



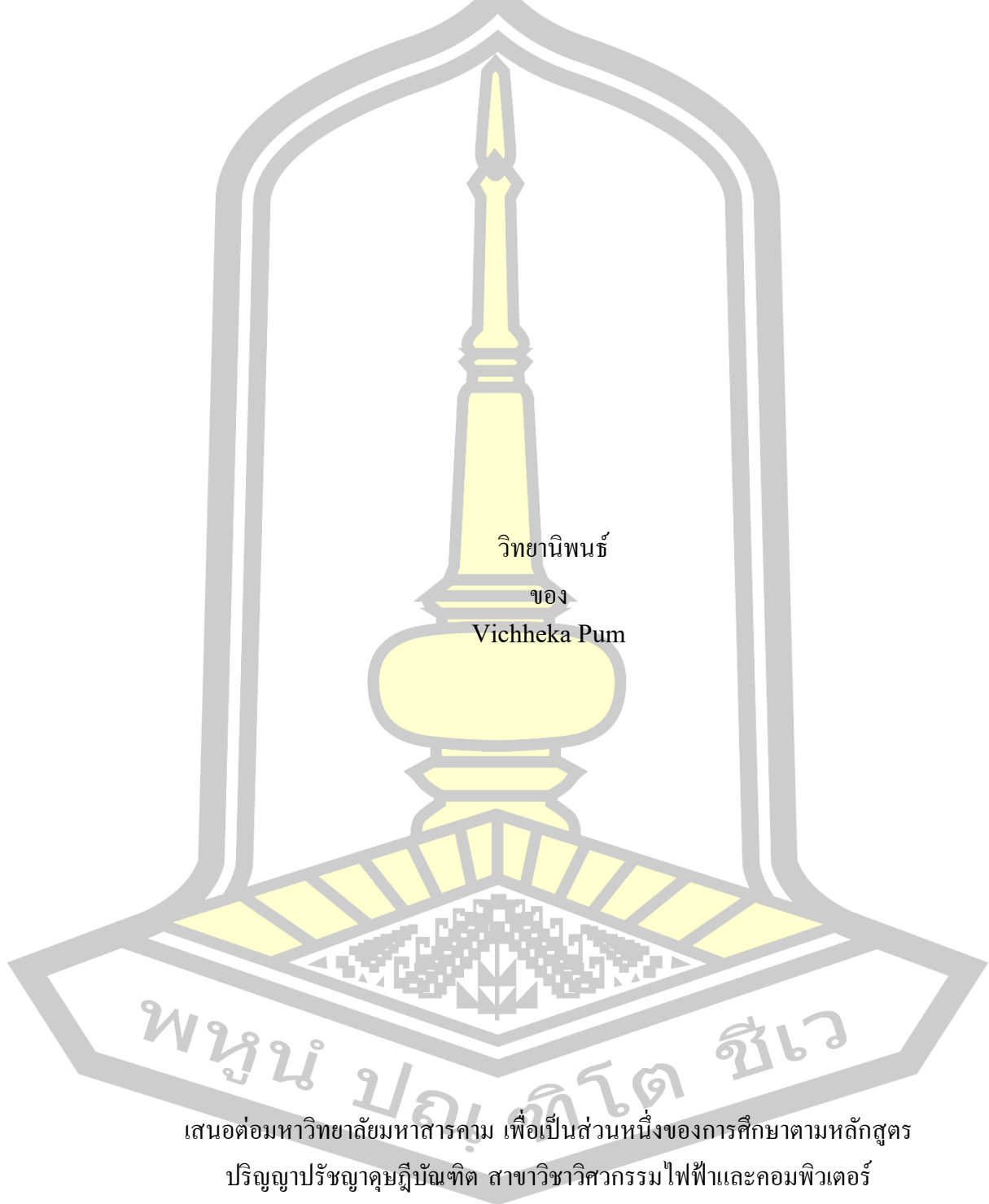
Optimization of Hybrid 1+ Proportional-Integral and Proportional-Integral-Derivative
Controller for Load Frequency Regulation in Nonlinear Two-Area Power Systems
Using Catch Fish Techniques

Vichheka Pum

A Thesis Submitted in Partial Fulfillment of Requirements for
degree of Doctor of Philosophy in Electrical and Computer Engineering
November 2025

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Optimization of Hybrid 1+ Proportional-Integral and Proportional-Integral-Derivative
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เสนอต่อมหาวิทยาลัยมหาสารคาม เพื่อเป็นส่วนหนึ่งของการศึกษาตามหลักสูตร
ปริญญาปรัชญาดุษฎีบัณฑิต สาขาวิชาวิศวกรรมไฟฟ้าและคอมพิวเตอร์

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The examining committee has unanimously approved this Thesis, submitted by Mr. Vichheka Pum , as a partial fulfillment of the requirements for the Doctor of Philosophy Electrical and Computer Engineering at Mahasarakham University

Examining Committee

Chairman

(Assoc. Prof. Anan Kruesubthaworn
, Ph.D.)

Advisor

(Nuttapon Chaiduangstri , Ph.D.)

Committee

(Prof. Worawat Sa-Ngiamvibool ,
Ph.D.)

Committee

(Assoc. Prof. Chonlatee Photong ,
Ph.D.)

Committee

(Assoc. Prof. Niwat Angkawisittpan
, Ph.D.)

Mahasarakham University has granted approval to accept this Thesis as a partial fulfillment of the requirements for the Doctor of Philosophy Electrical and Computer Engineering

(Assoc. Prof. Juckamas Laohavanich ,
Ph.D.)

Dean of The Faculty of Engineering

(Asst. Prof. Pondej Chaowarat , Ph.D.)
Dean of Graduate School

TITLE	Optimization of Hybrid 1+ Proportional-Integral and Proportional-Integral-Derivative Controller for Load Frequency Regulation in Nonlinear Two-Area Power Systems Using Catch Fish Techniques		
AUTHOR	Vichheka Pum		
ADVISORS	Nuttapon Chaiduangstri , Ph.D.		
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ABSTRACT

This project aims to propose an application of Catch Fish Optimization Algorithm Techniques (CFOA) to achieve the optimal calibration of hybrid 1+PI and PID Controller for automatic generation control of the nonlinear two-area power system model to guarantee stable frequency regulation even when faced with intricate challenges like GRC and GDB. The proposed algorithm utilizes mathematical modelling catch fish methods, allowing it to navigate the search space efficiently and avoid less advantageous local optima. The assessment of the suggested method is carried out through simulations on a two-area power systems model, incorporating 0.2 per unit load fluctuations, with ITAE serving as the performance metric. The results of study demonstrate that the hybrid controller significantly reduces overshoot, undershoot, and settling time while also maintaining stable tie-line power flow. The simulation shows the value of the ITAE just 0.0336, the controller proves to be highly effective and reliable. The proposed optimization techniques and hybrid 1+PI and PID controller highlight the suitability for complex multi-area power networks and suggest promising applications in future systems with renewable energy integration or rapidly changing loads.

Keyword : Catch Fish Optimization, Catch Fish Optimization Hybrid 1+PI and PID Controller, Load Frequency Control, Metaheuristic Optimization, Nonlinear Power System

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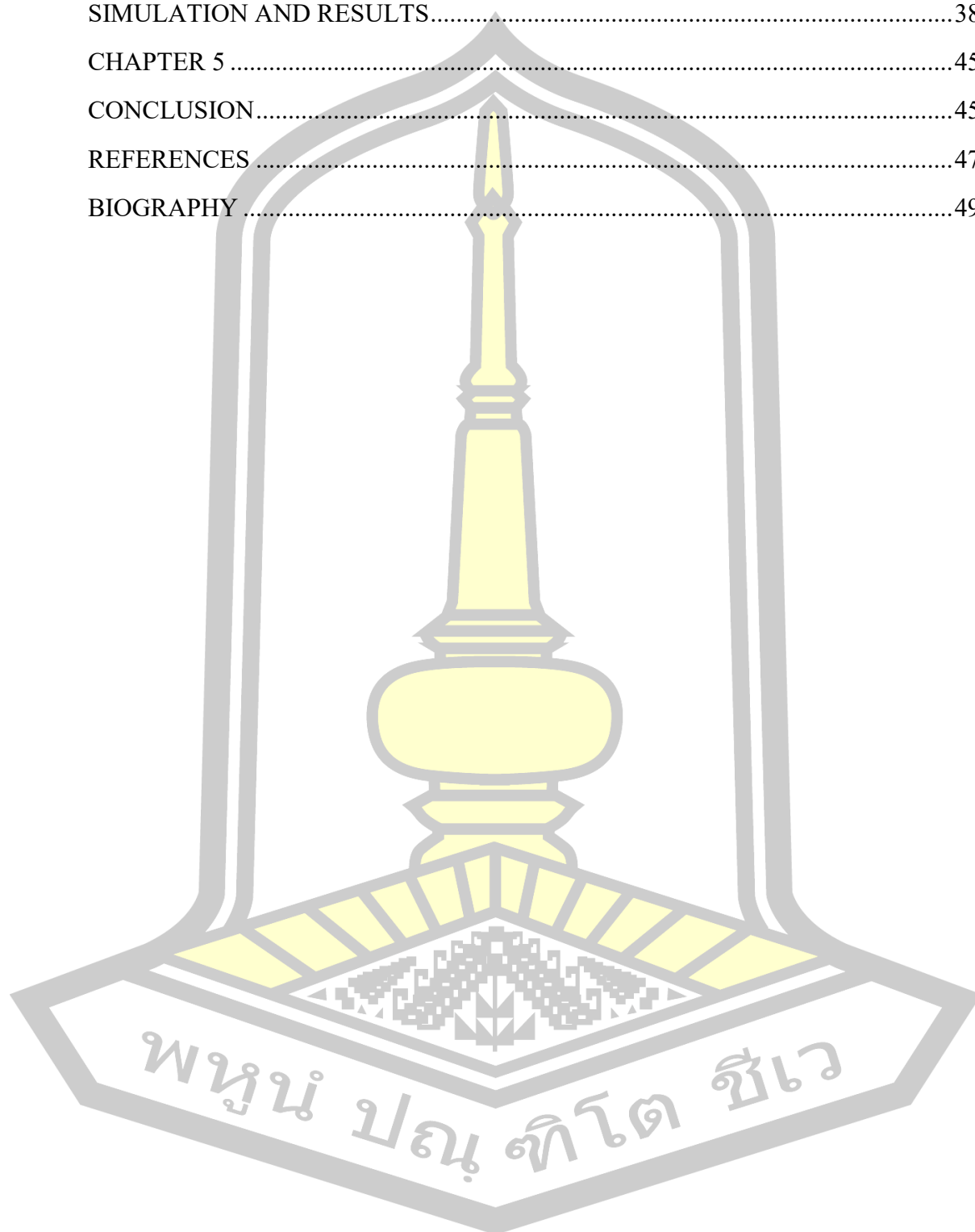
Should the contents of this thesis prove beneficial to future researchers or students undertaking similar studies, the research team humbly attributes all merit to the individuals acknowledged herein, as well as those not explicitly mentioned. Any shortcomings or errors in this thesis remain the sole responsibility of the author, and sincere apologies are hereby offered.

Vichheka Pum

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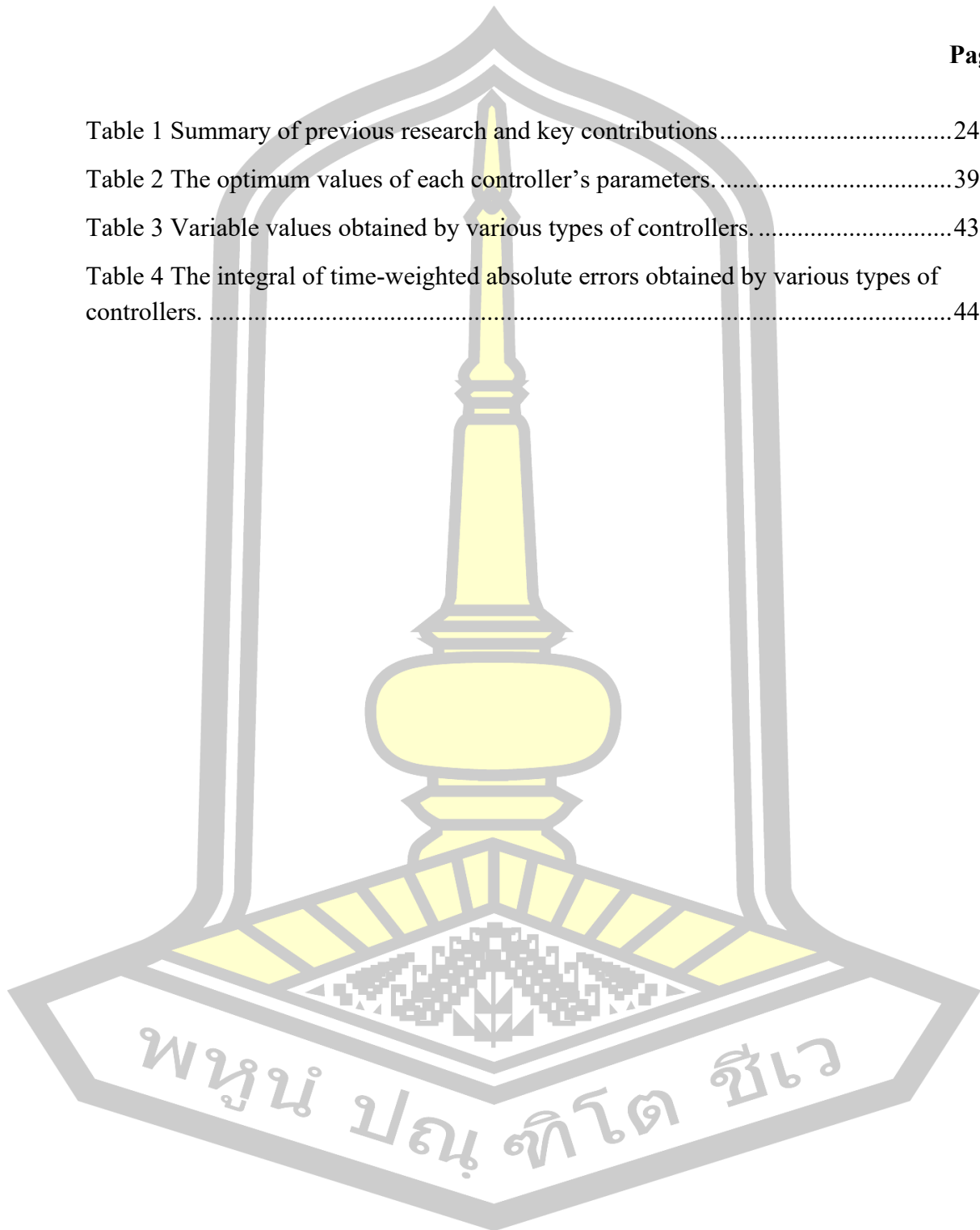
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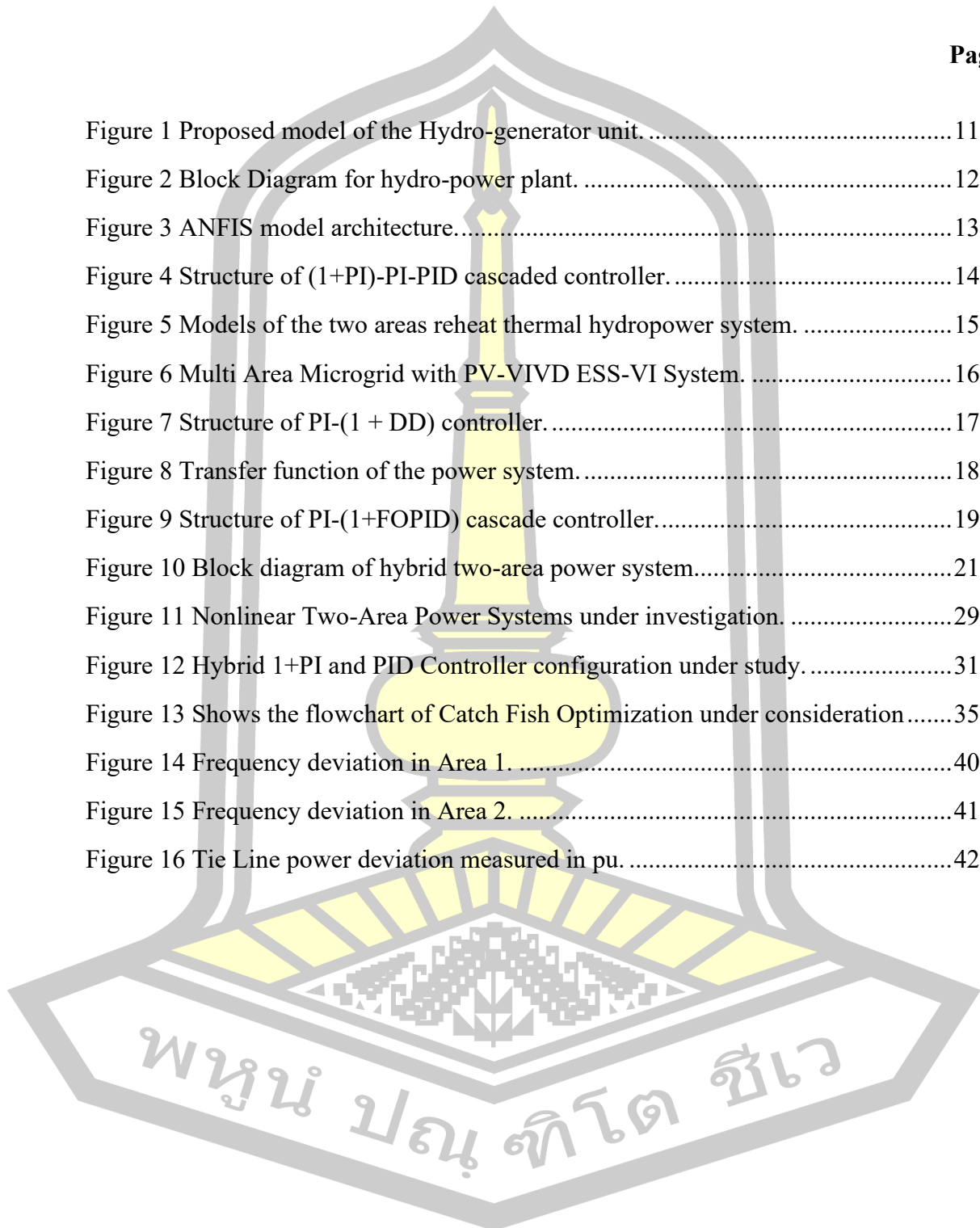
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CHAPTER 1

INTRODUCTION

1.1 General Aspects of Energy Usage

Energy is the cornerstone of modern civilization. From powering homes and industries to enabling transportation and communication, energy usage permeates every aspect of human life. When societies evolve, the demand for energy continues to rise significantly, prompting critical discussions around sustainability, efficiency, and equitable access. Energy, in its most fundamental sense, is the capacity to do work. It exists in various forms—mechanical, thermal, chemical, electrical, and nuclear. Energy can be transformed from one form to another based on their application. The ability to harness and utilize energy has been pivotal in shaping human progress. Historically, societies transitioned from manual labor and animal power to the use of fire, wind, and eventually fossil fuels and electricity. Today, energy is not merely a technical concept but a socio-economic drive that influences development, quality of life, and geopolitical dynamics.

Energy sources are broadly categorized into two types: renewable and non-renewable. The non-renewable energy sources are finite and depleted over time. They include coal, oil and simple forms in natural gas that have been used in household heating, electricity, and industrial processes. Another well-known source is nuclear energy which is derived from uranium fission, providing large-scale electricity with low greenhouse gas emissions but raises concerns about radioactive waste and safety. Another source is renewable energy. The following sources are naturally replenished and considered more sustainable such as Solar Energy that depends on sunlight hitting the photovoltaic cells generating electricity. Other sources such as Wind Energy, Hydropower, Biomass, Geothermal Energy take an important role in electricity generation for human's need.

Energy consumption varies significantly across regions due to differences in economic development, population size, industrial activities, and local climate. Developed nations typically exhibit higher per capita energy usage, driven by industrialization and consumer lifestyles. In contrast, developing countries often face energy access challenges, relying on traditional biomass and lacking infrastructure for modern energy systems. According to recent global statistics fossil fuels still account for approximately 80 percent of global energy consumption or speaking in another word as it is still a main source of generating every unit of electricity in the world. Renewable energy sources are growing rapidly too, especially solar and wind energy, but still represent a smaller share of the total energy utility. Electricity demand is increasing due to digitalization, urbanization, and electrification of transport and heating and another factor is increasing of the demand of electric vehicles in the new age of clean energy trend and country's requirement.

Energy systems involve multiple stages of conversion, from primary sources to secondary forms and finally to end-use services. For example, natural gas; primary form, is burned to produce electricity; secondary form, which powers appliance by every type of electrical equipment. Each conversion step incurs losses, often in the form of heat, making energy efficiency a critical metric. Therefore, every unit of power must be under monitored and consumed effectively to the end-users. At the same time improving energy efficiency in every aspect is another solution, means using less energy to perform the same task. This can be achieved through a lot of factors such as improving more advanced technologies (e.g., LED lighting equipment, high-efficiency motors), smart grids and demand-side management, building insulation and passive design, efficient transportation systems. When focusing on energy efficiency, it not only reduces energy units and costs but also mitigates environmental impacts and enhances energy security and sustainability of the power utility. Generally, energy access is linked to education, health, and economic opportunity. Lack of reliable energy hampers development, especially in rural and underserved communities as well as in developing countries. The concept of energy justice emphasizes fair distribution of energy benefits and burdens, ensuring that all populations have access to clean, affordable, and reliable energy systems.

1.2 Electrical Generation and Its Control

Electrical generation refers to the systematic process by which different forms of primary energy such as mechanical, chemical, thermal, or solar energy are transformed into electrical energy that can be distributed and utilized across residential, commercial, and industrial sectors through power lines known as large utility. This conversion is fundamental to modern infrastructure and is typically carried out in dedicated facilities known as electrical power plants. Within these plants, the transformation process is facilitated by generators, which are mechanical devices designed to convert rotational kinetic energy into electrical energy through electromagnetic induction.

The generators themselves are usually driven by turbines, which rotate because of energy input from various fuel sources and renewable energy sources. The fuel source can be conventional, such as natural gas, coal, and oil, which undergo combustion to produce high-pressure steam or gas that propels the turbine blades. Alternatively, nuclear power plants use controlled nuclear fission reactions to generate heat, which similarly produces steam to drive turbines. In recent decades, there has been a significant shift toward renewable energy sources, which offer cleaner and more sustainable alternatives and more environmentally friendly. For instance, wind turbines harness the kinetic energy of moving air masses, while solar power systems convert sunlight directly into electricity using photovoltaic cells or indirectly through solar thermal mechanisms.

Each energy source has its own conversion pathway and efficiency characteristics, but the final goal remains the same: to produce a stable and usable flow of electrical energy that meets the demands of modern society. The complexity of this process requires careful engineering design, operational control, and ongoing innovation to ensure reliability, safety, and environmental sustainability. While the process of generating electricity is undeniably essential to powering modern communities, it represents only one facet of a much broader and more complex challenge. Another equally important challenge is the precise and continuous control of that electrical generation. Without effective control mechanisms, even the most advanced generation technologies can lead to instability, inefficiency, and potential

hazards within the power system; somehow can lead to power disruption in distributions.

Control in electrical generation requires a wide range of engineering functions, including regulation of voltage and frequency of the power system (well-known as automatic voltage regulation; AVR, and load frequency control or LFC), synchronization of multiple generators to maintain stability of electricity system due to load disturbance, load balancing, and real-time response to fluctuations in disrupted demand. These functions are critical factors for all the existing supply sections to maintain the overall stability and reliability of the electrical grid. For instance, if the supply section of electricity generation does not match the demand at any given instances, it can result in frequency deviations, voltage fluctuation that may damage any electrical equipment which require stable and specific rated voltage or at least it reduces the device's lifespan, disrupt industrial operations and process, or even trigger widespread blackouts.

Moreover, efficient control ensures that electricity is produced and distributed in a manner that minimizes waste and optimizes resource usage. This includes economic dispatch strategies that determine which generators should operate at any given time to achieve the lowest possible cost and keep maintaining the meeting demand. It also involves integrating renewable energy sources such as solar and wind which are inherently variable and require sophisticated control systems to manage their intermittency and maintain grid equilibrium and stability.

Safety aspect is another paramount concern. Control systems are designed to detect faults, isolate affected components, and initiate protective actions to prevent cascading failures or to minimize the electrical fault to a restricted under controlled. These systems must operate with high precision and reliability, especially in large, interconnected power networks where disturbances can propagate rapidly to the voltage level and the frequency in the whole systems.

In the field of modern engineering, efficient control of electrical generation is not a supplementary feature, however it is a foundational discipline. It underpins the design, operation, and evolution of power systems, ensuring that electricity is not only generated but also delivered in a stable, secure, and sustainable manner. Engineers must therefore approach generation and control as two inseparable components of a

unified system, each reinforcing the other to meet the demands of modern energy infrastructure.

1.3 Interconnected Power Systems and PID Controller

Electrical power is an essential factor in every country in the world. It plays an important role in economic growth, technologies and many other demands. Due to the popular growth, electric demand is also increasing significantly and leads to constructing more electrical power plants in the rural areas and either government sections or private power companies have been investing so hard to reach the target level of growth. So, the main responsibility of each unit is to supply the necessary power to meet the users' power demand. Technically, when electrical power is in high demand at a very short time, it can be led to instability to the power lines include under-voltages and under-frequency phenomenon which makes it unreliable to the power stability. Therefore, frequency and voltage are the key parameters in every power plant and controlling them is a major concern.

To overcome the problem in a power system, a single generator can feed large and complex areas with the aid of inter-linked plants (generally being known as interconnected plants). The supply of power to neighboring companies is achieved through a Tie line power transfer mechanism. Nowadays, the generation of electrical power is not sufficient to cater for the increasing load demand due to the mismatch between load and generation. The frequency depends on the real power generation, and it should be balanced and remain constant in different operating conditions.

In grid powerplants, a change in active power generation at one power line affects the whole system's frequency. In general, the quality of the dual power plants mainly depends on the frequency which needs to be regulated properly for quality power supply. Usually, excitation voltage control and load frequency control (LFC) are non-interactive and can be modeled and analyzed independently. Modern power generation systems must maintain continuous electricity production to meet growing demand. As load increases whether due to industrial expansion, urbanization, or peak usage periods, the system must preserve its stability to ensure reliable operation. To

achieve this issue, Automatic Generation Control (AGC) is employed to regulate power output dynamically and maintain system equilibrium.

A critical aspect of AGC is Load-Frequency Control (LFC), which ensures that the supply of electrical power matches the demand while keeping the system frequency within acceptable limits. LFC is essential for maintaining reliability of power delivery, ensuring quality of voltage and frequency and responding to disturbances such as load fluctuations, generator failures, or any parameter shifts. These disturbances can cause unpredictable frequency deviations, which, if unmanaged, may lead to cascading failures or blackouts.

The Proportional-Integral-Derivative (PID) controller has long been recognized as a robust and effective tool in modern engineering applications, including power system control. Its advantages include simplicity in design, wide applicability across systems of varying complexity and strong performance in both linear and nonlinear circumstances. However, tuning PID parameters gains value and control boundaries remains a challenge. Improper tuning can degrade system performance or even destabilize it instead. Therefore, a good controller design is crucial as well.

One traditional method for PID tuning is the Ziegler-Nichols method, which offers two straightforward approaches based on system response characteristics. These methods help determine initial parameter values, which may then be refined through further analysis or simulation with the assistance of optimization techniques that are widely used in modern engineering technology. To avoid error tuning, designers often evaluate system performance using metrics such as minimum steady-state error, minimum overshoot and low settling time. These indicators help assess controller effectiveness without exhaustive manual testing.

As mentioned earlier, there are a lot of optimization techniques that have been proposed to solve complex issues due to system responses against rapid load disturbance such as Bee Algorithm optimization, Fuzzy Logic, etc. One of which is Catch Fish Optimization Algorithm (CFOA) known as another technical method inspired by nature-metaheuristic algorithm that mimics the behavior of rural fishermen during traditional fishing. It is designed to solve complex optimization problems by balancing exploration and exploitation just like fishermen adapt their

strategies to catch elusive fish. It has proven effective in identifying optimal parameter sets for control systems.

This study highlights the new proposed hybrid 1+PI and PID controller system optimized by applying CFOA techniques to take intelligent control in the proposed interconnected power systems to enhance the stability of the system with high efficiency generation control scenarios.

1.4 The Purposes of Study

This research aims to study these main points including:

1.4.1 To introduce a new hybrid controller consists of an integration between a conventional PID controller with a 1+PI controller structure to limit the restriction of the complex behavior under load disturbance.

1.4.2 To apply the new Catch Fish Optimization Algorithm (CFOA) to optimize all gain values of controller's parameters. CFOA introduces an innovative methodology inspired by human fishing practices.

1.4.3 To evaluate the system response under four distinct control strategies include a standard PI controller, a 1+PI controller with an added feedforward term, a conventional PID controller, and a new proposed hybrid controller that systematically integrates the functionalities of both 1+PI and PID controllers respectively.

1.4.4 To compare all the value of system response with four distinct controls applied to the system with the gains' value of each category.

1.5 Field of Study

In this research, numerical simulations will be conducted using the MATLAB/Simulink platform, which offers a robust environment for modeling, analyzing, and visualizing dynamic systems. The simulation framework was designed to evaluate the performance of advanced control strategies within a multi-area power system. To this end, a custom-developed MATLAB script (.m file) was created to implement the Catch Fish Optimization Algorithm (CFOA), a nature-inspired metaheuristic technique known for its effectiveness in solving complex optimization

problems. To assess the robustness and adaptability of the proposed control strategy, a step-load disturbance was introduced in Area 1 of the interconnected power system. This disturbance served as a benchmark scenario to evaluate the system's transient response, frequency stability, and control effectiveness under sudden load variations. The simulation results were analyzed to determine the impact of CFOA on system performance metrics, including overshoot, settling time, and inter-area oscillations.

1.6 Expected Result

After completely conducting this research, this given methodology and the proposed new catch fish optimization techniques used as a numerical method to estimate the best values of all the parameters of the controller will be expected as:

1.6.1 Enable to maintain load frequency under instant load disturbance of the two-area nonlinear interconnected power systems.

1.6.2 Propose new hybrid 1+PI and PID controller that integrates with high performance to stabilize the power generation.

1.6.3 Demonstrates impressive adaptability to load variations while maintaining system stability throughout both transient and steady-state phases of the response of the power systems.

In this research, Chapter 1 introduces the problems addressed to the design of the controller which is another main important challenge to give precise and continuous control of the electrical generation under step load disturbance in the power system. To overcome the complexity of numerical methods to solve for the optimal values of the parameters of the controller, catch fish optimization techniques will be introduced in this research. This technique is inspired by the conventional fish-catching methods utilized in rural communities. Moreover, the existing articles and related techniques which are used to estimate any gain values of parameters of the controller of interconnected power systems are also reviewed in Chapter 2. However, the comparison between each of their techniques is made to better understand the advantages and their limitations to develop another way to conduct the study on the optimization techniques. Chapter 3 discusses and highlights a new proposed hybrid

controller to Load Frequency Control (LFC) to maintain equilibrium under continuously changing operating conditions. The catch fish optimization techniques are also discussed in detail, and this investigation will be considered in further study as well. Chapter 4 provides a result of the study after conducting a numerical method via MATLAB/Simulink tool to calculate the best gain values optimized by CFOA techniques. All necessary values such as overshoot, undershoot, settling time and other related values are also revealed and discuss and make a comparison in this chapter. Finally, Chapter 5 provides conclusions and an outlook for future work related to this field.



CHAPTER 2

LITERATURE REVIEWS

2.1 General Aspects

The classification of existing optimization-based techniques applied to two-area interconnected power systems is multifaceted and can be approached from various perspectives. These classifications may be based on the nature of the optimization algorithm employed such as classical, heuristic, metaheuristic, or hybrid methods. The specific control objectives can be achieved by setting the target including load frequency control (LFC), tie-line power regulation, or system stability enhancement, the structural characteristics of the power system model (linear or nonlinear, continuous or discrete), or the integration of renewable energy sources and energy storage systems. Furthermore, distinctions can be drawn based on the dimensionality of the control strategy (single objective or multi-objective optimization), the computational complexity and convergence behavior of the algorithms, and their adaptability to real-time implementation. Such a comprehensive classification framework not only facilitates a deeper understanding of the current study but also assists in identifying gaps and other opportunities for future research in the domain of intelligent control of interconnected power systems.

2.2 Reviews of previous research and keys contributions

Technically, when electrical power is in high demand at a very short time, it can be led to instability to the power lines include under-voltages and under-frequency phenomenon which makes it unreliable to the power stability. To overcome the problem; in a power system, a single generator can feed large and complex areas with the aid of inter-linked plants (or known as interconnected plants). The supply of power to neighboring companies is achieved through a Tie line power transfer mechanism.

In 2023, a group of researchers conducted research on Optimal Neuro-fuzzy model and PID controller of a Hydro-generator unit from the identification of its LTI model [1]. The document presents a methodology for developing a neuro-fuzzy PID controller for hydro-generator units based on the identification of their linear time-invariant (LTI) models to enhance control performance in hydroelectric energy systems as shown in figure 1.

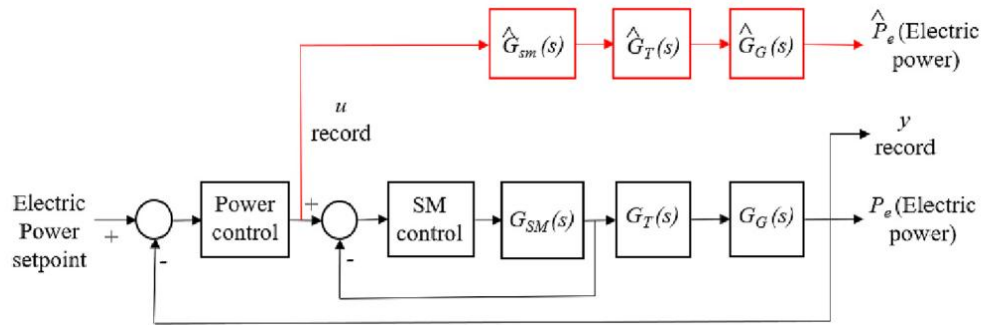


Figure 1 Proposed model of the Hydro-generator unit.

This paper presents a methodology for creating a neuro-fuzzy model and PID controller for a hydro-generator unit (HGU) based on its linear time-invariant (LTI) model. The methodology involves continuous time identification of the LTI model. A classic PID controller is developed to meet performance specifications. The neuro-fuzzy model is trained using cost functions like root mean square error (RMS error value). The study applies the methodology to the Hydro-Agoyán HGU, demonstrating effective power response under varying setpoints. Their research also provided a review of existing control techniques for hydraulic turbines which have been proposed, emphasizing both classic and modern approaches such as Classic PI control that has been extensively studied for stability and tuning while modern controls include nonlinear, optimal, and robust controls using state variable representations. The paper details the dynamic parameterization process for the servomotor, turbine, and generator. Their studies result from Hydro-Agoyán power plant revealed that the neuro-fuzzy systems may result in a more complex-solutions compared to other control techniques for some kind of systems depending on the operation dynamics. This issue must be carefully analyzed to apply the technique which satisfies an

equilibrium between complexity and proper or expected control performance. One of the objectives of this paper was to present a detailed methodology to apply neuro-fuzzy modeling for system identification using an LTI approach. This way, we can illustrate how the proposed methodology can be applied even for systems with high dynamics such as power generation systems.

Another research in 2021, Tilahun Weldcherkos, Ayodeji Olalekan Salau, and Aderajew Ashagrie conducted on the modeling and design of an automatic generation control for hydropower plants using Neuro-Fuzzy controller providing an experimental analysis of an Automatic Generation Control (AGC) system for hydropower plants using an Adaptive Neuro-Fuzzy Inference System (ANFIS) to improve frequency regulation during power generation [2]. This paper explores the modeling and design of an Automatic Generation Control (AGC) system for hydropower plants using an Adaptive Neuro-Fuzzy Inference System (ANFIS) to mitigate frequency deviations during power generation as shown in figure 2 and figure 3 respectively.

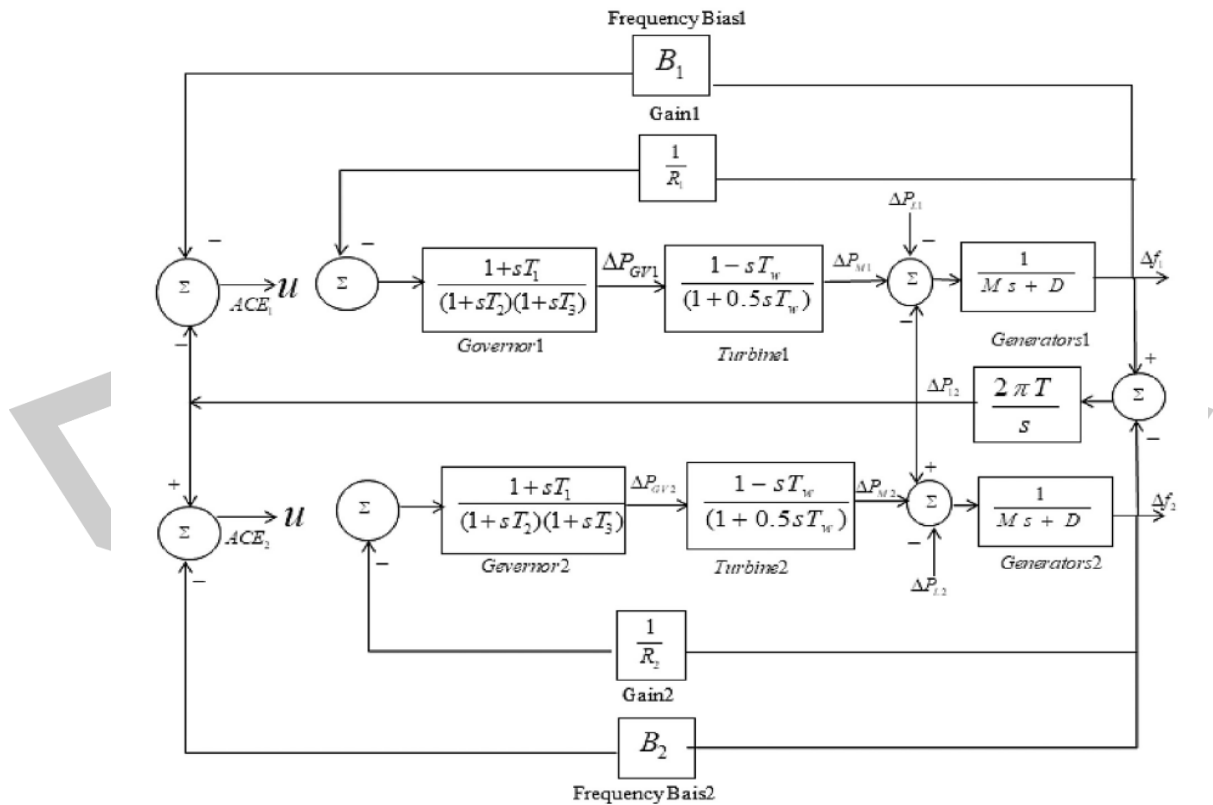


Figure 2 Block Diagram for hydro-power plant.

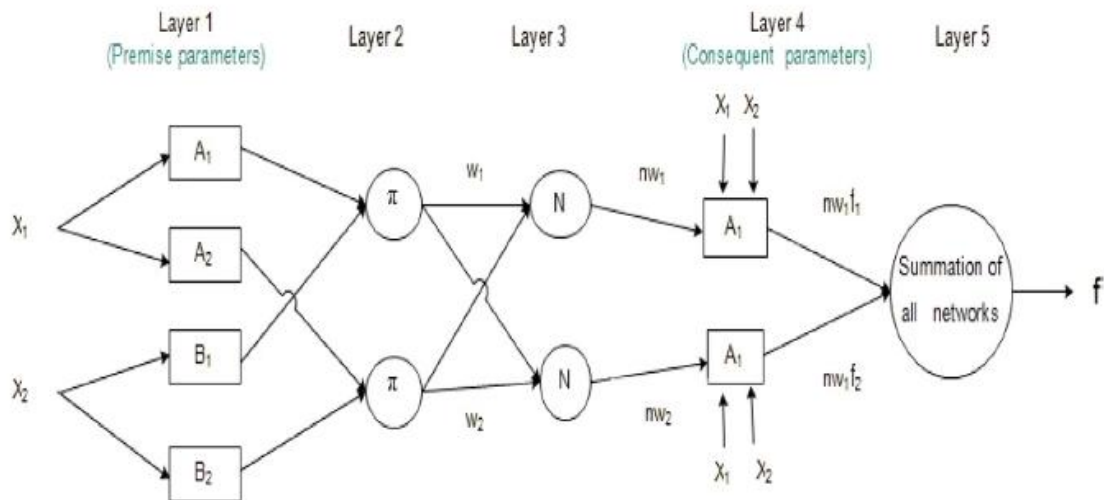


Figure 3 ANFIS model architecture.

The study compares the performance of conventional PID, Fuzzy Logic Controller (FLC), and ANFIS controllers using MATLAB simulations. The increasing mismatch between power generation and load demand leads to frequency deviations in hydropower systems. Frequency errors during power generation due to load disturbance are unavoidable, complicating the maintenance of steady generation frequency and tie-line flow. The results of their research indicated that frequency deviations arise from continuous load variations, making control challenges without a governor. The results show that Frequency deviations occur because of a continuous variation of loads, which makes the deviations difficult to control when a governor is not applied. Furthermore, the response of the AGC of the hydropower plant (in the single and double area) with step-load changes were under investigation. Their simulation results show that ANFIS controller performs better compared to the conventional PID controller as well as comparing to the other FLC. Further results indicate that the proposed ANFIS controller helps to speed up the performance of the AGC of the hydropower plant. The ANFIS controller not only improved the performance but also made the fuzzy inference system (FIS) less dependent on the expert system. The research concludes that ANFIS is the most effective controller for AGC in hydropower plants, with potential advantages for future studies.

In 2024, a group of researchers delivered a study on a hybrid optimization algorithm based on cascaded $(1 + PI)$ -PI-PID controller for load frequency control (LFC) in proposed interconnected power systems [3]. The document presented a research study on a hybrid optimization algorithm for cascaded $(1 + PI)$ PI-PID controllers that aimed at improving the efficiency of load frequency control (LFC) in the interconnected power systems. The controller consists of three main components: $(1 + PI)$, PI, and PID, each addressing different system dynamics. This study highlighted a novel cascaded controllers that combined each element to optimize and determine the optimal gains value by using an improved Artificial Bee Colony-Particle Swarm Optimization (IABC-PSO) algorithm for load frequency control in interconnected power systems. The proposed controller structure integrates traditional PID controllers to enhance performance and debugging capabilities. The IABC-PSO algorithm improves exploration efficiency by increasing scout bee occurrences to 10 percent for each employed bee. The performance of the algorithm was assessed using four benchmark functions, showing superior results compared to traditional methods. The study tested six configurations of the controller under 1 percent and 5 percent step load disturbances, demonstrating robust dynamic performance. The research study also mentioned the importance of Load Frequency Control in interconnected power systems to maintain the system synchronization and reliability because it can ensure the balance between generated power and load demand, crucial for system stability. Plus, the research introduces a cascaded $(1 + PI)$ -PI-PID controller design aimed at improving LFC performance. Figures 4 and 5 illustrated the model of the controller and structure of power plants of their research study.

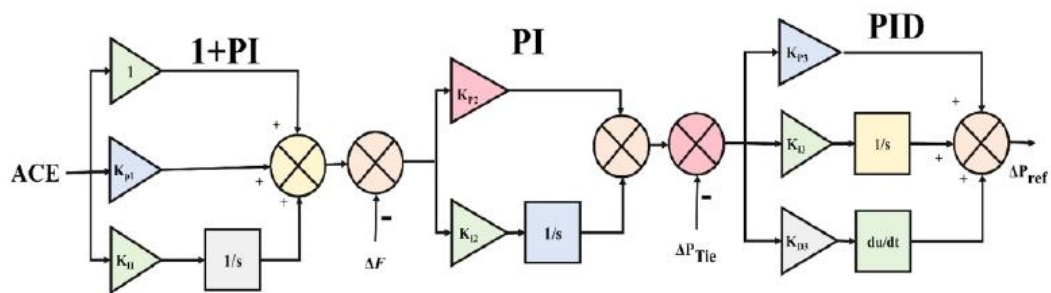


Figure 4 Structure of $(1+PI)$ -PI-PID cascaded controller.

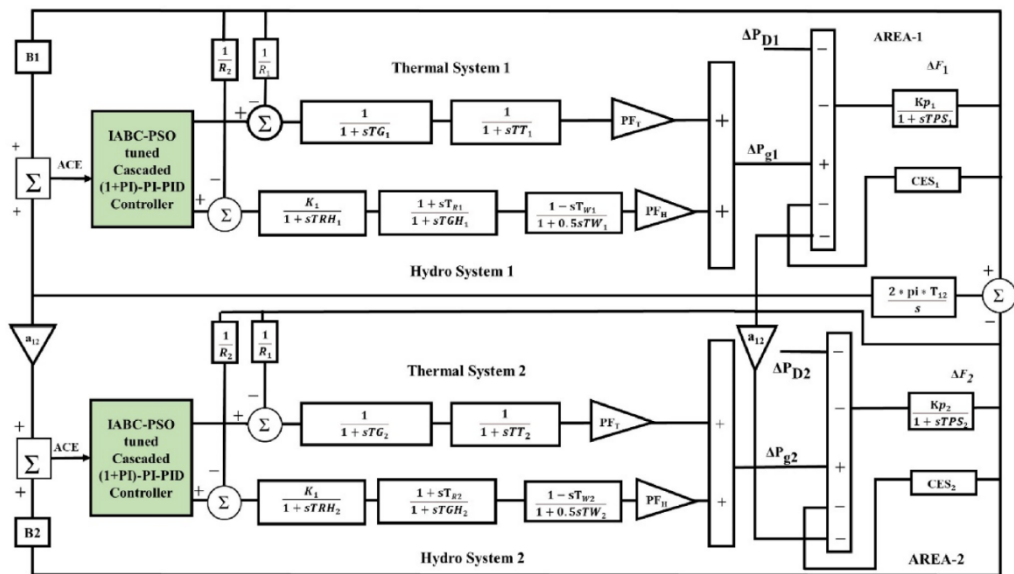


Figure 5 Models of the two areas reheat thermal hydropower system.

The objective functions for optimization include Integral Absolute Error (IAE), Integral Square Error (ISE), Integral of Time-Weighted Absolute Error (ITAE), and Integral Time Square Error (ITSE). The system includes hydro and thermal power plants, with a capacitive energy storage device for enhanced regulation. The study concludes that the IABC-PSO algorithm significantly improves load frequency control in power systems. Meanwhile, the hybrid optimization algorithm and cascaded controller configuration yield substantial performance enhancements. The proposed controller achieved minimal ITAE values and superior settling times across various scenarios. They also stated that in the future research should focus on scalability and applicability to other control problems within the real power industry.

Recently, in 2025, Amit Sharman and Navdeep Singh, researchers from India have studied on Enhancing multi-area microgrid stability with virtual damping and energy storage inertia techniques using hybrid lyrebird - Pattern search optimized PI-(1+DD) controller [4]. They discussed a research study on enhancing the stability of multi-area microgrids through a photovoltaic-based virtual inertia and damping energy storage system, utilizing advanced optimization techniques for controller tuning.

This research proposes a novel approach to improve the stability of multi-area microgrids using virtual inertia and damping techniques. The study integrates a photovoltaic-based virtual inertia and damping system with an energy storage system (ESS) as shown in the figure below.

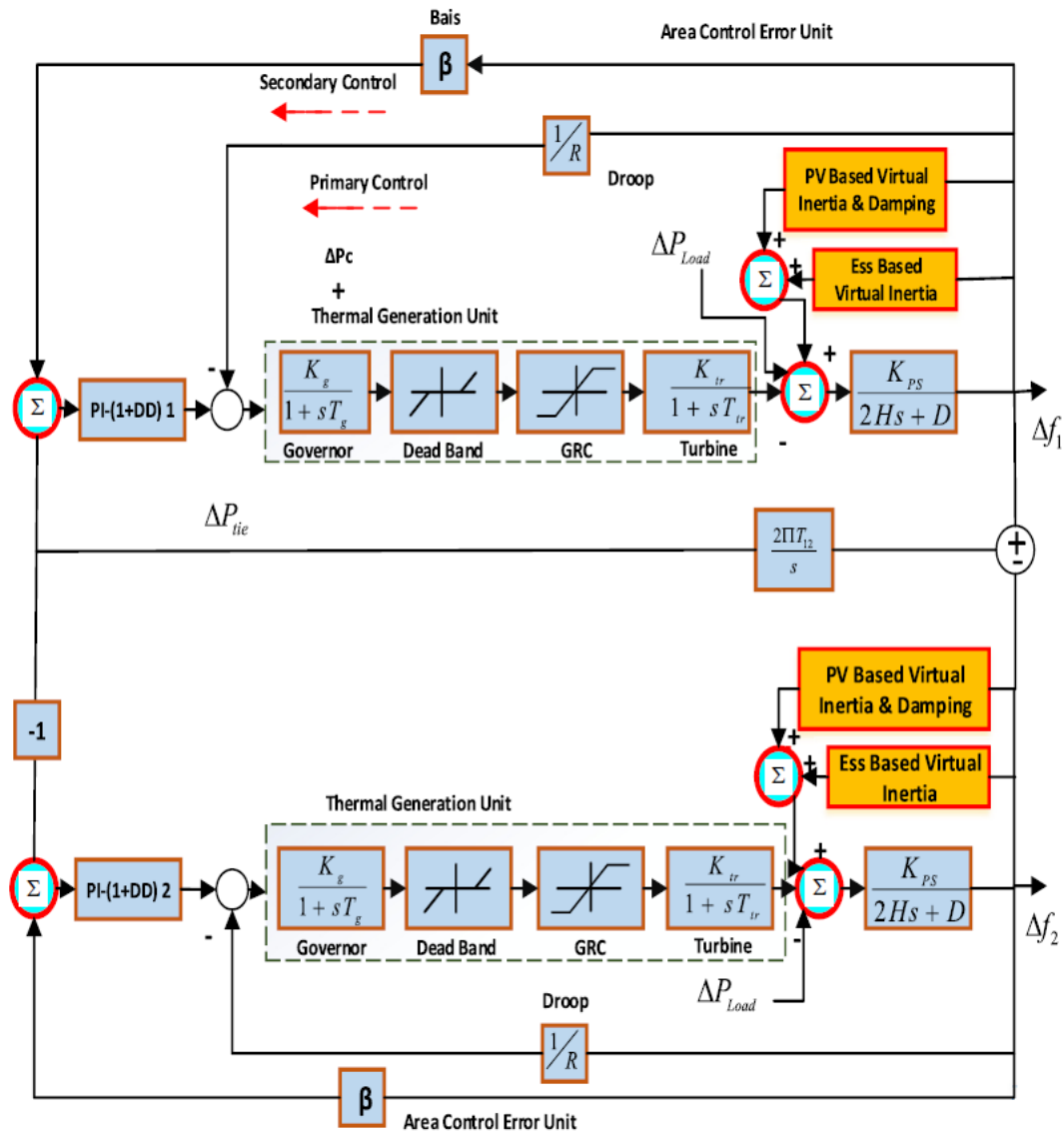


Figure 6 Multi Area Microgrid with PV-VIVD ESS-VI System.

Their optimization technique is employed to tune the gains' value of the PI-(1 + DD) controller parameters. The proposed model shows superior dynamic performance, achieving reductions in rise time by 18 percent, 5 percent, 4 percent, and 7 percent for different frequency changes compared to conventional systems.

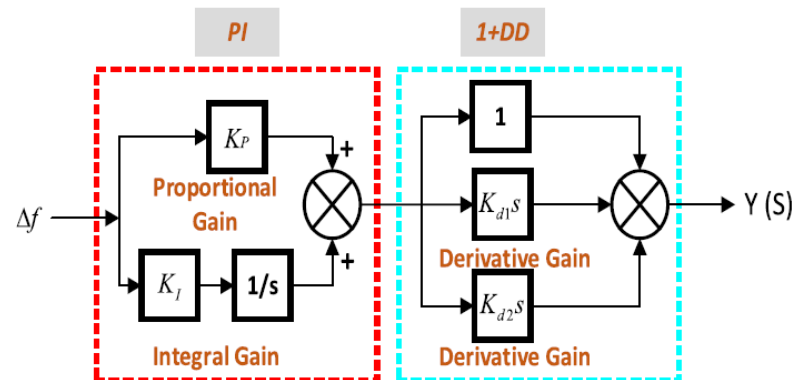


Figure 7 Structure of PI-(1 + DD) controller.

They also stated that the novel controller is designed to manage frequency variations effectively. The PI-(1 + DD) controller features a constant gain of 1 and adjustable parameters K_{d1} , K_{d2} , K_P , and K_I . The controller aims to improve system stability by reducing settling time and overshoot. To tune the gain values of controllers, the hybrid Lyrebird-Pattern Search (hLOA-PS) algorithm is applied which is inspired by the behavior of lyrebirds and aims to minimize the ITAE performance index. The result shows an 18 percent reduction in rise time value and a 33 percent reduction in settling time value compared to conventional systems. Moreover, there is a 90% reduction in overshoot for tie-line power changes using the proposed system.

Totally, the study emphasizes the importance of integrating renewable energy sources with effective control strategies for microgrid stability. The proposed PV-VIVD ESS-VI system enhances dynamic performance and resilience against parameter changes. Plus, future research could explore the integration of other renewable sources and advanced energy storage technologies.

Another research conducted in 2025, shows a Design of a novel cascade PI-(1+FOPID) controller to enhance load frequency control performance in diverse electric power systems [5]. They introduced a new cascade PI-(1+FOPID) controller to improve Load Frequency Control (LFC) performance in various electric power systems. This controller combines a conventional proportional-integral (PI) controller with a fractional-order PID (FOPID) controller using Wild Horse Optimizer (WHO) for fine-tune the controller's parameters based on the integral time absolute error

(ITAE) criterion. The performance of the suggested WHO-based controller is tested on four different power systems and compared to other approaches. The new proposed PI-(1+FOPID) cascade controller is a two-stage controller where the PI controller first manages the Area Control Error (ACE) signal, and its output then feeds into the (1+FOPID) controller.

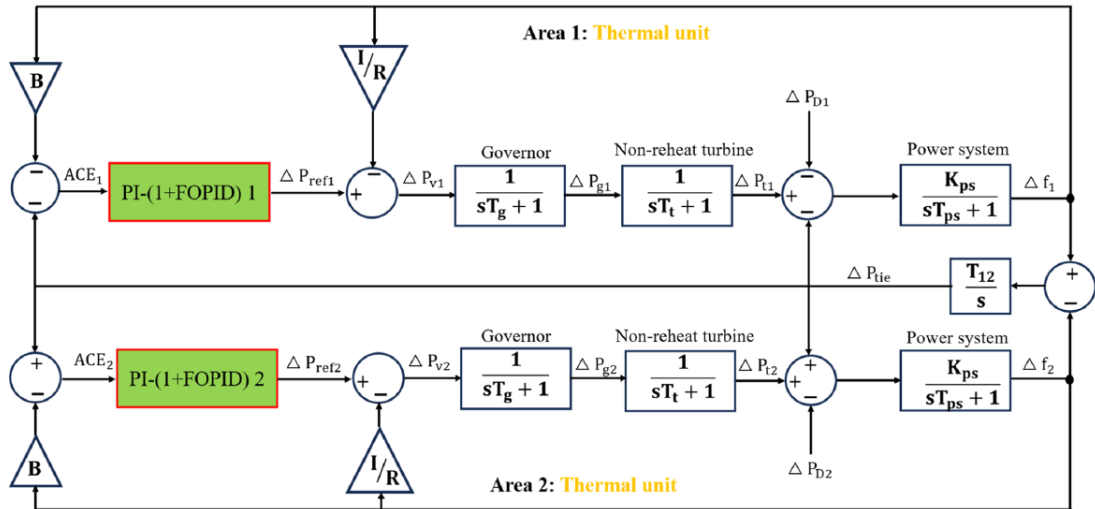


Figure 8 Transfer function of the power system.

The controller's performance is optimized using the Wild Horse Optimizer (WHO) algorithm. This population-based optimization method simulates the social behavior of wild horses, including grazing, mating, and group leadership. The objective function used for optimization is the integral of time-weighted absolute error (ITAE), which is a common metric in LFC studies for evaluating controller performance. The controller's effectiveness is tested on four different power systems: Two-area non-reheated thermal system, Two-area non-reheated thermal power system with governor dead band (GDB) nonlinearity, Two-area multi-source power systems and Three-area hydro-thermal power systems with generation rate constraints (GRC).

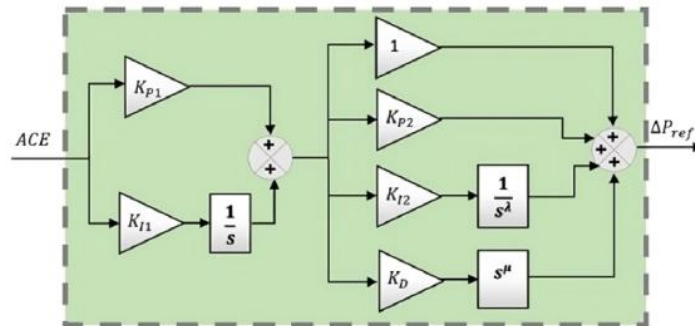


Figure 9 Structure of PI-(1+FOPID) cascade controller.

The results of the comparative analysis showed that the WHO-based PI-(1+FOPID) cascade controller can result in superior performance in reducing the integral of time-weighted absolute error (ITAE) value, settling time, overshoot, and undershoot of frequency deviations and tie-line power fluctuations. The controller achieved faster settling times. It also resulted in overshoot and undershoot values reduction. The proposed controller improved the overall ITAE value compared to the other controllers.

At the same time, another group of researchers presents a multi-stage controller designed to ensure frequency and voltage stability in a multi-area power network that includes both renewable and conventional energy sources [6]. The controller, referred to as the RSA-tuned optimal cascaded two-degree-of-freedom proportional integral control with a proportional derivative filter controller (RSA-(CC-2DOF (PI-PDF))), is applied for both Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) which are the main components of Automatic Generation Control (AGC) to make the model more realistic, the authors incorporate physical constraints like generation rate constraints (GRCs) and communication time delays (CTDs). The performance of this new controller is then compared to other state-of-the-art controllers to demonstrate its effectiveness. They proposed a new controller which combined cascaded two-degree-of-freedom proportional integral (2-DOF PI) with a proportional derivative filter (PDF). This controller is designed to handle both LFC and AVR issues simultaneously. The parameters for the controller are optimized using the Reptile Search Algorithm (RSA) technique, a metaheuristic

algorithm inspired by the hunting behavior of crocodiles. The primary objective function for this optimization is the suppression of the value of integral of time-weighted absolute error (ITAE), which is capable to reduce transient state and to minimize overshoots and undershoots of the system response. The model is tested on a two-area power system that includes conventional sources (hydro, thermal, gas, and diesel) and renewable sources (solar and wind). To enhance stability, an interline power flow controller (IPFC) is integrated into the tie-line between the two areas. The proposed controller demonstrates superior performance in stabilizing frequency and voltage. It achieves a faster settling time, frequency stabilization, and also demonstrates the minimum overshoot and undershoot value for both areas. Moreover, in tie-line deviation, a stable response is achieved while the value of ITAE of the system response getting lowest value too.

Another study in 2025 provides a technical view on Load frequency control resilience of hybrid power system with renewable energy sources and superconducting magnetic energy storage using FO-Fuzzy-PID controller [7]. The study investigates the application of an innovative adaptive fractional-order fuzzy proportional-integral-derivative (FO-Fuzzy-PID) controller to enhance Load Frequency Control (LFC) in power systems that integrate renewable energy sources (RES), such as wind and solar energy sources. To address the unpredictability of these energy sources, the controller is combined with a superconducting magnetic energy storage (SMES) system. The controller's parameters are optimized using the Particle Swarm Optimization (PSO) algorithm. The authors modeled hybrid two-area power systems that include diesel generators, wind power plants, and solar-thermal power plants, with SMES integrated into one of the areas. The proposed FO-Fuzzy-PID controller is designed to manage power frequency effectively. The Particle Swarm Optimization (PSO) algorithm is utilized to optimize the fuzzy parameters, such as membership function scaling factors and fuzzy inference weights, to enhance performance and stability.

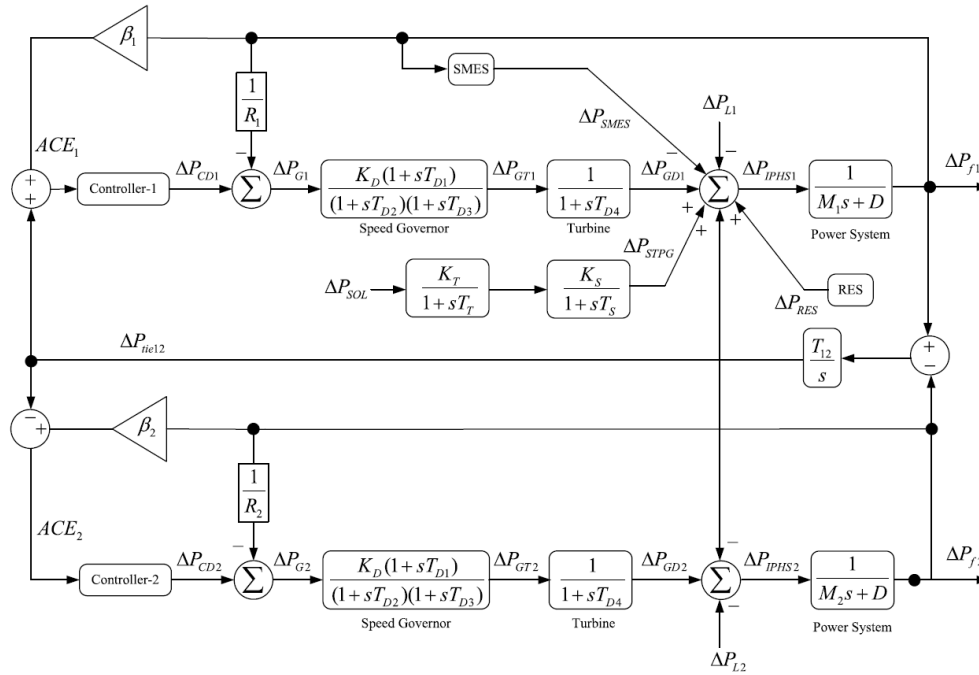


Figure 10 Block diagram of hybrid two-area power system.

Their simulation results demonstrate the proposed FO-Fuzzy-PID controller significantly improved system performance. When integrated with SMES, it achieved a high reduction in peak undershoot, effective improvement in settling time. The controller achieved the lowest integral of time-weighted absolute error (ITAE) value.

Back to 2015, another group of researchers also investigated on load frequency controller design via BAT algorithm for nonlinear interconnected power system [8]. This study proposes using a BAT algorithm to optimally tune the parameters of a PI controller for a Load Frequency Control (LFC) system. The objective is to enhance the performance of a two-area interconnected power system with nonlinearities. The study aims to prove the robustness of the BAT-based PI controller in stabilizing frequency and tie-line power under various load conditions and system nonlinearities. The study models a two-area interconnected power system, with Area 1 being a reheat thermal system and Area 2 being a hydro system. The model includes nonlinearities such as a governor dead band and Generation Rate Constraint (GRC). The objective is to minimize a performance index (J) defined as the integral of the sum of the squared frequency and tie-line power errors. The BAT algorithm is then used to find optimal PI controller parameters to minimize this

objective function. For comparison, the paper also uses the Simulated Annealing (SA) algorithm, which is another metaheuristic optimization method. The simulation results demonstrate that the BAT algorithm is superior to the SA algorithm in tuning the PI controller parameters. The BAT algorithm converges at a faster rate (45 generations) compared to SA (64 generations). The proposed BAT-based controller effectively damps frequency and tie-line power oscillations, achieving a smaller settling time and improving the overall system response. The performance indices (IAE, ITAE, ISE, and ITSE) for the BAT controller are significantly lower than those for the SA controller, confirming that it provides a better system response.

Later, in 2024, there is a study on a load frequency control strategy based on double deep Q-network and upper confidence bound algorithm of multi-area interconnected power systems [9]. Researchers introduced a new load frequency control (LFC) strategy that uses a Double Deep Q-Network (DDQN) combined with the Upper Confidence Bound (UCB) algorithm, called DDQN-UCB. The goal is to solve the problem of agent decision-making in a nonlinear environment and improve the control accuracy of LFC strategies that are based on reinforcement learning (RL). The research uses the IEEE multi-area LFC power system as a model for validation. The results showed that the proposed algorithm improved the pre-learning convergence accuracy by 57.5%. The LFC effectiveness test confirmed that the DDQN-UCB strategy enhances LFC accuracy. It also successfully stabilized the power exchange of the inter-area tie-line, thereby maintaining the stability of the whole power system.

Another recent study, conducted in 2025 is focused on Dynamic LADRC-Based CFOA-LSTM MPPT optimizer for enhancing Grid-Connected renewable energy sources [10]. This study introduces a new dynamic linear active disturbance rejection control (LADRC) strategy for hybrid photovoltaic/wind energy conversion systems (PV/WECS). The system is designed to enhance the performance of maximum power point tracking (MPPT). The control strategy integrates a wind turbine with a permanent magnet synchronous generator (PMSG) connected to the electrical grid. It also utilizes an efficient metaheuristic technique called the Catch

Fish Optimization Algorithm (CFOA) combined with Long Short-Term Memory (LSTM), referred to as CFOA-LSTM. The LADRC strategy is used to regulate the DC-Link voltage and control the active and reactive power by adjusting utility grid currents to ensure a unity power factor. The research proposes a dynamic LADRC-based CFOA-LSTM MPPT optimizer for a grid-connected PV/WEC system. The LADRC is designed to regulate the DC-Link voltage and control active and reactive power. The system's performance is tested under four operating conditions: First condition is Hard dynamic variations in radiation and wind speed. Second condition is the discontinuous time variations in PV irradiation and wind speed. The third condition is focusing on continuous time variations in PV irradiation and wind speed, and the last condition is using real-world weather data from the Pinglu Wind Farm in Shanxi province, China. The simulation estimations demonstrated that the proposed approach outperforms conventional control strategies in terms of tracking speed and robustness to both internal and external disturbances. In comparison with CFOA, PSO, CSA, and GHO, the proposed CFOA-LSTM-LADRC method successfully harvested the best GMP, outperforming all other methods. The proposed method was able to achieve the best GMP and duty cycle in just 0.05 seconds. The HIL experiments confirmed that the proposed technique provides better performance, lower ripple content, and enhanced power extraction compared to CSA and PSO. The study found that the proposed method achieved a power factor close to unity. The study's results are presented as an alternative to existing solutions for the Load Frequency Control (LFC) problem.

After surveying earlier research papers on the related field, all data is shown briefly in Table 1.

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Table 1 Summary of previous research and key contributions

Reference	System Components	Controller	Methodology
[1]	Hydro-generator	PID	Optimal Neuro-fuzzy model
[2]	Hydropower plants	PID, FLC, ANFIS	Neuro-fuzzy model
[3]	Interconnected power systems	Cascaded (1 + PI)-PI-PID	IABC-PSO
[4]	Multi-area microgrid	PI-(1+DD)	Virtual damping and energy storage inertia
[5]	Diverse electric power systems	Cascade PI-(1+FOPID)	Wild Horse Optimizer (WHO)
[6]	Multi-area power network	CC-2DOF (PI-PDF)	Reptile search algorithm (RSA)
[7]	Hybrid power system	FO-Fuzzy-PID	Particle swarm optimization (PSO)
[8]	Nonlinear interconnected power system	PI	BAT algorithm
[9]	Multi-area interconnected power systems	Deep Reinforcement Learning (DRL)	DDQN / UCB
[10]	Grid-connected renewable energy source	Dynamic LADRC	CFOA LSTM MPPT optimizer

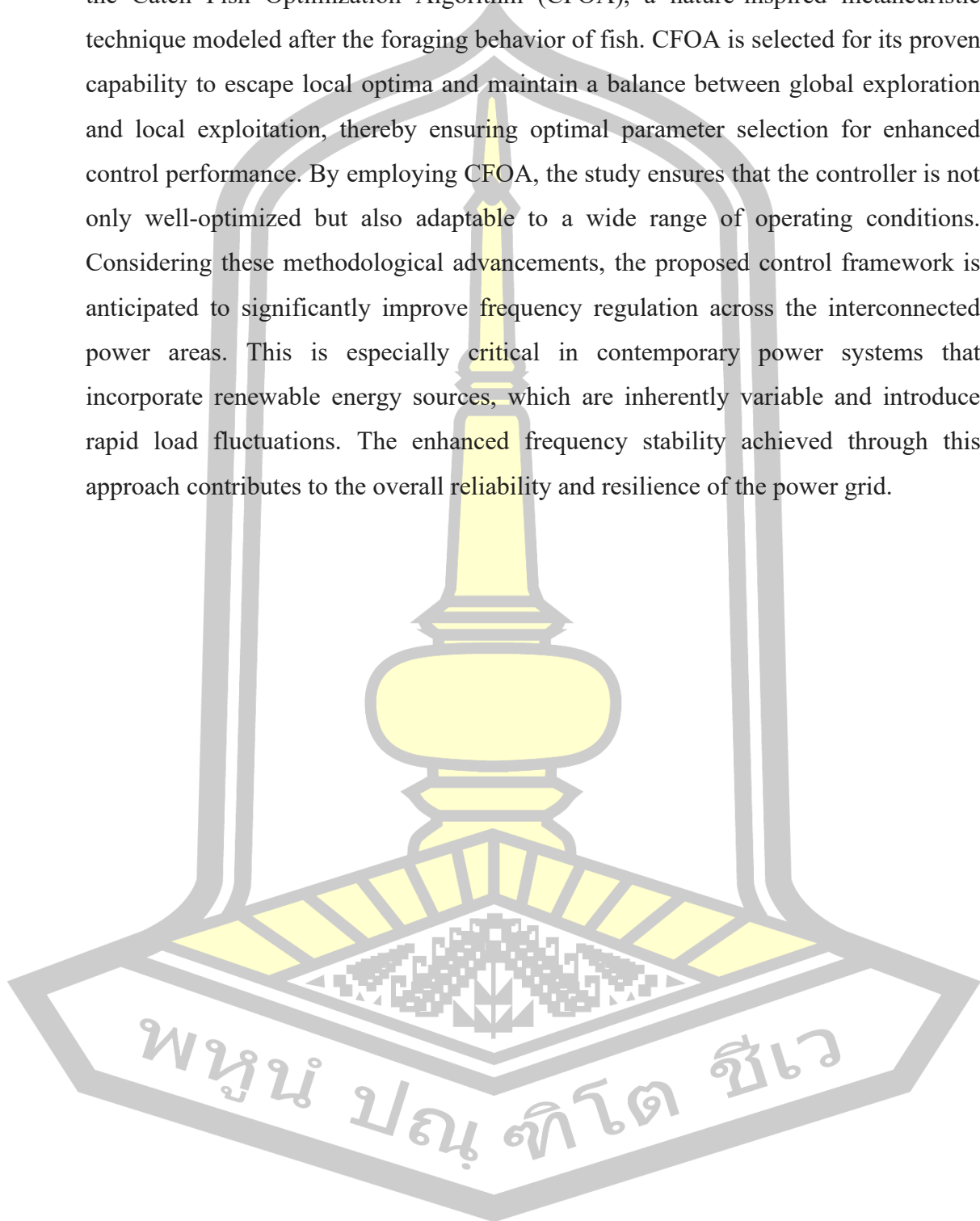
2.3 Conclusions

The studies above also note that increasing use of new energy sources interconnected to a wider capacity of generation can cause random disturbances and destabilize the load frequency of power systems. Meanwhile, metaheuristic techniques have shown high efficiency in determining the parameters gain values of any type of the controllers. It is noted that the traditional control methods like PI and PID algorithms have been widely used, but they have limitations in adapting to these disturbances and nonlinearities. The review also discusses the evolution toward more advanced, intelligent controllers and metaheuristic optimization algorithms. It notes that while these controllers have shown positive outcomes, there is still a need for more robust and advanced controllers. The review also offers more parameters for better performance. Furthermore, the papers focus on the attention given to the cascade configuration of controllers for PID, which provides rapid disturbance rejection and an extended set of tuning parameters for improved performance compared to single controllers.

After conducting literature reviews on the existing research, the researcher proposes a nonlinear two-area interconnected power system model to investigate the dynamic behavior of modern power networks under realistic operating conditions. The system is subjected to a step-load disturbance in one of the areas, effectively simulating abrupt changes in power demand that commonly occur in practical scenarios. This disturbance serves as a benchmark to evaluate the robustness and adaptability of the proposed control strategy. To address the challenges posed by such disturbances, the researcher introduces a novel hybrid control scheme that integrates the functionalities of a 1+PI controller with a conventional PID controller. The review indicates a gap in research focused on two-area nonlinear systems, which this paper aims to address.

This hybrid configuration is designed to leverage the complementary strengths of both control mechanisms—where the 1+PI component enhances steady-state performance and the PID component improves transient response. The systematic integration of these controllers aims to overcome the limitations typically associated with nonlinear and complex system behaviors, particularly under

fluctuating load conditions. The tuning of all controller parameters is performed using the Catch Fish Optimization Algorithm (CFOA), a nature-inspired metaheuristic technique modeled after the foraging behavior of fish. CFOA is selected for its proven capability to escape local optima and maintain a balance between global exploration and local exploitation, thereby ensuring optimal parameter selection for enhanced control performance. By employing CFOA, the study ensures that the controller is not only well-optimized but also adaptable to a wide range of operating conditions. Considering these methodological advancements, the proposed control framework is anticipated to significantly improve frequency regulation across the interconnected power areas. This is especially critical in contemporary power systems that incorporate renewable energy sources, which are inherently variable and introduce rapid load fluctuations. The enhanced frequency stability achieved through this approach contributes to the overall reliability and resilience of the power grid.



CHAPTER 3

PROPOSED METHODOLOGY

3.1 Introduction

As mentioned earlier in the previous chapters, power control is not supplementary, but it is foundational and crucial in power systems. It ensures electricity is generated and delivered securely, efficiently and reliably. Control functions include voltage and frequency regulation, generator synchronization, load balancing, and real-time response to demand fluctuations are inseparable. These are vital for grid reliability whilst mismatching between supply and demand can lead to frequency deviations or voltage fluctuations, damaging equipment and risking blackouts. In fact, in large, interconnected networks, disturbances can propagate rapidly, making precision and reliability essential.

This research undertakes a comprehensive comparative analysis of conventional control strategies and a novel hybrid control approach within the context of a nonlinear two-area interconnected power system. The study evaluates the dynamic performance and robustness of four distinct controller configurations including the conventional Proportional-Integral (PI) controller, the enhanced 1+PI controller, the well-known Proportional-Integral-Derivative (PID) controller, and a newly proposed hybrid controller that significantly integrates the features of both the 1+PI and PID methodologies.

The primary objective is to assess how these controllers respond under realistic operating conditions, particularly when subjected to nonlinear constraints that are inherent in modern power systems. Two critical nonlinearities are emphasized in the analysis: the governor dead band (GDB) and the generation rate constraint (GRC). These constraints are not merely theoretical artifacts but represent fundamental physical and operational limitations that significantly influence system behavior and control effectiveness. The governor dead band reflects the insensitivity region of the governor mechanism, where minor deviations in frequency do not trigger corrective

action, potentially leading to delayed system response. Meanwhile, the generation rate constraint imposes limits on the rate at which power output can change, ensuring mechanical and thermal safety of generation units. Both constraints introduce nonlinear dynamics that challenge traditional linear control methods and necessitate more adaptive and resilient control strategies. By incorporating these nonlinear elements into the simulation model, the study aims to provide a realistic evaluation of each controller's ability to maintain system stability, minimize frequency deviations, and ensure effective load-frequency control (LFC). The findings contribute to the ongoing development of advanced control techniques that can better accommodate the complexities of modern power grids, particularly in the presence of renewable energy integration and fluctuating load demands.

3.2 Nonlinear Two-Area Power Systems

In large-scale electrical power systems, the entire network is typically segmented into multiple control areas or regions, each responsible for maintaining its own frequency stability. This decentralized structure is essential for ensuring the overall reliability, robustness, and operational integrity of the interconnected grid. Within each control region, precise regulation of frequency and power exchange is critical, especially under dynamic load conditions and disturbances.

A widely adopted framework for analyzing such systems is the two-area Load Frequency Control (LFC) model, which serves as a foundational benchmark in LFC research. This model, as depicted in the referenced schematic diagram, effectively captures the structural and functional relationships between two interconnected control areas. It highlights the dynamic interactions that occur due to power transfer across the tie-line, a transmission link that facilitates energy exchange between regions. These interactions are influenced by fluctuations in load demand and generation, making the tie-line a key element in system stability studies.

Each control area within the model comprises several critical components, including a controller, governor, turbine, and a detailed representation of the power system itself. These elements work in concert to respond to rapid changes in system conditions, particularly those arising from oscillations in load and frequency. The

controller adjusts the system response based on deviations from nominal values, while the governor and turbine regulate mechanical input to the generator. Together, these components form a closed-loop control mechanism that aims to restore system equilibrium following disturbances.

The figure below illustrates a comprehensive visualization of this complex configuration, providing the interdependence and control pathways that govern system behavior. By studying this model, researchers can evaluate the performance of various control strategies under realistic operating conditions, contributing to the development of more resilient and adaptive power system controls.

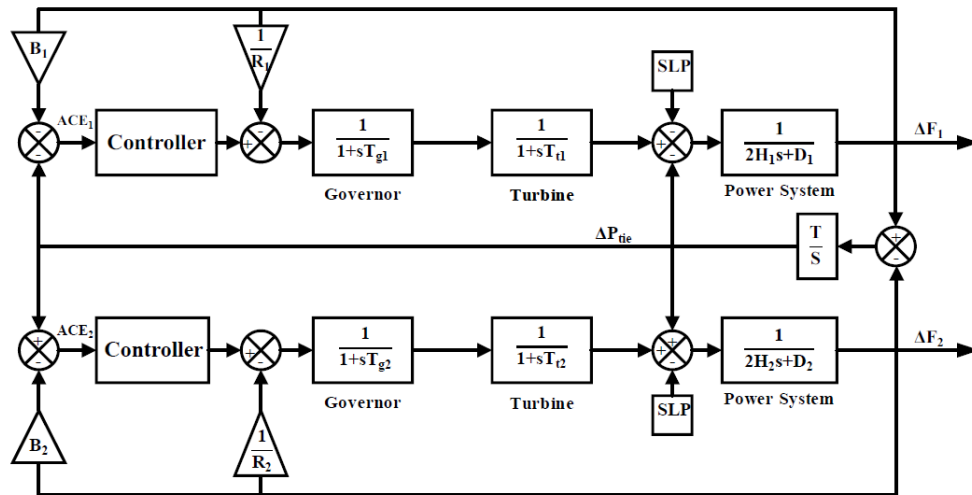


Figure 11 Nonlinear Two-Area Power Systems under investigation.

The nominal parameters adopted for the two-area power system are defined as follow:

$$\begin{aligned}
 F &= 60 \text{ Hz}; & R_1 &= 0.05 \text{ MW/Hz}; & R_2 &= 0.0625 \text{ MW/Hz}; \\
 B_1 &= 20.6 \text{ Hz/MW}; & B_2 &= 16.9 \text{ Hz/MW}; & \text{SLP} &= 0.2 \text{ pu}; \\
 T_{g1} &= 0.2 \text{ s}; & T_{g2} &= 0.3 \text{ s}; & T_{t1} &= 0.5 \text{ s}; & T_{t2} &= 0.6 \text{ s}; \\
 H_1 &= 5; & H_2 &= 4; & D_1 &= 0.6; & D_2 &= 0.9; & T &= 2 \text{ s}.
 \end{aligned}$$

The essence of the load frequency control mechanism is found in the calculation of the Area Control Error (ACE), which indicates the overall deviation within each control area. This error metric accounts for both the local frequency deviation and the net power transfer across the tie-line connecting to the neighboring area.

The computed ACE is then fed into the controller to generate appropriate control signals, which are subsequently transmitted to the power generation units to restore the system frequency to its nominal value. The formulation of ACE differs slightly for each area to reflect the direction of power flow. For instance, in Area 1, a change in ACE occurs when the local frequency decreases or when power flows out to Area 2. The ACE for Area 1 can be calculated using Equation (1):

$$ACE1 = B_1\Delta f_1 + \Delta P_{tie} \quad (1)$$

In contrast, Area 2—being the receiving side of the power transfer—has its own value of ACE calculated with an opposite convention, as shown in Equation (2):

$$ACE2 = B_2\Delta f_2 - \Delta P_{tie} \quad (2)$$

These equations facilitate the design of control mechanisms that effectively respond to both internal disturbances within each area and external influences arising from interconnected area power exchanges. The detailed system parameters used in the model are already provided above.

3.3 Hybrid 1+PI and PID Controller

In this study, a hybrid controller structure is designed by integrating the set of 1+PI controllers with the conventional PID controllers to enhance the performance of frequency regulation estimation in multi-area power systems exhibiting nonlinear characteristics. Figure 12 shows the proposed hybrid cascading controller's configuration.

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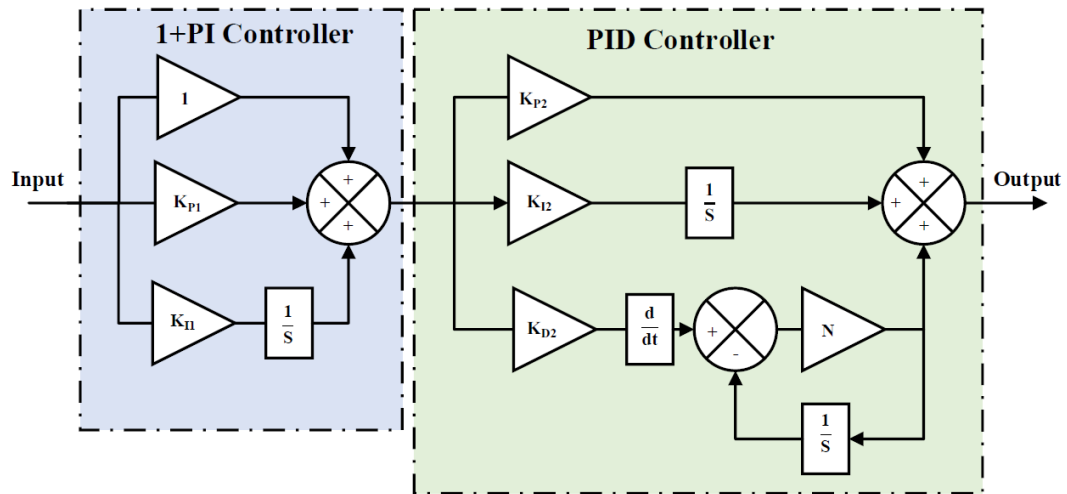


Figure 12 Hybrid 1+PI and PID Controller configuration under study.

The structure of the proposed hybrid controller, as shown in Figure 2, comprises of two integrated main components. This integrated structure enables the controller to tackle system errors thoroughly by providing both swift corrective measures and efficient long-term error prevention strategies. The control signal produced in the initial stage is then routed to the second component, the PID controller which follows a traditional structure comprising proportional, integral, and derivative elements. To reduce the effects of high-frequency noise, especially during swift load changes, the derivative term is subjected to a low-pass filter characterized by a specific coefficient N . The proposed hybrid controller integrates the advantages of both control strategies, resulting in improved performance in managing system dynamics during both transient state and steady-state conditions. The dual-layer configuration enhances the overall quality of the system control and is expected to achieve more effective error suppression compared to using only a single controller.

3.4 Catch Fish Optimization Algorithm (CFOA) Technique

Catch fish optimization algorithm (CFOA) is a human-based meta-heuristic algorithm proposed by Jia et al. in 2024 to mimic the catching behavior of fishermen. With the advantages of few parameters and a simple structure, CFOA has been proved to be superior to DE, GA, PSO, GWO, WOA, and other classical meta-heuristic

algorithms, and has strong optimization ability in test functions and clustering problems. Since the algorithm has just been proposed, no other researcher has yet conducted an in-depth study on CFOA. Thus, it is firstly proposed that the CFOA enhance the performance of the controller.

This study applies the Catch Fish Optimization Algorithm to determine the best parameters for a hybrid controller that integrates the frameworks of 1+PI and PID controllers, with the goal of effectively managing Load Frequency Control (LFCX in a nonlinear two-area power system as mentioned earlier in the system transfer function.

Catch fish optimization algorithm is a metaheuristic algorithm inspired by the catching behavior of fishermen in ponds. Fishermen will rely on their own knowledge and intuition when catching fish, and they are also able to cooperate with other fishermen in catching fish with their tools. Moreover, fishermen will work together to salvage the fish after surrounding them. CFOA represents a metaheuristic optimization technique that draws inspiration from the conventional fish-catching methods utilized in rural communities. The core idea that represents "stirring the water to catch fish" encapsulates the equilibrium between exploratory inquiry and cooperative problem-solving in unpredictable contexts.

Initialization process: The populations in the CFOA initialization process are randomly generated as in many metaheuristic algorithms. Assuming that there are N fishermen in the D -dimensional search space, the population matrix of fishermen can be represented by mathematical equation (3)

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,j} & \cdots & x_{1,D} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,j} & \cdots & x_{2,D} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i,1} & x_{i,2} & \cdots & x_{i,j} & \cdots & x_{i,D} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{N,1} & x_{N,2} & \cdots & x_{N,j} & \cdots & x_{N,D} \end{bmatrix} \quad (3)$$

As previously noted, every fisher is a potential solution for the problem, and by utilizing its proposed values for the decision variables, the problem's objective function can

be assessed. Equation (4) symbolizes the calculated value of the objective function derived from the fishers.

$$F(X) = [fit_1, fit_2, \dots, fit_N] = [function(X_1), function(X_2), \dots, function(X_N)] \quad (4)$$

In the equation, fit_i and $function(X_i)$ represent the objective function value assessed for the i th fisher. Each X_i represents a fisher position, which is initialized in the following representation:

$$X_{i,j} = lb_j + rand \times (ub_j - lb_j), i = 1, 2, \dots, N \quad (5)$$

where $X_{i,j}$ is the position of the i th fisher in the j th dimension. ub_j and lb_j denote the upper and lower boundaries of the j th dimension in the problem space. Metaheuristic algorithms usually contain two phases: exploration and exploitation. In CFOA, the switch from exploration to exploitation is controlled using parameter S . When $S < 0.5$, CFOA performs the exploration behavior; vice versa, CFOA performs the exploitation behavior.

The calculation of parameter S can be obtained from Equation (6).

$$S = \frac{t}{T} \quad (6)$$

where t and T denote the current iteration number and the maximum iteration number.

Independent Search and Group Capture: CFOA has two search methods in the exploration phase: independent search and group capture. The fisherman will choose one search method for catching fish in each iteration and switch between the two methods by the catch rate parameter α . The parameter α can be obtained from Equation

$$\alpha = \left(1 - \frac{3}{2}S\right)^{\frac{3}{2}S} \quad (7)$$

When the catch rate α is higher (i.e., $\alpha > p$), fishermen choose to catch fish by independent search. Fishermen will disturb the water while fishing, forcing fish to poke out of the water to breathe. The fishermen will recognize the location of the fish by observing the ripples produced by the fishes' breathing. At the same time, the fisherman would correct his position based on the catch of others. The strategy is updated as shown below.

$$X_{i,j}(t+1) = X_{i,j}(t) + (X_{r,j}(t) - X_{i,j}(t)) \times \text{Exp} + \text{rand} \times s_j \times R \quad (8)$$

This dual-phase mechanism allows CFOA to alternate efficiently between exploration (Equations 9–12) and exploitation (Equations 13–14), thereby improving the algorithm's ability to converge towards a global optimum solution.

$$\text{Exp} = \frac{\text{fit}_i - \text{fit}_p}{\text{fit}_{\max} - \text{fit}_{\min}} \quad (9)$$

$$R = \text{Dis} \times \sqrt{|\text{Exp}|} \times \left(1 - \frac{\text{EF}_s}{\text{MaxEF}_s}\right) \quad (10)$$

$$\text{Fisher}_{i,j}^{T+1} = \text{Fisher}_{i,j}^T + (\text{Fisher}_{\text{pos},j}^T - \text{Fisher}_{i,j}^T) \times \text{Exp} \times r_s \times s \times R \quad (11)$$

$$\text{Fisher}_{c,i,j}^{T+1} = \text{Fisher}_{c,i,j}^T + r_2 \times (\text{Center}_c - \text{Fisher}_{c,i,j}^T) + \left(1 - \frac{2 \times \text{EF}_s}{\text{MaxEF}_s}\right)^2 \times r_3 \quad (12)$$

$$\sigma = \sqrt{\left(2 \left(1 - \frac{\text{EF}_s}{\text{MaxEF}_s}\right)\right) / \left(\left(1 - \frac{\text{EF}_s}{\text{MaxEF}_s}\right)^2 + 1\right)} \quad (13)$$

$$\text{Fisher}_i^{T+1} = \text{Gbest} + \text{GD}\left(0, \frac{r_4 \times \sigma \times |\text{mean}(\text{Fisher}) - \text{Gbest}|}{3}\right) \quad (14)$$

The operational structure of CFOA is summarized in the flowchart shown in Figure below.

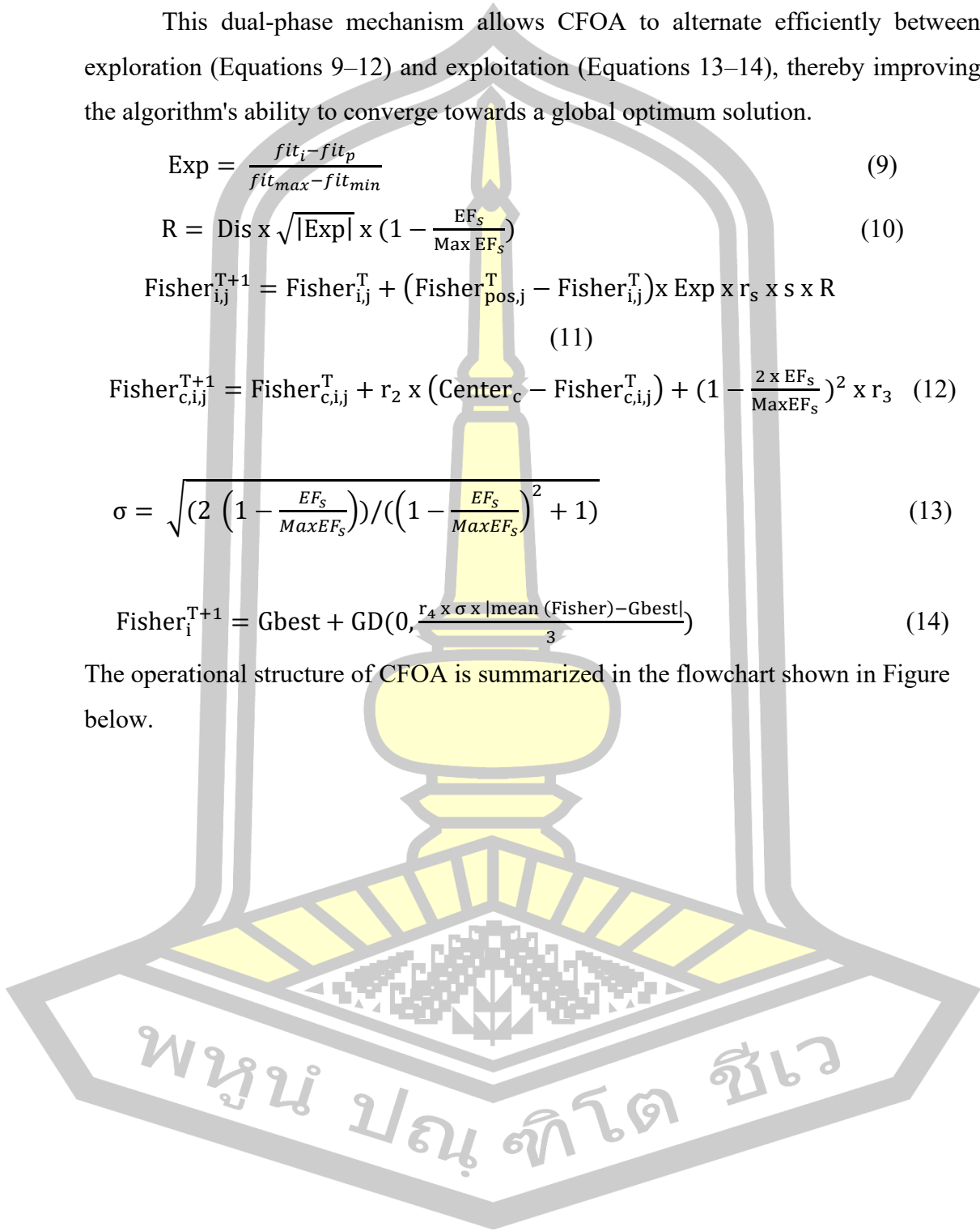
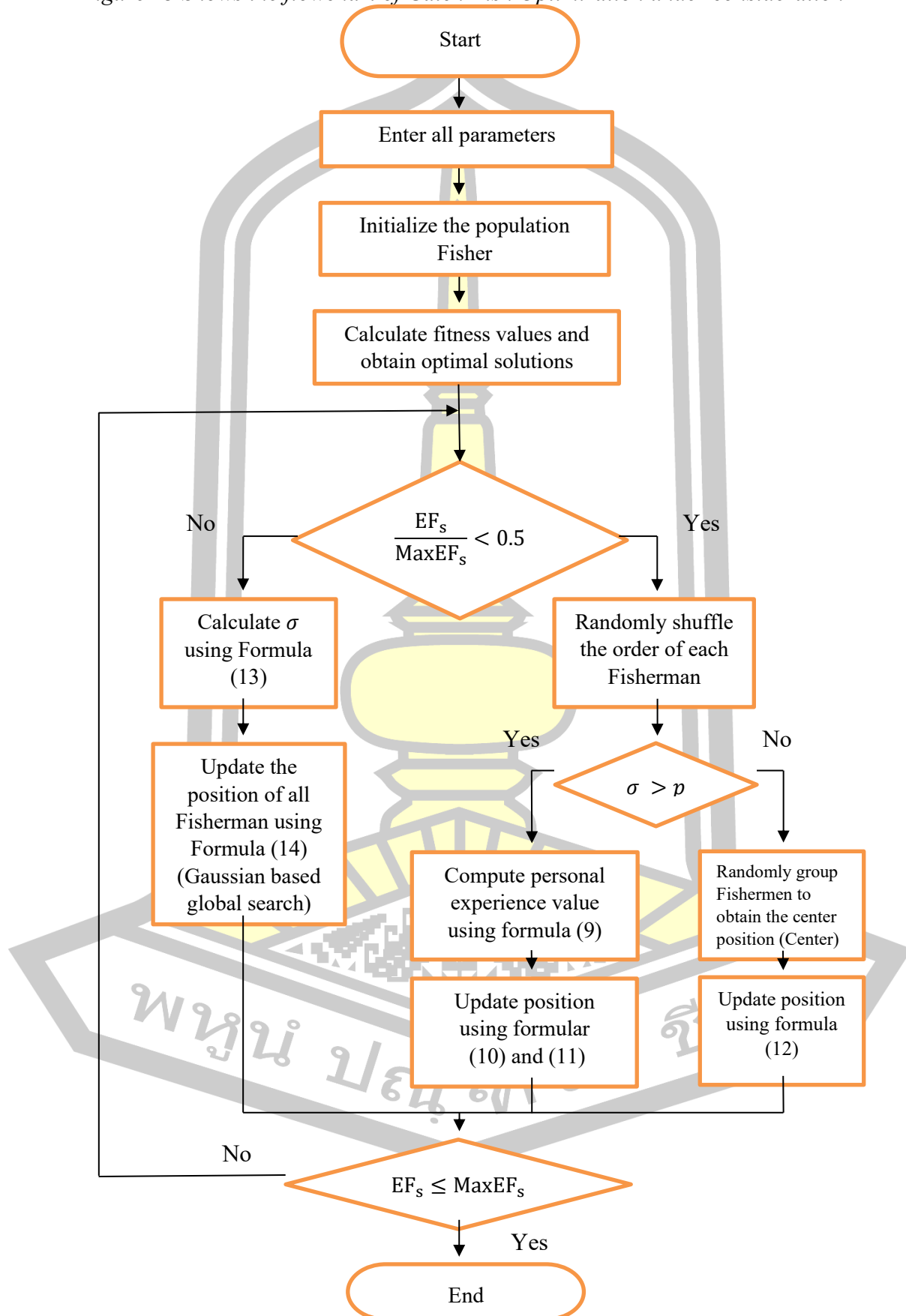


Figure 13 Shows the flowchart of Catch Fish Optimization under consideration



3.5 An application of Catch Fish Optimization for tuning gain values in Hybrid 1+PI and PID Controller in Load Frequency Regulation

In this study, the Catch Fish Optimization Algorithm (CFOA) is utilized as a metaheuristic technique to fine-tune the parameters of a hybrid control strategy that combines the 1+PI and PID controllers. This hybrid configuration is applied to a nonlinear two-area interconnected power system for the purpose of enhancing load frequency control (LFC) performance. The CFOA is selected due to its adaptive search capabilities and its effectiveness in navigating complex, multidimensional optimization landscapes. The parameter search space for the controller gains is systematically bounded within the interval value $[0, 2]$. This range is carefully chosen to encompass the values that significantly influence the dynamic response of the system while avoiding excessive gain magnitudes that could lead to undesirable oscillatory behavior or system instability. By constraining the search space, the algorithm maintains a balance between exploration and control system feasibility.

Throughout the optimization process, which is capped at a maximum of 100 fitness evaluations ($\text{MaxEFs} = 100$), the CFOA iteratively evaluates candidate solutions based on a well-defined performance criterion. The objective function employed is the Integral of Time-weighted Absolute Error (ITAE), as formulated in Equation (9). This metric integrates the time-multiplied absolute deviations of key variables system, the frequency deviations in both control areas ($\Delta f_1(t)$, $\Delta f_2(t)$) and the tie-line power flow deviation ($\Delta P_{\text{tie}}(t)$) over the simulation period:

$$\text{ITAE} = \int_0^{30} (t \cdot (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{\text{tie}}(t)|)) dt \quad (9)$$

During the early stages of the optimization (when the ratio $\text{EFs}/\text{MaxEFs} < 0.5$), the algorithm prioritizes global exploration. It employs a Gaussian distribution mechanism to disperse agents around the best global solution (G_{best}), thereby reducing the risk of premature convergence to local optima. As the number of evaluations approaches the maximum threshold, the CFOA transitions into a collective encirclement phase. In this phase, the algorithm leverages swarm intelligence and accumulated agent experience to refine solution accuracy and converge toward the optimal parameter set.

3.6 Conclusions

In summary, this study presents a comprehensive evaluation of the dynamic performance of a nonlinear two-area interconnected power system subjected to a step-load disturbance of 0.2 per unit (pu.) applied to Area 1. The system configuration, as illustrated in Figure 1, serves as the foundation for assessing the effectiveness of four distinct control strategies: (1) a standard Proportional-Integral (PI) controller, (2) a 1+PI controller enhanced with a feedforward term, (3) a conventional Proportional-Integral-Derivative (PID) controller, and (4) a hybrid controller that systematically integrates the functionalities of both the 1+PI and PID controllers. To ensure a fair and consistent basis for comparison, all controllers were tuned using the Catch Fish Optimization Algorithm (CFOA), a nature-inspired metaheuristic technique known for its ability to escape local minima and balance global exploration with local exploitation. The parameter search space was constrained within the range of 0 to 2, and the optimization process was limited to a maximum of 100 evaluation iterations. The optimized parameter for each controller is subsequently used in simulation scenarios to analyze system responses under identical disturbance conditions. Meanwhile, numerical simulations are conducted using the MATLAB/Simulink platform, chosen for its high fidelity, repeatability, and suitability for real-time control applications. A custom-developed MATLAB script (.m file) implementing the CFOA was seamlessly integrated with the Simulink-based power system model. The simulation framework included detailed representations of generation units, control systems, transmission line delays, and nonlinear constraints such as Generation Rate Constraint (GRC) and Governor Dead Band (GDB), all embedded within a cohesive modeling environment. The step-load disturbance applied to Area 1 served as a benchmark to evaluate transient response, frequency stability, and control effectiveness. Simulation results were analyzed to assess the impact of CFOA-based tuning on key performance metrics, including overshoot, settling time, and frequency oscillations across both areas. The findings demonstrate the robustness and adaptability of the proposed hybrid control strategy, highlighting its potential for enhancing stability and reliability in modern power systems.

CHAPTER 4

SIMULATION AND RESULTS

In this study, the dynamic performance of a nonlinear two-area power system is evaluated under a step load disturbance of 0.2 per unit (pu) applied to Area 1, based on the system configuration illustrated in Figure 3.1 in the previous chapter. This study aims to evaluate the system response under four distinct control strategies:

- A standard PI controller,
- A 1+PI controller with an added feedforward term,
- A conventional PID controller, and
- A hybrid controller that systematically integrates the functionalities of both the 1+PI and PID controllers.

To ensure an equitable and consistent basis under the comparison, all controllers are tuned using the Catch Fish Optimization Algorithm (CFOA). As a metaheuristic technique, CFOA offers notable advantages in escaping local minimum and effectively balancing global exploration with local exploitation. Parameter tuning is performed within a predefined range of 0 to 2, using a maximum of 100 evaluation iterations. The resulting optimized parameters for each controller are summarized in Table 2. These values are then used in subsequent simulations to assess and compare the system responses across the four control strategies. This study used the MATLAB/Simulink platform for conducting numerical simulations. A custom-developed .m script implementing the CFOA was integrated with the power system model and controller architecture, and with 0.2 (pu) step-load disturbance was applied to Area 1. Simulink was selected as the main simulation tool because of its exceptional fidelity, consistent repeatability, and appropriateness for real-time control applications. The simulation model presents a detailed framework, including components for generators, control systems, transmission line delays, and nonlinear constraints like GRC and GDB, all seamlessly integrated within a cohesive simulation environment.

After conducting the simulation with MATLAB/Simulink platform as a numerical method, all data are listed in Table 2.

Table 2 The optimum values of each controller's parameters.

Area	Controller	Parameters				
		K_{P1}	K_{I1}	K_{P2}	K_{I2}	K_{D2}
Area 1	PI	0.5539	0.7518	-	-	-
	1+PI	0.0513	0.7387	-	-	-
	PID	-	-	0.6931	1.9999	0.8630
	1+PI and PID	1.9999	1.9999	1.6068	1.9999	0.6017
Area 2	PI	0.0852	0.4023	-	-	-
	1+PI	0.0005	0.0052	-	-	-
	PID	-	-	1.9317	1.1121	1.7343
	1+PI and PID	1.9974	1.9969	1.0383	1.5405	1.9907

The simulation results shown in Figures 14 to Figure 16 clearly indicate that the CFOA-optimized Hybrid 1+PI and PID controllers provide superior performance compared to traditional controllers across various metrics. This provides exceptional performance in mitigating delays, minimizing overshoot and undershoot, and decreasing settling times in both domains. Furthermore, the proposed controller exhibits enhanced regulation of tie-line power deviations, thereby improving inter-area power connection.

The frequency response in Area 1, as shown in Figure 14, significantly indicates that the CFOA-optimized Hybrid 1+PI and PID Controller achieves the lowest undershoot when compared to all other controllers evaluated. The system demonstrates a more rapid and stable convergence to steady-state conditions when compared to the standard PI, 1+PI, and conventional PID controllers. The frequency response transitions seamlessly back to nominal value, exhibiting minimal long-term fluctuation or steady-state error. The distinctive dynamic characteristics highlight the

effectiveness of CFOA techniques in pinpointing globally optimal control parameters. The resulting controller demonstrates an impressive adaptability to load variations while maintaining system stability throughout both the transient and steady-state phases of the response.

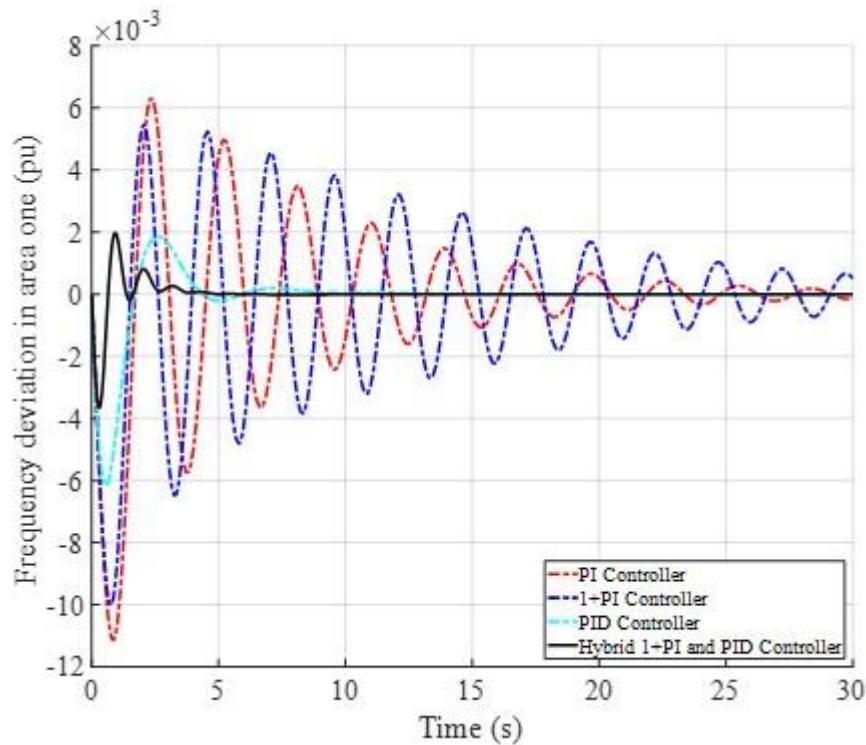


Figure 14 Frequency deviation in Area 1.

According to the simulation results as shown in Figure 14, which clearly illustrate the frequency deviation response in Area 2 due to a load disturbance applied to Area 1, it can be observed that the Hybrid 1+PI and PID Controller maintains stable control performance, despite Area 2 not being directly affected by the disturbance.

In the initial transient phase, the hybrid controller shows a significant benefit in reducing overshoot and oscillations relative to the other controllers. The response curve demonstrates impressive smoothness and efficient damping, unlike the significant oscillatory behavior observed in PI and PID controllers, which frequently exhibit notable underdamping.

Moreover, the hybrid controller reaches the steady-state condition faster than its alternatives and maintains a remarkably low steady-state error. The frequency deviation in Area 2 gradually approaches zero value in a consistent and reliable way.

A key component in the context of multi-area LFC systems, the results highlight the controller's capacity to efficiently coordinate control activities across interconnected regions.

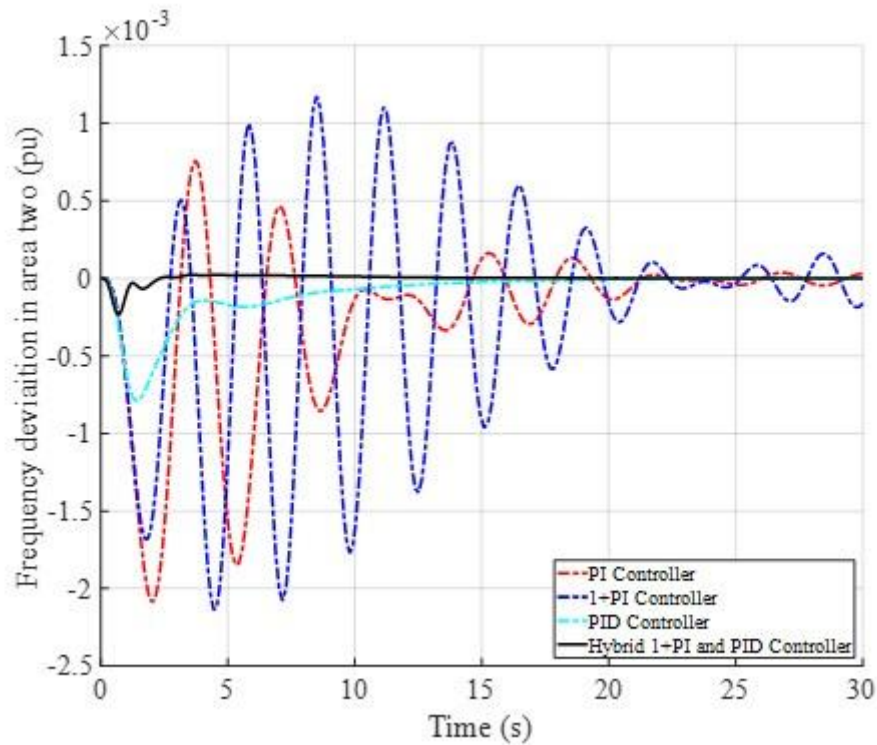


Figure 15 Frequency deviation in Area 2.

As illustrated in Figure 16, the tie-line power variance between Areas 1 and 2 highlights the superior performance of the Hybrid 1+PI and PID Controller. This controller consistently demonstrates robust and reliable behavior under dynamic conditions, particularly during load disturbances. Its effectiveness is evident in its ability to maintain tie-line power stability, which is a critical indicator of successful frequency regulation in interconnected power systems.

This result is consistent with prior research findings in the domain of frequency control, reinforcing the controller's credibility and dependability. Notably, during the initial phase of the disturbance, when system fluctuations are typically most pronounced, the hybrid controller exhibits a remarkable ability to suppress abrupt

changes in tie-line power flow. This early-stage responsiveness is crucial for minimizing the propagation of instability across the network.

When benchmarked against traditional control strategies such as standalone PI, 1+PI, and PID controllers, the Hybrid 1+PI and PID Controller consistently maintains minimal variance throughout the entire simulation period. This indicates a high degree of precision and adaptability in managing power exchange between areas.

Moreover, the controller's dynamic response is characterized by minimal overshoot and undershoot, ensuring that the system does not experience excessive deviations from the desired operating point. Its smooth and timely reaction to disturbances underscores its capability to regulate power distribution efficiently and accurately. This level of performance is essential for maintaining system reliability, especially in modern grids where fluctuations can arise from renewable energy integration and variable load demands.

In summary, the Hybrid 1+PI and PID Controller not only meets but exceeds the expectations for tie-line power regulation, offering a promising solution for enhancing the stability and resilience of interconnected power systems.

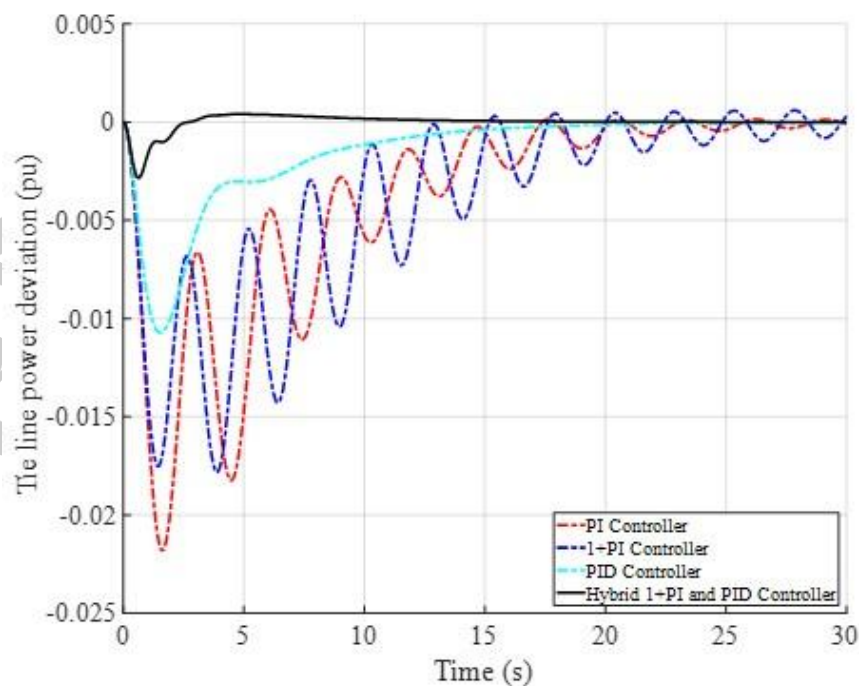


Figure 16 Tie Line power deviation measured in pu.

The Hybrid 1+PI and PID Controller exhibits the fastest convergence to a steady-state condition among all tested configurations, while simultaneously minimizing oscillatory behavior throughout the system's dynamic response. This rapid stabilization is a critical attribute in the context of interconnected power systems, where swift and smooth recovery from disturbances directly influences the reliability of power exchange between regions.

In multi-area load frequency control (LFC) environments, transmission lines function as vital conduits that link distinct control zones. These tie-lines not only facilitate energy transfer but also serve as indicators of system balance and coordination. Any deviation in tie-line power flow can signal instability or imbalance in generation and demand across areas, potentially compromising system integrity.

The hybrid controller's ability to dampen oscillations and achieve equilibrium quickly ensures that tie-line power remains stable and well-regulated, even under fluctuating load conditions. This contributes significantly to the overall robustness and efficiency of multi-area LFC schemes. By maintaining consistent power flow across interconnected regions, the controller supports seamless coordination between control areas, reduces the risk of cascading failures, and enhances the resilience of the grid.

Thus, the hybrid controller's superior dynamic performance provides a rapid convergence and reduced oscillations with a highly effective solution for maintaining balanced tie-line power flow, which is fundamental to the dependable operation of modern multi-area power systems.

Table 3 Variable values obtained by various types of controllers.

Controller	Δf_1			Δf_2			ΔP_{tie}		
	OS	US	ST	OS	US	ST	OS	US	ST
PI	0.0063	-0.0111	15.393	0.0007	-0.0020	5.9446	0.0001	-0.0217	19.477
1+PI	0.0054	-0.0100	24.803	0.0011	-0.0021	12.762	0.0006	-0.0178	24.296
PID	0.0018	-0.0061	3.4336	0.0001	-0.0007	0.0001	0.0001	-0.0107	10.635
1+PI and PID	0.0019	-0.0036	1.1314	0.00022	-0.0002	0.0001	0.0004	-0.0028	1.6428

Remark: OS = Overshoot (pu.), US = Undershoot (pu.), ST = Settling Time (s),

ITAE = Integral-Time weight Absolute Error

Table 4 The integral of time-weighted absolute errors obtained by various types of controllers.

Controller	ITAE
PI	1.0920
1+PI	1.5983
PID	0.2465
1+PI and PID	0.0336

The system response behaviors observed from the simulations clearly demonstrate the effectiveness of the CFOA in tuning the controller parameters. The CFOA-optimized Hybrid 1+PI and PID Controller exhibits superior stability across both transient and steady-state dynamics.

Its rapid, smooth response and the ability to significantly suppress tie-line power deviations are strongly aligned with the lowest achieved value of the numerical performance index, ITAE value, which was recorded at 0.0336 as illustrated in Table 3. This indicates that the system can effectively minimize time-weight accumulated errors under a specific dynamic condition.

In contrast, the other controllers such as PI, 1+PI, and conventional PID, while capable of reducing deviations to some extent, exhibit pronounced oscillatory behavior and significantly higher overshoot and tie-line deviation. These characteristics could compromise long-term system stability, particularly in interconnected multi-area networks.

These findings clearly validate that the combination of a hybrid control structure with an efficient tuning mechanism such as CFOA not only enhances the performance of multi-Area LFC but also provides a balanced, reliable, and dynamically superior solution when compared to conventional controllers across all any major performance metrics.

CHAPTER 5

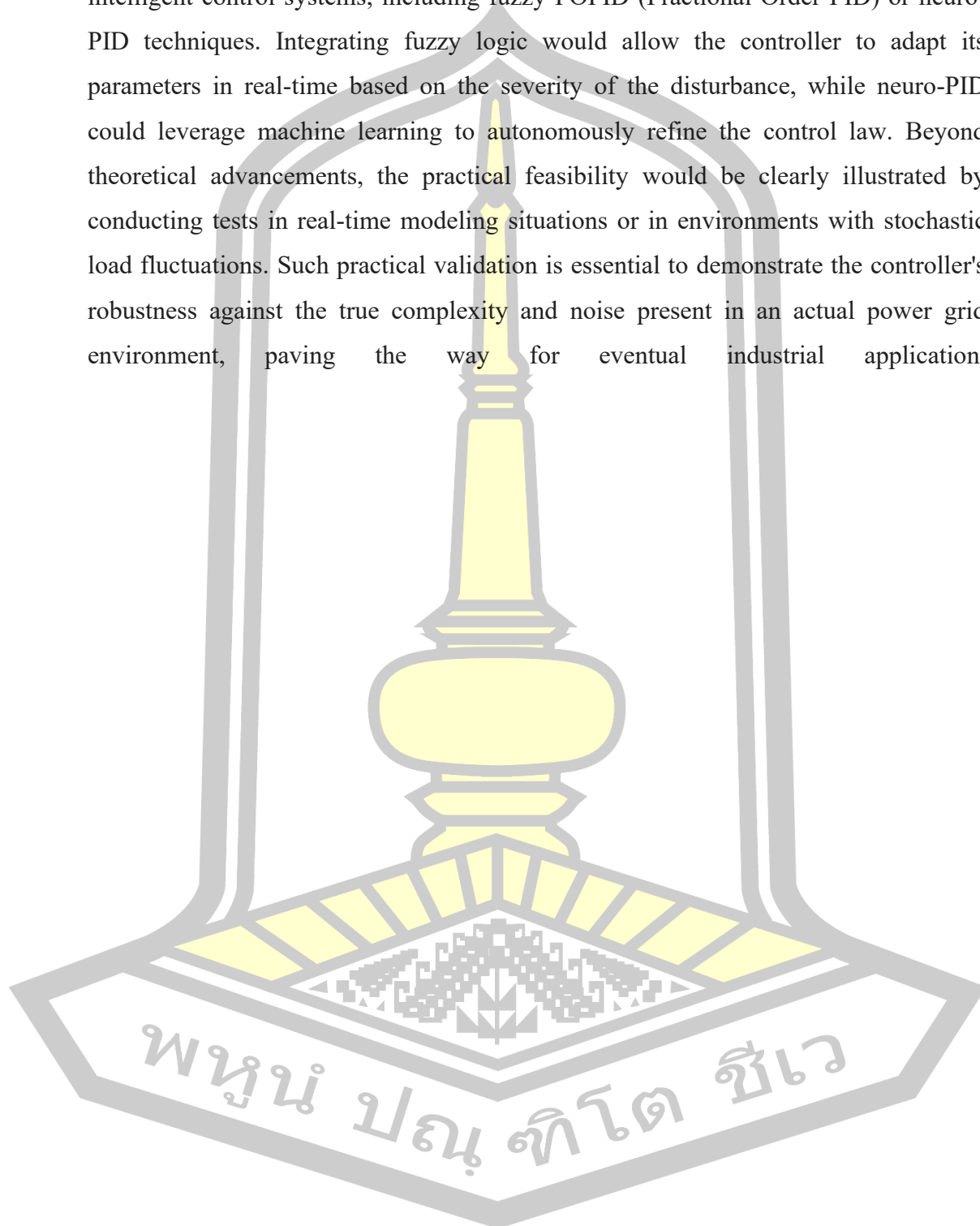
CONCLUSION

This paper proposes a solution for load frequency management in nonlinear two-area power systems by designing a hybrid control scheme that combines the advantages of both 1+PI and PID controllers. The core innovation lies in this hybrid structure: the 1+ PI component offers superior tracking and steady-state error reduction, which is crucial for handling sustained load imbalances, while the PID component provides robust transient response and damping of oscillations following sudden disturbances. In short, this synergy results in a control action that is both quick and precise.

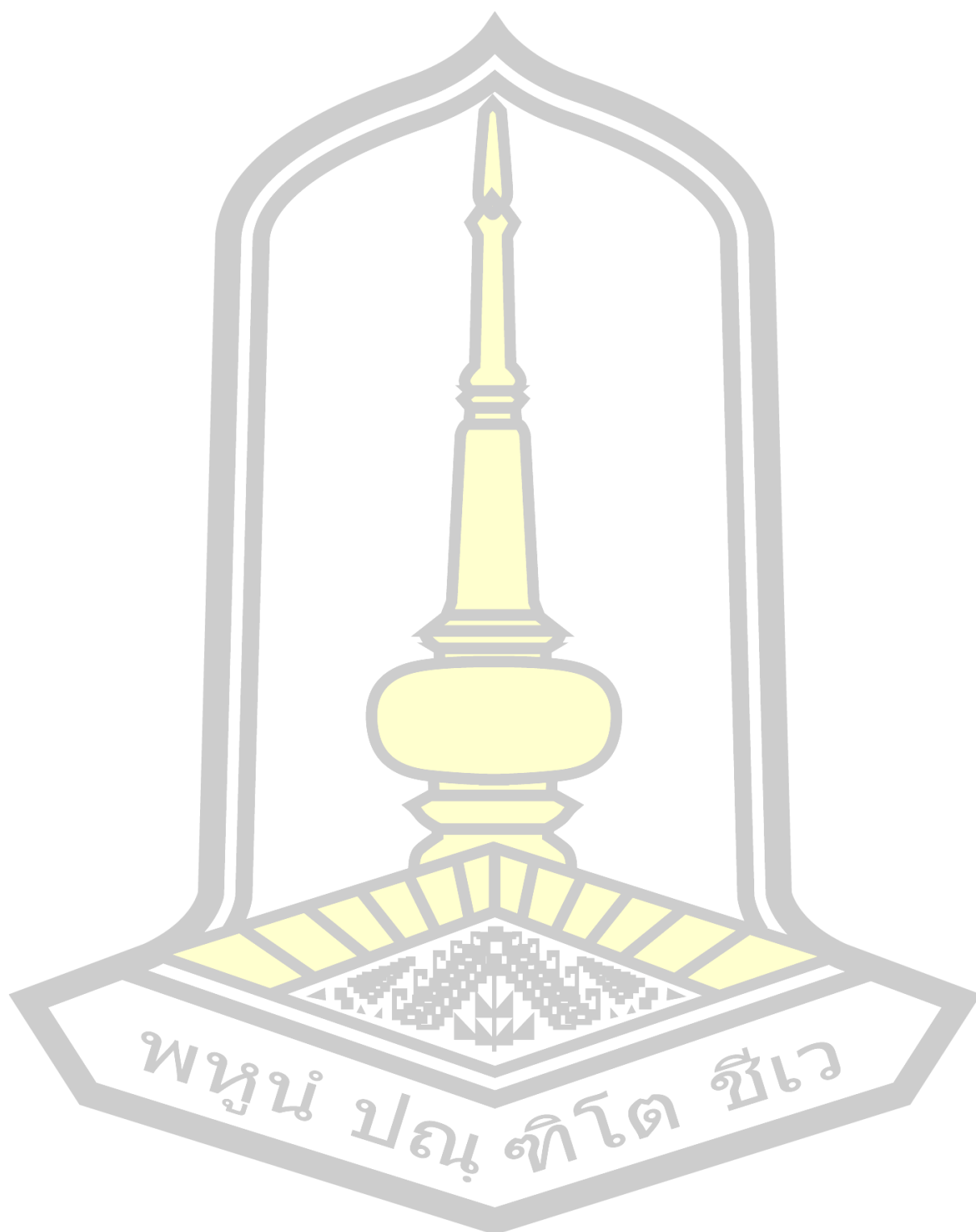
The Catch Fish Optimization Algorithm (CFOA), a metaheuristic approach modeled by traditional fishing methods seen in nature, was used to optimize the controller parameters. This method provides a strong framework for parameter optimization in the control systems, successfully mitigating local minimum while maintaining a balance between exploration; searching a wide range of potential solutions and exploitation which is refining the best-found solutions. CFOA's unique mechanism, which simulates the behavioral pattern of catch fish; specifically, their coordinated hunting strategy, ensures a thorough and unbiased search of the multi-dimensional parameter space, guarantees that the global optimal or near-optimal controller settings are identified for the nonlinear system.

After applying the numerical method by using MATLAB simulation, as discussed in detail in the previous chapter, the study's conclusions show the advantages of the CFOA-based hybrid design works to enhance frequency regulation in the inter-linked power areas, particularly in systems that incorporate renewable energy sources and quickly fluctuate load. The inherent variability of renewables like solar and wind power introduces significant complexity; the proposed controller effectively manages these rapid variations by providing fast and stable frequency restoration. This flexible design provides a scalable solution that meets the requirements of modern power networks by supporting various operational scenarios, including isolated and interconnected modes.

Future progress may be achieved by incorporating CFOA with sophisticated intelligent control systems, including fuzzy-FOPID (Fractional Order PID) or neuro-PID techniques. Integrating fuzzy logic would allow the controller to adapt its parameters in real-time based on the severity of the disturbance, while neuro-PID could leverage machine learning to autonomously refine the control law. Beyond theoretical advancements, the practical feasibility would be clearly illustrated by conducting tests in real-time modeling situations or in environments with stochastic load fluctuations. Such practical validation is essential to demonstrate the controller's robustness against the true complexity and noise present in an actual power grid environment, paving the way for eventual industrial application.



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BIOGRAPHY

NAME Mr. Vichheka Pum

DATE OF BIRTH 23-Nov-1993

PLACE OF BIRTH Phnom Penh, Cambodia

ADDRESS Khmounh sub-district, Sen Sok district, Phom Penh, Cambodia

POSITION Student

EDUCATION 2012 High School Diploma, Preah Sisowath High School, Phnom Penh, Cambodia
2017 Bachelor's Degree in Electrical Engineering, Faculty of Engineering, Mahasarakham University, Thailand
2025 Doctor of Philosophy (Ph.D.) in Electrical and Computer Engineering, Faculty of Engineering, Mahasarakham University, Thailand

