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Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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Abstract

This study presents a detailed investigation aimed at enhancing load frequency control (LFC) within a three-area non-reheat power system through the integration of energy storage devices. The primary objective is to evaluate the impact of minimizing power flow across tie lines between areas versus allowing it to fluctuate freely based on demand. This comparison seeks to determine the effects on LFC parameters under both scenarios. Additionally, the research examines the potential benefits of incorporating or excluding power tie lines in the objective function to achieve superior LFC performance. To conduct this analysis, two controller designs were employed: a Proportional-Integral-Derivative Filter (PIDF) optimized using the Mountain Gazelle Optimizer (MGO) and a hybrid controller that merges fuzzy logic with MGO (Fuzzy PI-PIDF). The performance of the LFC system was assessed using the Integral Time-Absolute Error (ITAE) as the objective function, which considers area control error, including frequency deviations and power tie-line interactions. The ITAE was also utilized to evaluate frequency deviations independently, excluding power tie lines from the objective function. Simulation results demonstrate the effectiveness of the proposed controllers in improving LFC system performance. Notably, the PIDF controller, tuned by MGO and based on ITAE that focuses solely on frequency deviation, significantly outperformed the other controllers, achieving substantial reductions in overshoot, undershoot, and settling time.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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Keywords: load frequency control, Mountain Gazelle Optimizer, Integral Time-Absolute Error, power tie line.

استراتيجيات تدفق القدرة عبر خطوط الربط لتعزيز التحكم في تردد الحمل في شبكات القوى الكهربائية متعددة المناطق

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الملخص:

تقدم هذه الدراسة تحليلاً متعمقاً لتعزيز أداء نظام التحكم في تردد الأحمال (Load Frequency Control – LFC) في شبكة قوى كهربائية ثلاثية المناطق غير مجهزة بإعادة تسخين (Non–reheat)، وذلك من خلال دمج أجهزة تخزين الطاقة. يهدف البحث إلى تقييم تأثير تقليل تدفق القدرة عبر خطوط الربط (Tie lines) مقارنة بالسماح لها بالتقلب الحر وفقاً للطلب، فضلاً عن استقصاء جدوى تضمين أو استبعاد خطوط الربط في دالة الهدف للوصول إلى أداء أمثل.

لتحقيق أهداف الدراسة، تم اعتماد تصميمين أساسيين للتحكم؛ الأول هو متحكم تناظري–تكامل–تفاضلي ذو مرشح (PIDF) مُحسّن باستخدام خوارزمية غزال الجبل (Mountain Gazelle Optimizer – MGO)، والثاني هو متحكم هجين يدمج المنطق الضبابي مع خوارزمية (Fuzzy PI–PIDF) MGO. تم تقييم أداء النظام استناداً إلى مؤشر التكامل الزمني للخطأ المطلق (ITAE) كدالة هدف، سواء باحتساب خطأ التحكم الكلي في المنطقة (متضمنًا انحرافات التردد وتفاعلات خطوط الربط) أو بالتركيز حصراً على انحرافات التردد بمعزل عن خطوط الربط.

أظهرت نتائج المحاكاة فعالية عالية للمتحكمات المقترحة في الارتقاء بأداء النظام. وتجدر الإشارة إلى أن متحكم (PIDF) المُعدل بواسطة خوارزمية (MGO) والمبني على مؤشر (ITAE) الموجه لانحرافات التردد حصراً قد تفوق بشكل ملحوظ على بقية المتحكمات،

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

محققاً تحسينات جذرية تمثلت في تقليل قيم التجاوز (Overshoot)، والهبوط (Undershoot)، ووقت الاستقرار (Settling time).

الكلمات الدالة: التحكم في تردد الأحمال، خوارزمية غزال الجبل، التكامل الزمني للخطأ المطلق، خطوط الربط الكهربائي، تخزين الطاقة.

1. Introduction

Load frequency control (LFC) is a crucial function in power systems that ensures the balance between generation and demand of active power, and maintains the system frequency within acceptable limits. LFC is especially important for interconnected power systems, where the frequency deviation can affect the stability and reliability of the whole network. LFC also regulates the power exchange between different control areas and minimizes the effects of disturbances and load variations. LFC can be achieved by using various control strategies, such as proportional-integral-derivative (PID) controllers, fuzzy logic controllers, neural network controllers, and adaptive controllers.

However, LFC faces new challenges due to the integration of renewable energy sources, such as wind and solar power, which introduce uncertainties and nonlinearities into the power system dynamics. Moreover, LFC is affected by the presence of time delays in the communication and data transmission between sensors, controllers, and actuators. Therefore, LFC requires modern and intelligent solutions that can cope with these issues and ensure the optimal performance of the power system. Some recent studies have proposed novel methods for LFC, such as equivalent input disturbance-based LFC, sampling LFC, and LFC for multi-area power systems with renewable energy penetration. These methods aim to improve the robustness, stability, and efficiency of LFC under various scenarios and conditions. LFC is still an active and important research topic that has significant implications for the future of power systems [1-3].

2. Literature Review

Load Frequency Control (LFC) in multi-area and hybrid interconnected power systems has been extensively researched to

http://www.doi.org/10.62341/istj-vol39-2-aa37

address supply dynamics, high variations in Renewable Energy Sources (RES), and system non-linearities. Early and classical approaches heavily relied on conventional Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers to maintain power balance and control tie-line power flows [4, 5]. However, the inherently dynamic and unpredictable nature of RES-based generation often leads to power quality issues and frequency fluctuations [6].

To overcome these challenges, recent research has evolved toward advanced controller tuning and optimization methodologies. These include metaheuristic optimization algorithms—such as Harmony Search, Bacterial Foraging, Particle Swarm, and Genetic Algorithms [7- 10] as well as advanced control frameworks like Model Predictive Control (MPC), Fuzzy Logic Systems, Artificial Neural Networks (ANN), Fractional-Order PID (FOPID), and intelligent filtering techniques [11–16, 17–21]. Table 1 gives a summary of some previous studies in the area.

2.1 Summary of Previous Studies

Table 1: Summary of previous studies in the area

Reference	Title	Summary of Work	Conclusion
[9, 10]	Model Predictive Control (MPC) in Industrial and Power Processes	Explored the application of predictive control algorithms to handle multi-variable constraints and forecast future plant responses in dynamic systems.	Demonstrated superior capability in managing constraints and minimizing transient deviations during severe load shifts.
[11, 12]	Advanced Control & Optimization Strategies for Complex Grid Operations	Evaluated industrial MPC frameworks and constraint-tuning methods for large-scale energy scheduling and grid stabilization.	Highlighted that predictive architectures significantly enhance system robustness compared to static linear controllers.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

Reference	Title	Summary of Work	Conclusion
[13, 14]	High-Performance Model Predictive Control & Fuzzy Logic Implementations	Investigated advanced process control and fuzzy-PI hybrid structures applied to multi-area power networks.	Showed effective suppression of frequency oscillations and improved adaptability under varying operating points.
[15, 16]	Hybrid Metaheuristics and Fuzzy-PI Enhancements for LFC	Proposed intelligent tuning of PID/PI controllers using hybrid algorithms (such as Genetic Algorithms combined with Particle Swarm Weighting) and fuzzy logic.	Achieved substantial reductions in settling time and overshoot across multi-area interconnected systems.
[17, 18]	Fractional-Order Controllers and ANN Integration in Multi-Area Grids	Introduced Fractional-Order PID (FOPID) and Artificial Neural Network (ANN)-based adaptive tuning for renewable-integrated power plants.	Confirmed that FOPID and ANN structures provide superior degrees of freedom and robust performance against renewable generation intermittency.
[19, 20]	Nature-Inspired Algorithms (Firefly & Metaheuristics) for LFC Optimization	Applied modern metaheuristic optimization algorithms (like the Firefly algorithm and swarm techniques) to calibrate controller gains.	Validated that bio-inspired algorithms reliably escape local minima and yield optimal PID parameters for multi-area stability.
[21, 22]	Forecasting and Estimation Techniques (Kalman Filtering & SMES Integration)	Implemented Kalman filtering algorithms for wind power prediction and smoothing prior to LFC integration, alongside energy storage.	Proved that predictive filtering of renewable inputs drastically reduces unexpected disturbance impacts on system frequency.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems
http://www.doi.org/10.62341/istj-vol39-2-aa37

3. System Description and Modeling

3.1 System Description

In this work, a three-area non-reheat thermal system is adopted. Each area is equipped with a single generator, turbine, and governor, as well as loads and energy storage systems. When the load increases or a malfunction develops in the system that causes the frequency to decelerate or accelerate, the controller must modify the system settings to restore stability. Each of the three areas of the system illustrated in Figure 1 contains one turbine, one governor, and one generator.

Areas one, two, and three each have a rating of 2000 MW [22-25]. To boost the system's performance, energy storage devices are also added. The power rating for each area is 2000 MW, and the system inertia for each area is 5.

As indicated in table 2, the tie-line maximum power sharing across areas is 200 MW, and the frequency base factor B is 0.425 for each location, also the synchronization coefficients between areas are T_{12}, T_{23}, and T_{31}. For each area, the LFC Participation Factor is equal to 1. K_{ps} is the power system's gain. Each load and generation block, as shown in Figure 1, represents a first-order equation. There are also first-order equations characterizing the governors and turbines.

Table 2: Three-area system parameters

Parameter	Area 1	Area 2	Area 3
Speed regulation (R)	2.4	2.4	2.4
Tie max (MW)	200	200	200
Inertia constant (H)	5	5	5
Base power	2000 MW	2000 MW	2000 MW
Governor time constant (T_g)	8×10^{-2}	8×10^{-2}	8×10^{-2}
Turbine time constant (T_t)	0.3	0.3	0.3
K_{ps}	120	120	120
B	0.425	0.425	0.425
T_{ps}	20	20	20
a	1	1	1
$T_{12} = T_{23} = T_{31}$	0.08674	0.08674	0.08674

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

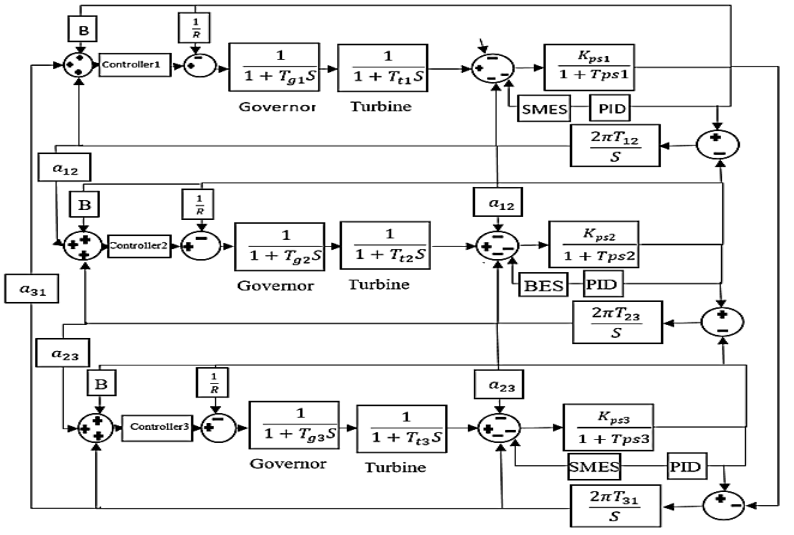


Figure 1: Single-line diagram for a three-area non-reheat system that incorporates storage energy

3.2 Modeling of Energy Storage Systems

- Superconducting magnetic energy storage SMES Model:

Superconducting magnetic energy storage (SMES) is a type of energy storage that stores energy by using the magnetic field produced by a superconducting coil. When an electric current flows through the coil, high-temperature superconductors generate a tremendous magnetic field. The stored energy can then be released by reversing the current flow, allowing for a large amount of energy to be discharged quickly. Power grid stabilization, peak shaving, and load leveling are all common uses for SMES systems [26, 27]. Power (P) and magnetic energy (E) calculations are as follows:

$$E = 0.5LI^2 \tag{1}$$

$$P = \frac{\partial E}{\partial t} = LI\frac{\partial I}{\partial t} = VI \tag{2}$$

where E represents the stored energy (J), L is the inductance (H), V is the voltage (V), and I denotes the direct current (A).

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems
http://www.doi.org/10.62341/istj-vol39-2-aa37

In this study, the SMES system is used as a first-order transfer function:

$$G_{\text{SMES}} = \frac{K_{\text{SMES}}}{1+T_{\text{SMES}}s} \quad (3)$$

gain K_{SMES}=0.98 , time constant TSMES= 0.03s

- Battery Energy Storage (BES) Model:
Battery energy storage is a device that converts chemically produced energy from renewable sources such as solar and wind into electrical energy, which is then stored in batteries for later use. As the globe progresses toward a more sustainable energy future, this technology is becoming increasingly crucial. In this study, which will employ quick response types of BES devices, a first-order equation will be employed to represent the BES [26, 27]:

$$G_{\text{BES}} = \frac{K_{\text{BES}}}{1+T_{\text{BES}}s} \quad (4)$$

where gain $K_{\text{BES}} = 1.8$, and time constant $T_{\text{BES}} = 0$.

3.3 Problem Formulation & Control Strategies

The purpose of this article is to increase system stability, reduce overshoot, undershoot, and settling time by determining appropriate controller parameters. Two objective functions (ITAE) are proposed:

- ITAE with Power Tie-Lines Included (Area Control Error):
Minimizes the area control error (ACE) in each area, which is a function of the frequency deviation Δf and the power tie-line ΔP_{tie}:

$$\text{ITAE} = \int_0^t t\,|ACE_1 + ACE_2 + ACE_3|dt \quad (5)$$

Where:

$$ACE_1 = \Delta f_1 + \Delta P_{\text{tie12}} + \Delta P_{\text{tie31}} \quad (6)$$

$$ACE_2 = \Delta f_2 + \Delta P_{\text{tie23}} + \Delta P_{\text{tie12}} \quad (7)$$

$$ACE_3 = \Delta f_3 + \Delta P_{\text{tie23}} + \Delta P_{\text{tie31}} \quad (8)$$

http://www.doi.org/10.62341/istj-vol39-2-aa37

- ITAE with Frequency Deviation Only (Excluding Power Tie-Lines):

The second objective function is formed in equation (9) based on the ITAE criterion which considers only the summation of frequency deviations (Δf) in each area and does not consider the tie-line power interactions. This formulation permits the optimization algorithm to consider pure frequency regulation and system stability separately from the tie-line exchange constraints and to give them precedence.

$$\text{ITAE} = \int_0^t t\,|\Delta f_1 + \Delta f_2 + \Delta f_3|dt \quad (9)$$

3.4 Controller Design:

The control strategy proposed includes a hybrid controller combining a PIDF (PID controller with a derivative filter) and a Fuzzy-PI controller. The parameters are optimized using the Mountain Gazelle Optimizer (MGO) [29].

Four distinct controller configurations are evaluated:

1. Fuzzy PI-PIDF based on MGO with power tie-line included in the objective function.
2. PIDF based on MGO with power tie-line included in the objective function.
3. Fuzzy PI-PIDF based on MGO without power tie-line in the objective function.
4. PIDF based on MGO without power tie-line in the objective function.

3.5. Hybrid Controller

The control strategy proposed in this article is a hybrid controller that combines a PIDF is a PID controller with a derivative filter, additionally, PI controller based on fuzzy logic controller. The PID parameters are tuned using the (MGO). Additionally, other PID controllers are integrated into storage energy systems to enhance system performance. Figure 2 below illustrates FPI-PID.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

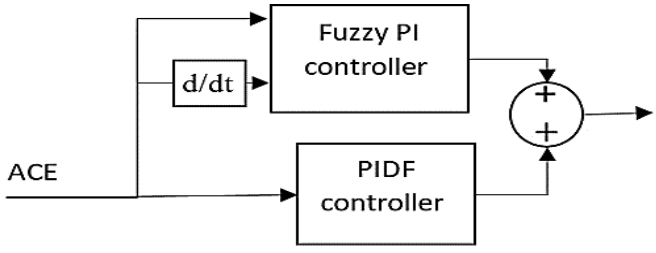


Figure 2. Fuzzy PI-PID controller

To achieve better outcomes and performance, a PID controller with a derivative filter will be used. To lessen the noise signal, the value of this filter can be changed. A PID controller with a filter [30] is shown in Figure 3 below.

$$U_{PID}(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{N}{1+N\frac{1}{s}} \quad (10)$$

Where Kp: proportional gain, Ki: integral gain, Kd: derivative gain, and N: derivative filter.

The proportional, integral, derivative, and filter parameters will be obtained by MGO.

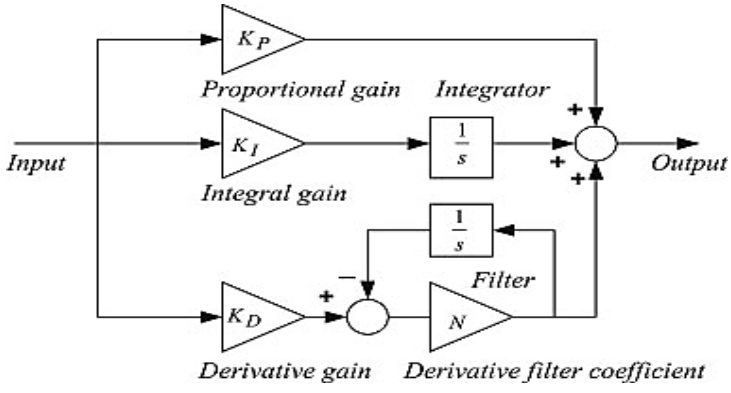


Figure 3 : PID controller with filter

3.5 Fuzzy-PI controller

A fuzzy PI controller is a type of control system that uses fuzzy logic and proportional-integral (PI) control to regulate the behavior of a system. It combines the advantages of both fuzzy logic and PI control as illustrated in figure 4 to provide an efficient and robust control solution.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

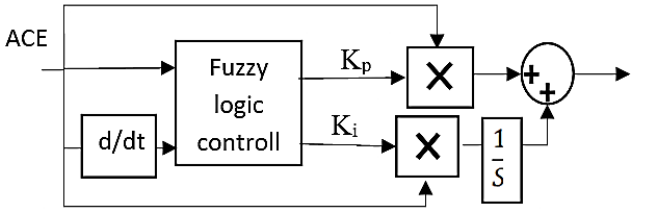


Figure 4: : Fuzzy logic control PI

The fuzzy PI controller uses fuzzy logic to determine the appropriate output for a given input, while the PI controller adjusts the output based on the error between the desired output and the actual output. This combination allows for more accurate control than either method alone [23-24].

In this article, online tuning for a PI controller is achieved by using a fuzzy logic controller, which determines the best parameters for the PI controller.

The Fuzzy Logic Controller (FLC) is a system that uses fuzzy logic to process input data and produce an output. It consists of four main components: fuzzification, a Fuzzy Inference System (FIS), a rule-based system, and defuzzification. Before the input data is sent to the fuzzification process, it must be preprocessed by normalizing or scaling the measurement quantities. This preprocessing step transforms the crisp value into a fuzzy set, which is then used by the FIS to execute all reasoning schemes and generate an output. Finally, the output is defuzzified to obtain a crisp value.

Membership functions (MFs) such as Gaussian, bell-shaped, trapezoidal, and triangular are used to design a Fuzzy Logic Controller (FLC). Tuning fuzzy control is a difficult task that involves rule tuning and MFs tuning, which may not be effective.

To obtain an optimum and robust FLC, the system's parameters have been tuned. However, for real-time applications, symmetrical triangular MFs (STMFs) are preferred due to their simplicity compared to other MFs. The rule base of an FLC is composed of membership functions and control rules. The output of the FLC is a fuzzy set that needs to be transformed by a defuzzification scheme into a numeric value. Due to this study's focus on defuzzification schemes, five triangular MFs are utilized. These five MFs were selected using five linguistic variables, which include the input and

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

output of FLC for negative large (NL), negative small (NS), zero (ZE), positive small (PS), and positive large (PL). The input/output MFs of the FLC are shown in Figure 5. The 25 rule two-dimensional rule-base for ACE, dACE, and FLC output is shown in Table 3. This study employs Mamdani and centroid methods [31] for FIS and defuzzification, respectively.

Table 3: Fuzzy rule for outputs/inputs fuzzy logic controller

	DACE				
ACE	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PL	PL	PL

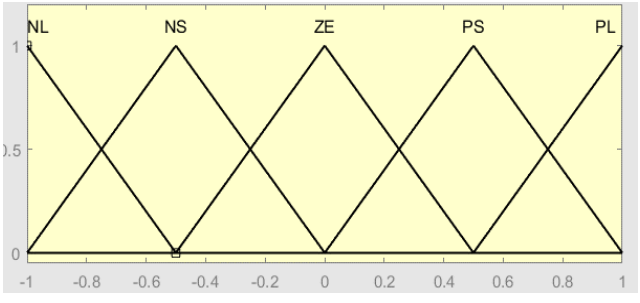


Figure 5. Membership function MF of input/output of the fuzzy logic controller

4. Result and discussion

In this study, MATLAB 2024b was employed to simulate a three-area non-reheat power system integrated with energy storage. MGO is utilized to determine the optimal PIDF controller parameters aimed at enhancing system stability and minimizing frequency deviations. The Integral Time-Absolute Error (ITAE) criterion is formulated using two approaches: one accounting for Area Control Error (ACE) incorporating tie-line power (Eqs. 5–8), and the other focusing solely on direct frequency deviations (Eq. 9). Furthermore, the performance of the proposed MGO-tuned PIDF controllers evaluated both with and without tie-line power in the objective function is benchmarked against the hybrid Fuzzy PI-PIDF

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

controller, which demonstrated superior performance in previous work. The multi-step load perturbation profiles applied to each area are illustrated in Figure 6.

Figure 7 depicts the convergence curve for iteration with ITAE for the proposed approaches to obtain system parameters with and without power tie-line in objective functions. The ITAE values of these methods are used to evaluate their performance. According to the results, MGO without a power tie-line in the objective function has the lowest ITAE of 0.0842 within 70 iterations. MGO with a power tie-line comes in second with an ITAE of 0.0924 within 90 iterations. According to ITAE MGO, the best and fastest parameters to optimize the system response without a power tie-line in the objective function. Table 4 the PID controller parameters for the system with and without power tie-line in objective functions.

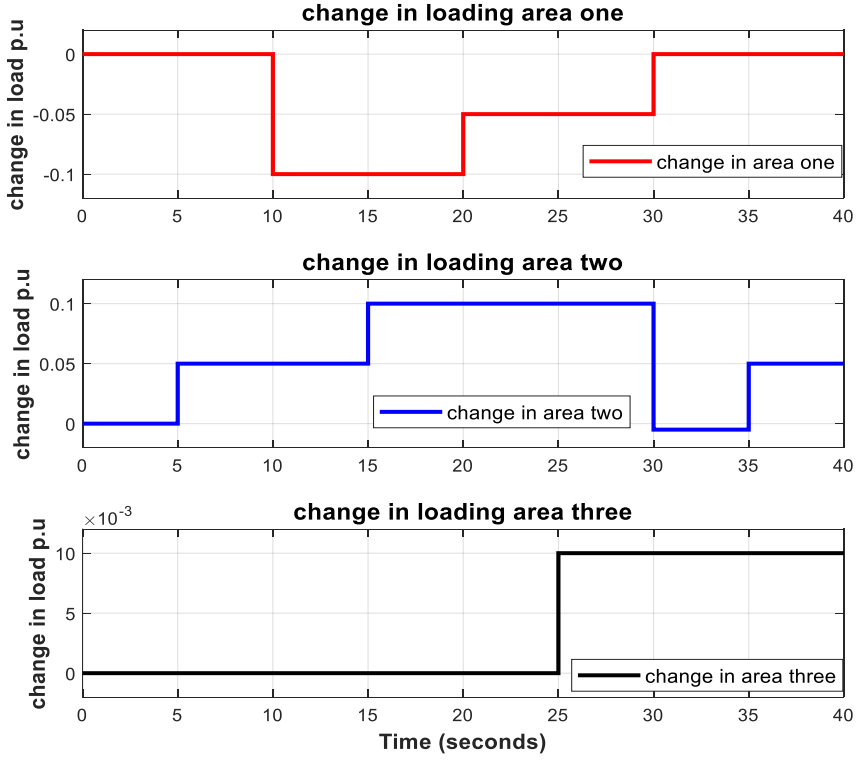


Figure 6. Change in loads in each area for a three-area system

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

Table 4: PID controller parameters in each area with ITAE in each case

Technique	ITAE	Controller	Area	K_p	K_i	K_d	N
MGO without power tie-line in objective function	0.0842	System controller	1	299.85	2.00	69.96	265.58
			2	299.99	2.12	69.91	200.00
			3	11.82	2.00	10.96	1987.94
		Energy storage controller	1	99.84	100.00	2.01	1459.18
			2	17.12	99.99	2.00	1902.38
			3	99.77	99.80	7.83	203.51
MGO with power tie-line in objective function	0.0924	System controller	1	300.00	249.99	69.90	383.25
			2	300.00	250.00	70.00	1721.92
			3	300.00	249.99	70.00	1696.02
		Energy storage controller	1	7.98	9.57	2.00	200.04
			2	5.59	99.95	2.00	200.00
			3	3.01	3.21	2.00	200.10

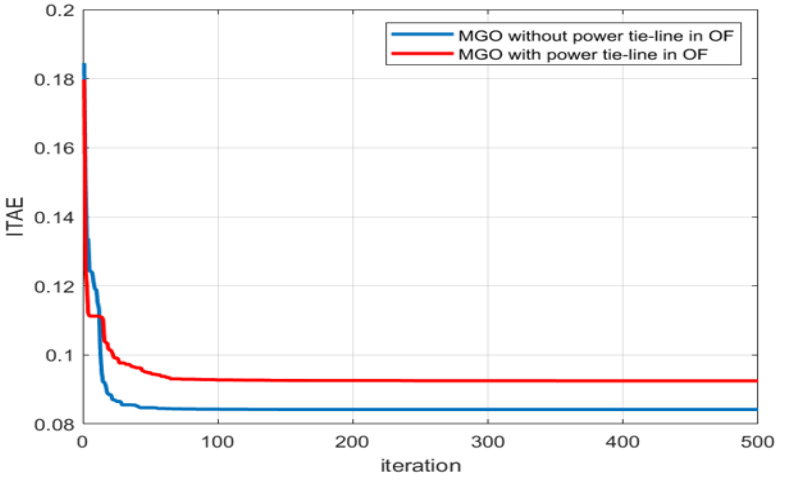


Figure 7. Convergence curve for the proposed methods to obtain parameters of system with and without power tie-line in objective function

According to the changes in loads shown in Figure 6, the response of Area One is presented in Figure 8 Load changes occurred multiple times in Areas One and Two, with a single change in Area Three to test the controller's performance. The controllers were designed to minimize frequency deviation. Fuzzy PI-PIDF controller based on MGO with power tie-line in objective function,

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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Fuzzy PI-PIDF controller based on MGO without power tie-line in objective function, PID based on MGO with power tie-line in objective function, and PID based on MGO without power tie-line in objective function were used in this study. MGO without power tie-line in objective function proposing the Best response due to its shorter settling time, absence of system oscillations, and lower steady-state error. Table 5 provides detailed information on the maximum overshoot, maximum undershoot, and settling time for each technique.

Figure 9 demonstrates the controllers' performance in area two. MGO without a power tie-line in the objective function proposing the best response due to its shorter settling time, absence of system oscillations, and lower steady-state error. Table 6 provides detailed information on the maximum overshoot, maximum undershoot, and settling time for each technique.

Figure 10 demonstrates the controllers' performance in area three. MGO without a power tie-line in the objective function is proposed as the best response due to its shorter settling time, absence of system oscillations, and lower steady-state error. Table 7 provides detailed information on the maximum overshoot, maximum undershoot, and settling time for each technique.

Table 5: Comparison between the proposed techniques in are one MOS, MUS, and ST

Tech	sec	MOS	MUS-	ST	Tech	MOS	MUS-	ST
MGO without power tie-line	5	0.1e-4	0.1e-4	2.5	MGO with power tine-line	0.7e-4	1.1e-4	2.6
	10	0.3e-4	0	3.2		4.6e-4	0.6e-4	2.6
	15	0.1e-4	0.1e-4	2.4		0.7e-4	1.1e-4	2.5
	20	0.13e-4	0.1e-4	3.1		1.14e-4	2.16e-4	2.6
	25	0	1.23e-4	2.5		0.1e-4	2.5e-4	2.5
	30	0.1e-4	0.3e-4	3.1		1.94e-4	3.5e-4	2.4
	35	0.1e-4	0.1e-4	2.5		0.7e-4	1.1e-4	2.5
Fuzzy-MGO without power tie-line	5	0.15e-3	2.3e-4	3	Fuzzy-MGO with power tie-line	0.7e-4	0.9e-4	2.6
	10	1.5e-4	0	5		3.8e-4	0.5e-4	3.7
	15	0.15e-3	2.3e-4	3		0.7e-4	0.9e-4	2.3
	20	0	0.8e-4	5		0.15e-4	1.9e-4	3.75
	25	0.1e-4	1.23e-4	3		0.1e-4	2.5e-4	2.4
	30	0.8e-4	0.9e-4	5		1.5e-4	3.24e-4	3.3
	35	0.15e-3	2.3e-4	3		0.7e-4	0.9e-4	2.4

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

http://www.doi.org/10.62341/istj-vol39-2-aa37

Table 6: Comparison between the proposed techniques in are two MOS, MUS, and ST

Tech	sec	MOS	MUS-	ST	Tech	MOS	MUS-	ST
MGO without power tie-line	5	0.1e-4	5.5e-4	2.5	MGO with power tine-line	0.3e-4	6e-4	2.6
	10	0	1e-4	3.2		1.8e-4	1e-4	2.6
	15	0.1e-4	5.5e-4	2.4		0.3e-4	6e-4	2.5
	20	0.5e-4	0	3.1		0.7e-4	1.1e-4	2.6
	25	0	0.4e-4	2.5		0	0.3e-4	2.5
	30	11.7e-4	0.15e-4	3.1		13.2e-4	1.8e-4	2.4
	35	0.1e-4	5.9e-4	2.5		0.3e-4	6.6e-4	2.5
Fuzzy-MGO without power tie-line	5	0.2e-4	5.5e-4	3	Fuzzy-MGO with power tie-line	1.4e-4	6e-4	2.6
	10	1	0.8e-4	5		2.2e-4	1e-4	3.7
	15	0.2e-4	5.5e-4	3		1.4e-4	6e-4	2.3
	20	0.5e-4	0.6e-4	5		0.6e-4	1e-4	3.75
	25	0	0.4e-4	3		0	0.3e-4	2.4
	30	11.7e-4	1e-4	5		13.2e-4	2.2e-4	3.3
	35	0.2e-4	5.9e-4	3		1.4e-4	6.6e-4	2.4

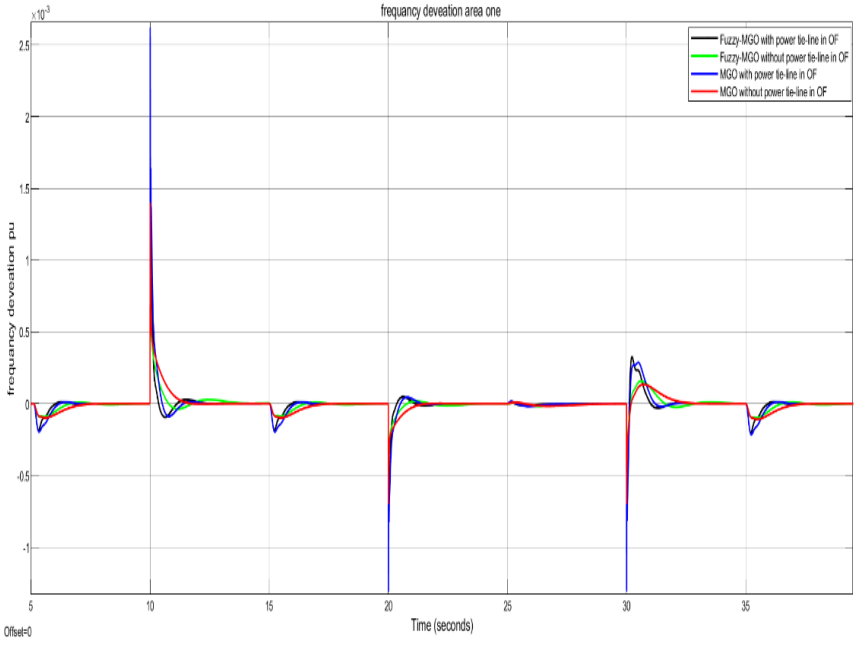


Figure 8. Frequency deviation in area one for the proposed controllers

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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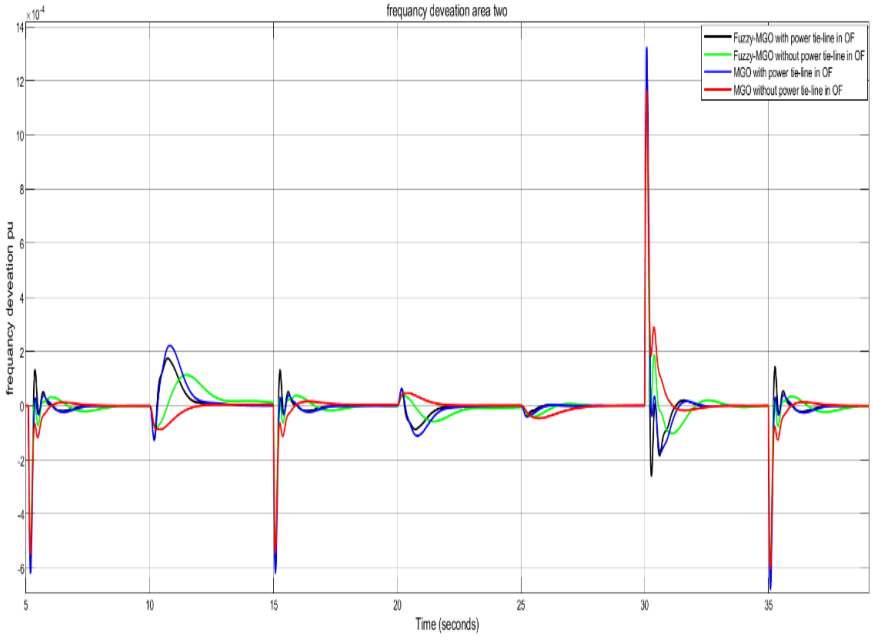


Figure 9. Frequency deviation in area two for the proposed controllers

Table 7: Comparison between the proposed techniques in are three MOS, MUS, and ST

Tech	sec	MOS	MUS-	ST	Tech	MOS	MUS-	ST
MGO without power tie-line	5	4e-5	1.8e-3	2.2	MGO with power tine-line	4e-5	2.3e-3	2.4
	10	1.4e-3	0	3.2		2.63e-3	0.15e-3	3.6
	15	4e-5	1.8e-3	2.1		4e-5	2.3e-3	2.5
	20	0	0.7e-3	3.1		0.11e-3	1.3e-3	3.6
	25	0.013e-3	0	2.1		0.018e-3	0.0013e-3	2.5
	30	0.2e-3	0.7e-3	3.1		0.32e-3	1.3e-3	3.4
	35	4e-5	1.8e-3	2.1		4e-5	2.3e-3	2.5
Fuzzy-MGO without power tie-line	5	0	1.8e-3	2.1	Fuzzy-MGO with power tie-line	0	2.3e-3	2.3
	10	1.4e-3	0.2e-4	3.2		2.63e-3	0.145e-3	3.7
	15	0	1.8e-3	2.1		0	2.3e-3	2.3
	20	0.014e-3	0.69e-3	3.2		0.1e-3	1.3e-3	3.75
	25	0.012e-3	0	2.2		0.018e-3	0.0012e-3	2.4
	30	0.21e-3	0.69e-3	3.1		0.31e-3	1.3e-3	3.3
	35	0	1.8e-3	2.2		0	2.3e-3	2.4

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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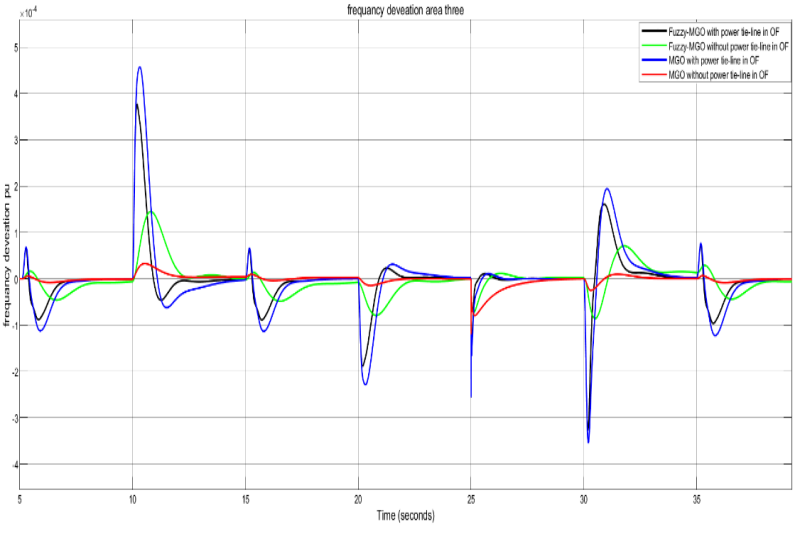


Figure 10. Frequency deviation in area three for the proposed controllers

Figures 11-13 depict the tie-line power between different areas for all the techniques utilized. The fuzzy-MGO, which incorporates power tie-lines in its objective function, demonstrated the best performance in managing power tie-lines between areas that either absorb or supply sudden changes in load. The maximum power transfer observed was $2{,}1 \times 10^{-4}\ p.u.$ from area two to area three, attributed to a sudden load change of 0.1 $p.u.$ removed from area two at the 30th second. Additionally, no oscillations were evident in the tie-line power. Following closely, the MGO technique, which also includes power tie-lines in its objective function, presented the second-best response for tie-line power. The maximum power transfer recorded was $2.6 \times 10^{-4} p.u.$ from area two to area three, due to a sudden change in load of $0.1 p.u.$ removed from area two at the 30th second. Like the fuzzy-MGO, no oscillations appeared in tie-line power. Conversely, the PID based on MGO exhibited the worst performance in managing power tie-lines between areas. The maximum power transfer recorded was 3.5×10^{-4} from area three to area one at the 16th second. It was noted that the PID based on MGO failed to reset the change in power tie-line to zero, signifying that this technique maintained the change in power tie-line above the scheduled or nominal values.

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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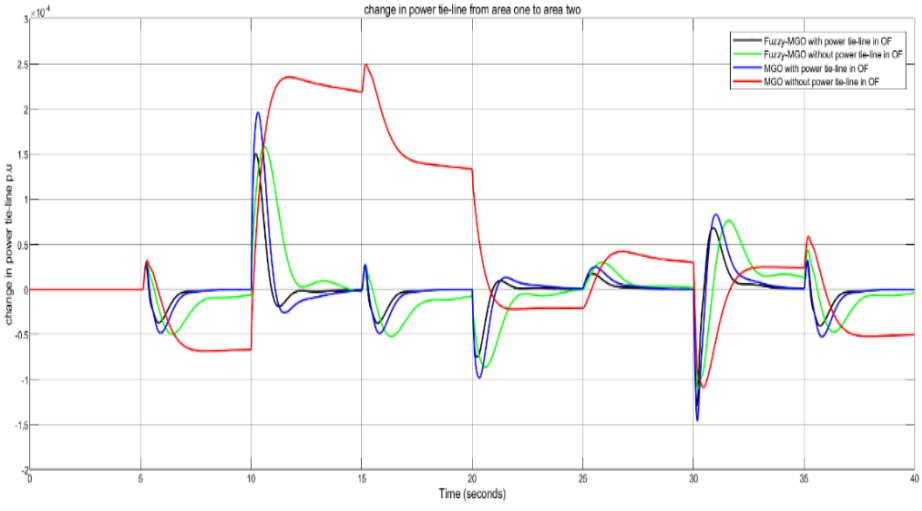


Figure 11. Change in power tie-line from area one to area two for the proposed controllers

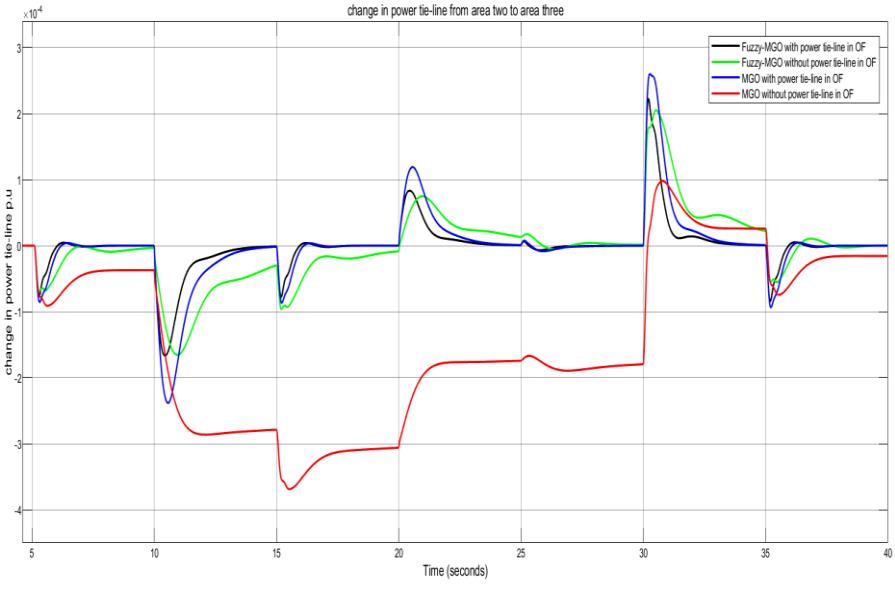


Figure 12. Change in power tie-line from area two to area three for the proposed controllers

Tie-Line Power Flow Strategies for Enhanced Load Frequency Control in Multi-Area Power Systems

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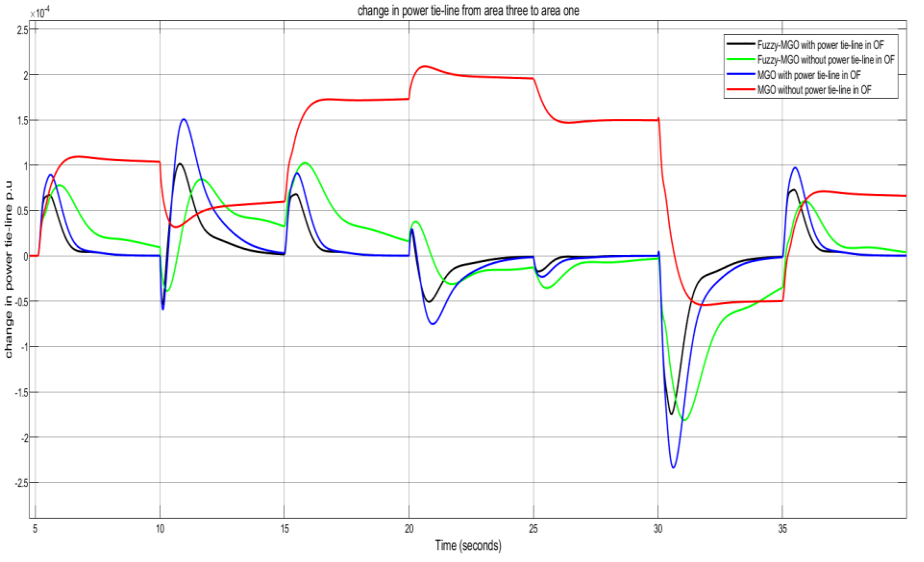


Figure 13. Change in power tie-line from area three to area one for the proposed controllers

5. Conclusion

This study provides a thorough analysis of load frequency control (LFC) within a three-area non-reheat system, emphasizing the performance of the PIDF controller tuned by MGO and the hybrid fuzzy PI-PIDF controller based on MGO controller. MATLAB 2024b was employed in this work. We introduced Integral Time-Absolute Error (ITAE) objective functions both with and without the consideration of power tie lines. System performance was evaluated based on area control error (ACE), frequency deviation (Δf), and power tie-line changes (ΔPtie-line). The simulation results confirm the effectiveness of the proposed controllers in enhancing LFC. Notably, the PIDF controller tuned by MGO, which focused on frequency deviation without including power tie lines in the objective function, demonstrated superior performance characterized by reduced overshoot, undershoot, and settling time. The MGO-based PIDF controller effectively managed power tie-line changes, achieving a maximum transfer of $3.7 \times 10^{-4} pu$ which around 2.2 MW from area three to area two. Additionally, the fuzzy PI-PIDF controller based on MGO, utilizing ITAE focused on ACE,

also exhibited commendable performance, particularly regarding power tie-line management. This study advances the understanding of LFC in non-reheat systems and underscores the importance of both PIDF and fuzzy PI-PIDF controller based on MGO controllers. The results obtained show that the noninclusion of power tie lines in the objective function has a positive effect on LFC parameters, improving system performance and having a little impact on power tie-line flow. In general, these controllers have a great potential to improve the stability and reliability of power systems in load frequency control. Future work should focus on the use of these controllers in larger scale power systems and their robustness in different operating conditions.

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