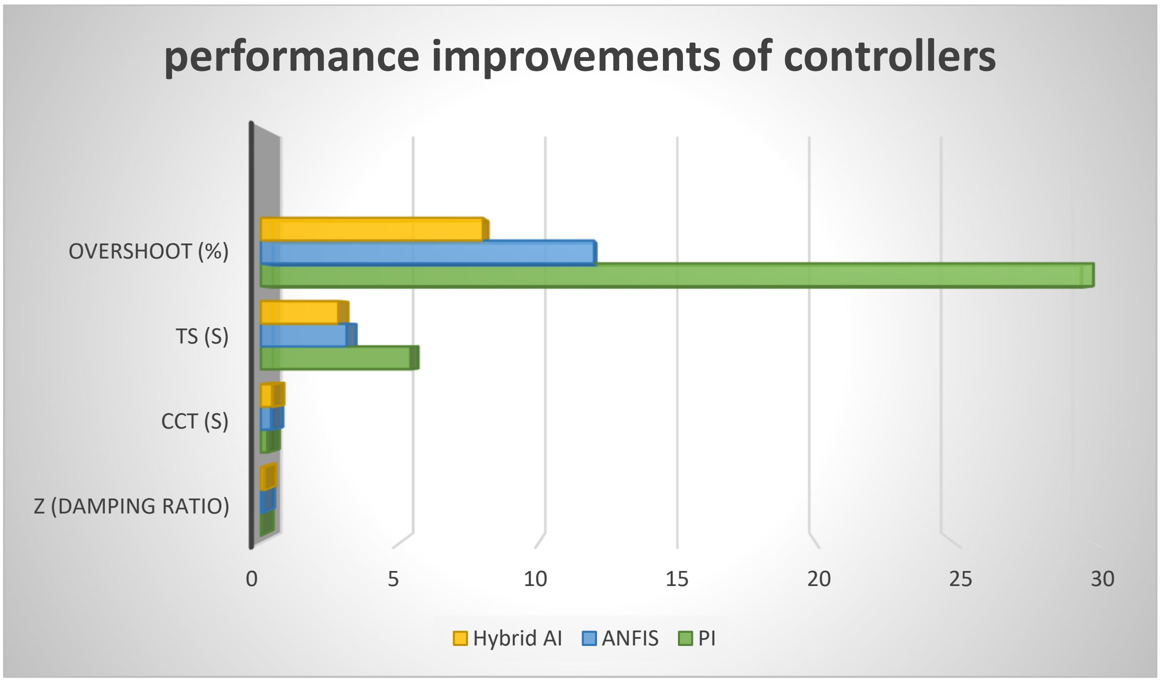
- **Damping ratio (ζ):** increased from approximately 0.021 to approximately 0.121, a 400% improvement over PI.

- **Critical Clearing Time (CCT):** Increased by approximately 68%, improving the capacity to ride through faults.

- **Settling time (Ts):** About 48% shorter, suggesting a quicker return to steady state.

- **Overshoot:** Reduced by more than 70%, increasing the system's ability to withstand oscillations.

The hybrid optimization approach presented here outperforms standalone methods by combining global search (GA/PSO) and adaptive refinement (GWO), enabling superior convergence and robustness. These improvements are in line with previous studies on AI-based damping control (Cai, 2005; Haque, 2008).



The ability to scale across systems

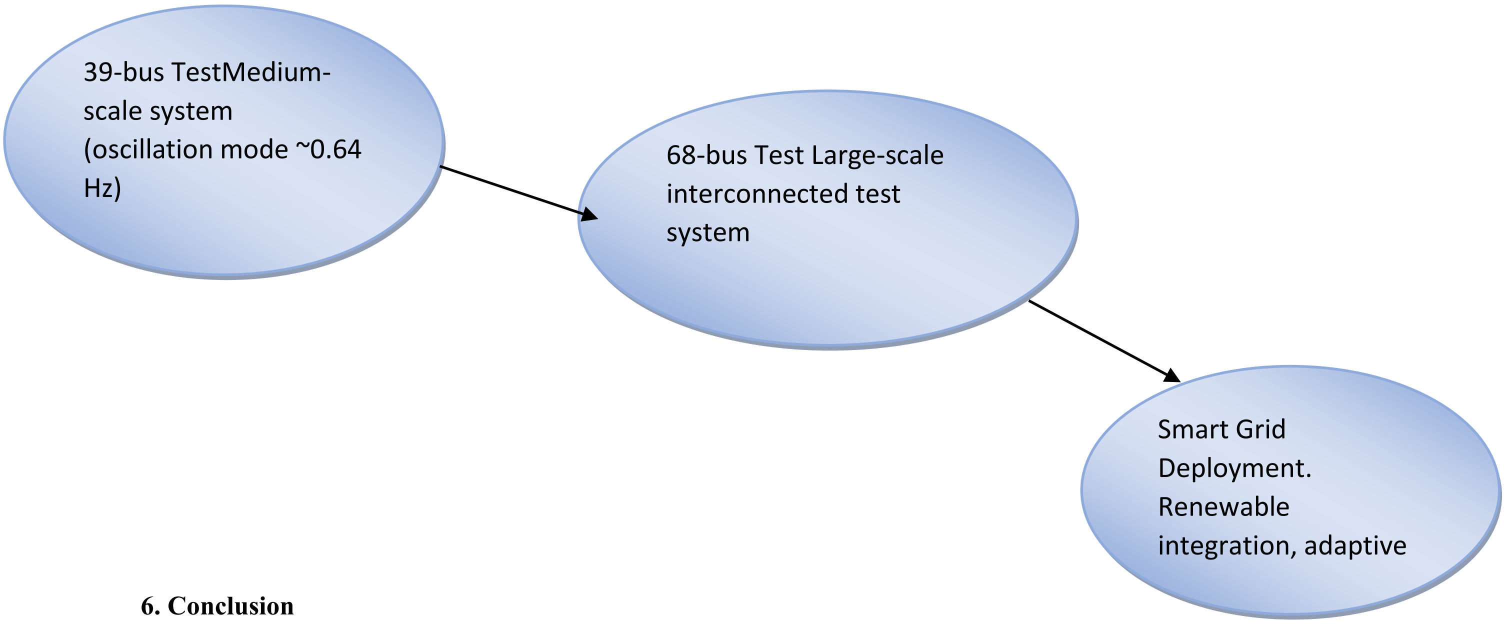
Both the IEEE 39-bus (medium-scale) and IEEE 68-bus (large-scale interconnected system) were used to verify the robustness of the suggested controller. It was confirmed that the Hybrid AI approach is not restricted to particular system sizes or configurations by the consistent performance benefits shown across both testbeds. According to Kumar, Srivastava, and Singh (2007), traditional controllers frequently show performance degradation in big interconnected grids, making this especially important. The scalability of the hybrid AI controllers for real-world power system applications is demonstrated by their capacity to maintain gains across scales.

Relevance in Practice and Preparedness for Deployment

An approach to smart grid stability management that is ready for deployment is the suggested Hybrid AI-optimized FACTS controllers. In situations involving the integration of renewable energy sources when system dynamics are extremely uncertain, their versatility guarantees robustness, improved transient stability margins, and efficient mitigation of low-frequency inter-area oscillations. Noroozian et al. (1997) have observed that while FACTS devices on their own offer flexibility, sophisticated controllers are necessary to fully utilize their dynamic potential. With the use of hybrid artificial intelligence, FACTS can function as intelligent stabilizing agents in contemporary grids.

Additionally, the penetration of solar and wind energy is growing, which makes the stab severe.According to Padiyar (2006) and Haque (2008), the suggested strategy provides a route for utility-scale adoption and is consistent with the development of AI-driven smart grids.

Scalability Validation Workflow:



6. Conclusion

One of the most urgent issues in the current energy transition era is the stability of large-scale power networks. Maintaining system security under small-signal and transitory disturbances has become much more difficult due to rising electrical demand, widespread adoption of renewable energy, and growing regional grid interconnection. While severe transient occurrences like three-phase faults and rapid load changes continue to challenge the resilience of grid infrastructures, low-frequency inter-area oscillations in the 0.2–0.8 Hz range continue to threaten the dynamic security of power networks. Due to their reliance on linearized models and incapacity to adjust to nonlinear, unpredictable, and time-varying situations, traditional techniques like Power System Stabilizers (PSS) have reached their performance limits (Padiyar, 2006).As a result, more sophisticated solutions are being sought after, and Flexible AC Transmission Systems (FACTS) are showing promise as dynamic control enablers.

Both steady-state and transient performance can be supported by FACTS devices, such as the Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC), which can quickly and controllably inject reactive or series compensation into the network (Noroozian et al., 1997). However, the way supplemental damping controllers are designed has a significant impact on how successful they are. Early FACTS damping controllers were based on traditional designs such lead-lag structures or PI (Kumar et al., 2007). However, these methods were proven to be poorly scalable to large interconnected networks and extremely sensitive to changes in system parameters.Adaptability and nonlinearity handling were introduced by further research on Fuzzy Logic Controllers (FLCs) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) (Haque, 2008; Cai, 2005). These intelligent controllers were successful in simulations, but they had problems with scalability, convergence, and parameter adjustment.

A hybrid AI-optimized ANFIS damping controller for FACTS devices was created in this study to get over these restrictions. It incorporates hybrid metaheuristic optimization frameworks (GA+PSO, PSO+GWO) to offer reliable parameter tuning. In contrast to solo optimization algorithms, which either have limited global exploration (PSO, GWO) or premature convergence (GA), the hybrid methods made use of the complementing advantages of both strategies. A multi-objective optimization function was created to improve critical clearing time (CCT), reduce settling time (Ts), and maximize damping ratio (ζ) all at once.making certain that transient stability and small-signal stability were handled equally.

The 39-bus New England system and the 68-bus NY–NE linked system, two benchmark IEEE networks that provide medium- and large-scale test environments, were used to evaluate the methodology. PSCAD was used for electromagnetic transient studies, while MATLAB/Simulink was used for eigenvalue analysis. The Hybrid AI-ANFIS controller regularly outperformed standalone, fuzzy, lead-lag, and PI ANFIS controllers, according to the results. In comparison to baseline controllers, the suggested controller quantitatively enhanced the damping ratio by over 400%, prolonged the CCT by around 68%, decreased the settling time by over 48%, and lessened rotor angle overshoot by more than 70%.Time-domain swing curves verified quicker damping and robust recovery under extreme fault circumstances, whereas eigenvalue migration plots demonstrated a distinct shift of crucial oscillatory modes toward the left-half plane.

This study's experimental validation of the suggested controller using a Hardware-in-the-Loop (HIL) framework was one of its main contributions. An oscilloscope and data recording interface were used to record the outputs of the experimental setup, which included a dSPACE DS1104 system for real-time simulation of IEEE test networks, a DSP (TMS320F28335) for controller execution, and an FPGA (Xilinx Spartan-6) for FACTS device emulation. With regard to switching delays, computational latencies, and hardware nonlinearities, this configuration offered a realistic test environment to confirm the viability of hybrid AI optimization in real time (Padiyar, 2006).The test scenarios included load changes of ±20%, three-phase fault recovery at Bus 16, and inter-area oscillation damping (~0.64 Hz). The long-standing gap between theoretical simulations and real-world applications was closed when experimental results showed constant variances of less than 5% from simulation findings.

This study is innovative because it combines intelligent control (ANFIS), FACTS-based stabilization, hybrid AI optimization, and real-time HIL validation. This work shows a whole pipeline from theoretical formulation to practical validation, whereas previous research mostly concentrated on simulation studies of FACTS controllers. The technique was successfully scaled across two IEEE test systems, demonstrating that the framework is both deployment-ready for smart grids and effective in academic testbeds.

Practical Consequences

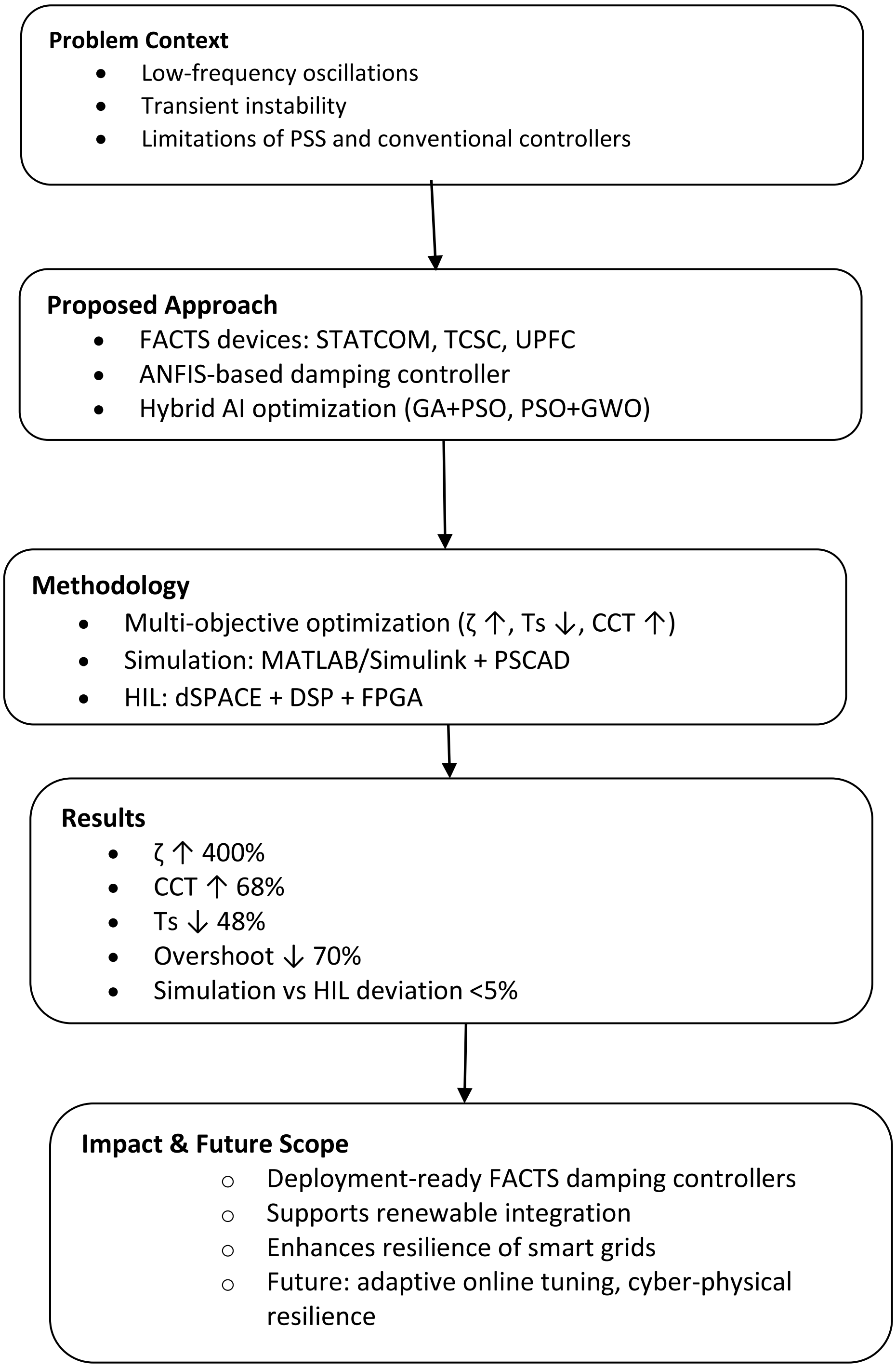
The research's findings pave the door for the practical implementation of FACTS controllers enhanced by AI methods. The suggested controller is especially appropriate for grid situations with a high concentration of renewable energy sources and interconnections because of its capabilities to adjust to load fluctuations, enhance fault recovery margins, and dampen inter-area oscillations consistently. The necessity of adaptive and intelligent stabilizing solutions is only going to increase with the growing use of solar and wind power, which introduce intermittency and low inertia.

Prospective Scope

- Even if the study shows a lot of promise, further developments could yet be made. Work in the future can investigate

- Including dispersed and renewable energy sources, especially hybrid AC/DC microgrids and DC grids, where dynamic stability issues are different.
- Cyber-physical resilience, which analyzes how well Hybrid AI-FACTS controllers function in the event of packet loss, wide-area communication delays, or cyberattacks.
- Adaptive online optimization frameworks, in which hybrid metaheuristics continually modify controller parameters in response to changing grid circumstances in real time.
- Pilot-scale validation in utility networks, applying the findings of HIL to field deployments where transmission systems already use FACTS devices.
- AI-enhanced cooperative management of various FACTS devices, wherein geographically dispersed controllers can better address wide-area oscillations by coordinated dampening

Contribution & Outcomes:



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