

DEVELOPMENT OF AN ADAPTIVE AND FLEXIBLE AUTOMATIC
GENERATION CONTROL SCHEME FOR POWER SYSTEM SPLITTING

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GENERATION CONTROL SCHEME FOR POWER SYSTEM SPLITTING**

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ABSTRACT

DEVELOPMENT OF AN ADAPTIVE AND FLEXIBLE AUTOMATIC GENERATION CONTROL SCHEME FOR POWER SYSTEM SPLITTING

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This study develops an adaptive and flexible Automatic Generation Control (AGC) scheme to enhance load-frequency regulation in multi-area power systems, with a particular focus on maintaining effective control during network splitting and reconnection events. The proposed AGC evaluates splitting conditions in real time and autonomously identifies coherent areas using frequency-based generator coherency analysis. Upon detecting a splitting event, it reconfigures control loops and operational modes in compliance with ENTSO-E standards, ensuring uninterrupted frequency regulation in both interconnected and islanded conditions.

To ensure adaptivity under varying system dynamics, the proposed AGC incorporates a hybrid PI control strategy. The integral gain (I_{GAIN}) is dynamically adjusted based on Area Control Error (ACE) trends and is further adaptively determined through a correlation-based approach that maps I_{GAIN} to key system parameters. These values are organized within a scenario-based look-up table, enabling the AGC to adapt its control parameters in response to varying system conditions, thereby enhancing performance during network splitting in complex power systems. The scheme also includes a constrained optimization-based reserve

activation strategy, replacing conventional market-based allocation to improve reserve deployment following network splitting.

The proposed method is validated through software-in-the-loop (SIL) simulations on both the IEEE test network and a dynamic model of the Turkish transmission system. Evaluation across various scenarios confirms that the AGC maintains robust, regulation-compliant performance, offering a scalable solution for dynamic and uncertain grid environments where conventional AGC methods may be inadequate under evolving system conditions.

Keywords: Automatic Generation Control (AGC), Adaptive AGC Schemes, Load-Frequency Control (LFC), Power System Splitting, ENTSO-E

ÖZ

GÜÇ SİSTEMİ AYRIŞMASI İÇİN UYARLANABİLİR VE ESNEK BİR OTOMATİK ÜRETİM KONTROL YAPISININ GELİŞTİRİLMESİ

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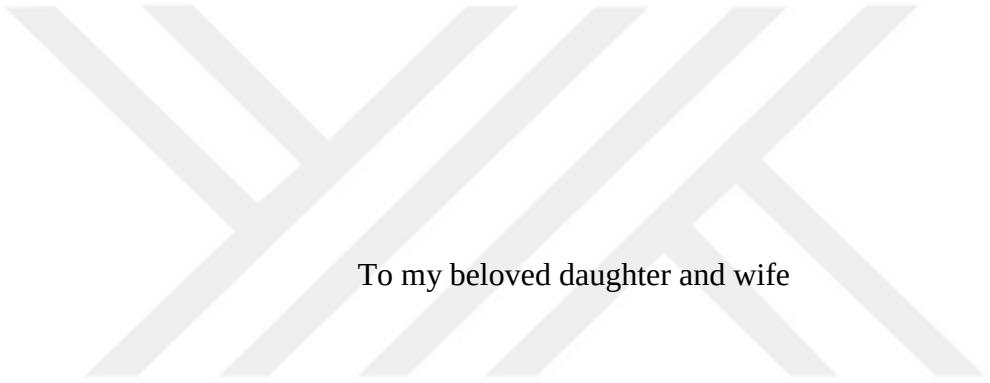
Bu çalışma, özellikle şebeke ayrışması ve yeniden senkronizasyon durumlarında etkin kontrolü sürdürmeye odaklanarak, çok bölgeli güç sistemlerinde yük-frekans kontrol performansını artırmak amacıyla uyarlanabilir ve esnek bir Otomatik Üretim Kontrol (AGC) yapısı geliştirmektedir. Önerilen AGC, ayrışma koşullarını gerçek zamanlı olarak değerlendirir ve frekans ölçümlerine dayalı jeneratör tutarlılık analizi yoluyla senkron bölgeleri otonom şekilde tanımlar. Şebeke ayrışma olayının tespit edilmesinin ardından, kontrol döngülerini ve işletme modlarını ENTSO-E standartlarına uygun biçimde yeniden yapılandırarak hem enterkonnekte hem de ada koşullarda kesintisiz AGC sağlar.

Sistem dinamiklerinin değişkenliğine karşı uyarlanabilirlik sağlamak amacıyla, AGC yapısında hibrit bir PI kontrol stratejisi uygulanmaktadır. İntegral kazancı (I_{GAIN}), Alan Kontrol Hatası (ACE) eğilimlerine göre dinamik olarak ayarlanmakta ve ayrıca I_{GAIN} 'in temel sistem parametreleriyle olan ilişkisini esas alan korelasyon tabanlı bir yaklaşımla adaptif şekilde belirlenmektedir. Bu değerler, senaryo tabanlı bir arabul tablosu içerisinde düzenlenmiş olup, AGC'nin değişen sistem koşullarına uygun şekilde kontrol parametrelerini uyarlamasına olanak tanımakta ve böylece

karmaşık güç sistemlerinde şebeke ayrışmaları sırasında performansın artırılmasını sağlamaktadır. Ayrıca yapı, geleneksel piyasa temelli tahsis yöntemlerinin yanında, şebeke ayrışması sonrasında rezervlerin daha etkin kullanılmasını sağlayan kısıt optimizasyonuna dayalı bir rezerv aktivasyon stratejisini de içermektedir.

Önerilen yöntem, IEEE test sistemi ve Türkiye iletim sistemine ait dinamik bir model üzerinde geliştirilen yazılım-içinde-döngü (SIL) simülasyonlarıyla doğrulanmıştır. Farklı senaryolar altında yapılan çalışmalar, AGC yapısının sağlam, yönetmelik uyumlu ve ölçeklenebilir bir kontrol çözümü sunduğunu ortaya koymakta; geleneksel AGC yöntemlerinin yetersiz kalabildiği dinamik ve belirsiz şebeke koşulları için etkili bir alternatif sunmaktadır.

Anahtar Kelimeler: Otomatik Üretim Kontrolü (AGC), Adaptif AGC Şemaları, Yük-Frekans Kontrolü (LFC), Güç Sistemi Ayrışması, ENTSO-E



To my beloved daughter and wife

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LIST OF ABBREVIATIONS

ABBREVIATIONS

ACE	Area Control Error
ACS	ACE Control Signal
AGC	Automatic Generation Control
ANN	Artificial Neural Network
AVR	Automatic Voltage Regulator
CCPP	Combined Cycle Power Plant
CDF	Cumulative Distribution Function
CET	Central East Time
CSV	Comma-Separated Value
DFRL	Deep Forest Reinforcement Learning
ENTSO-E	European Network of Transmission System Operators for Electricity
FCC	Frequency Containment Control
FRC	Frequency Restoration Control
FRR	Frequency Restoration Reserves
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
LFC	Load Frequency Control
MPC	Model Predictive Control
OPC	Open Platform Communication
PFC	Primary Frequency Control

PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PMU	Phasor Measurement Unit
PP	Power Plant
PSO	Particle Swarm Optimization
PSS	Power System Stabilizer
RCC	Regional Coordination Center
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SFC	Secondary Frequency Control
SIL	Software-In-the-Loop
SLSQP	Sequential Least Squares Quadratic Programming
TSO	Transmission System Operator
WAMS	Wide-Area Measurement System

LIST OF SYMBOLS

SYMBOLS

i	Control area index
ACE_i	Area control error at area i
$\Delta P_{tie,i}$	Total tie-line power deviation at area i
β_i	Bias factor at area i
Δf_i	Frequency deviation at area i
$P_{sch,j}$	Scheduled power flows for tie line j
$P_{act,j}$	Actual power flows
TL_i	The number of tie-lines in area i
$f_{set,i}$	Setpoint frequency at area i
$f_{act,i}$	Actual frequency measurement at area i
$P_{REQ,i}$	Total required active power for area i
P_{GAIN_i}	Proportional gain at area i
I_{GAIN}	Integrator gain at area i
T_i	Integral time constant at area i (I_{GAIN}^{-1})
k	Index of a generating unit in area i
$P_{set,k,i}$	Power setpoint for unit k in area i
$a_{k,i}$	Participation factor of unit k in area i

R_i	The number of reserve units (generators) in area i
β_{total}	Total bias factor of the interconnected system
$P_{gen,k,i}$	Installed capacity of generator k in area i
N	The number of control areas
$\Delta f_{gen_{k-1,k}}$	Frequency differences between adjacent generator pairs
f_{thres}	Frequency threshold of splitting
K_i	Coherent group of i
$g_{k,i}$	k^{th} generator in a coherent group i
K	The set of coherent groups
Pg_k	k^{th} generator dispatch
$Pgmin_k$	Predefined minimum dispatch threshold for k^{th} generator
m_i	AGC operation mode in area i
M	Set of AGC modes
F_{act}	Set of actual frequency measurements
β	Set of bias factors
d	Data point index for the interpolation
y_d	d^{th} pair of data points as (ACE, ACS)
Y	Set of y
v_d	Efficient I_{GAIN} value for d^{th} pair
V	Set of v
$func_{int}$	Interpolating function

H	Average inertia
$\sum H \cdot P$	Total Inertia Contribution
X	Corresponding network parameter
$\rho_{I_{GAIN}, X}$	Pearson correlation coefficient between I_{GAIN} and X
$cov(I_{GAIN}, X)$	Covariance between I_{GAIN} and X
σ	Standard deviation parameter
C	Total Inertia Contribution value in bilinear interpolation
A	ACE value in bilinear interpolation
t_0	Initial time of SLSQP
t_f	Final time of SLSQP
$P_{min,k}$	Minimum power output limit of unit k
$P_{max,k}$	Maximum power output limit of unit k
$P_k(t)$	Active power output of unit k
$Ramp_k$	Ramp rate limit for unit k
Δt_{min}	Minimum time interval between reserve activations
$p\text{-value}$	Parameter of statistical significance
t_{stat}	Test statistic value
$F_t(t_{stat})$	CDF of the t-distribution

CHAPTER 1

INTRODUCTION

The structure and operation of traditional power grids have undergone significant transformations in recent years. Rising energy demands and growing environmental concerns have driven the integration of diverse energy resources, introducing new operational challenges. One critical issue is ensuring reliable and stable frequency control in synchronized, multi-area power systems, such as those in the European Network of Transmission System Operators for Electricity (ENTSO-E) region. Addressing these complexities requires advanced and reliable Automatic Generation Control (AGC) systems, which are essential not only for maintaining frequency stability and regulating tie-line power flows but also for managing emergency scenarios, including network splitting events.

1.1 Research Problem and Motivation

In recent years, large, interconnected power systems like ENTSO-E have experienced an increasing number of system separation incidents due to growing operational complexity, reduced system inertia, and the expanding share of renewable energy sources. These events have highlighted a critical vulnerability in current control frameworks: The inability of conventional AGC systems to operate effectively during and after network splitting. Often, AGC enters a frozen or inactive state, leaving isolated areas without proper frequency regulation and leading to delayed recovery or instability. This trend underscores the need for AGC solutions that can sustain continuous, autonomous, and adaptive control, regardless of topological changes or disturbances, to ensure secure and resilient power system operation.

The primary research challenge of this study is to enhance the availability and adaptability of AGC in power systems under varying conditions. In extreme fault scenarios, such as the loss of significant generation capacity or critical transmission lines, the system's stability and synchronization can be severely compromised, potentially leading to system failure. To mitigate these risks, it is essential to identify and manage any network splitting that may occur. The coherency of synchronous generators plays a vital role in this process, enabling intentional splitting as a preventative measure against widespread failures. Additionally, system operators may manually initiate splitting as a part of remedial actions in specific situations. Following a split, AGC must continue operating seamlessly to maintain effective load-frequency control (LFC). Moreover, each separated control area will exhibit distinct dynamic characteristics, necessitating an adaptive control approach tailored to the unique conditions of each region.

A significant challenge arises when splitting fundamentally alters the operational conditions of AGC. In such events, the unified characteristics of the interconnected system are replaced by distinct operational environments in each separate area. These new conditions demand tailored frequency control strategies, as each split area has different frequency control requirements, generation capacities, and load demands. Consequently, conventional AGC methods, designed for interconnected systems, may fail to deliver the desired performance or even exacerbate instability in isolated regions.

Another critical challenge is the implementation of advanced adaptive control techniques in AGC, which is inherently complex due to practical limitations and computational constraints. While adaptive control is essential for increasing AGC performance under dynamic conditions, it introduces significant technical challenges such as increased system complexity in control design and implementation, computational limitations that restrict real-time adaptability, and ensuring system stability across both transient and steady-state operations.

To effectively address these challenges, integrating adaptive control techniques into AGC is crucial. Adaptive control enables the system to dynamically adjust its parameters in real-time, adapting to the unique conditions of each split area. This involves:

- Recalibrating integral gain to match operational needs,
- Optimizing reserve management for efficient resource utilization, and
- Maintaining continuous and robust frequency stability across all separated regions.

By incorporating these advanced techniques, AGC can achieve better performance, ensuring independent and effective control of each split area, even under the complex and evolving conditions introduced by network splitting.

1.2 The Scope and Novelty

The novelty of this work lies in the development of a flexible and adaptive AGC scheme capable of operating seamlessly under network splitting conditions. This approach ensures continuous and effective control of isolated areas while facilitating a smooth merging process during system reconnection. Unlike many complex adaptive control methods that are difficult to implement in real-world applications, this study introduces a practical and flexible PI control method designed for operational efficiency and reliability.

The proposed AGC scheme employs a dynamically adjusted PI controller, where the I_{GAIN} is fine-tuned in real time using a look-up table. This look-up table is generated through a comprehensive correlation analysis and iterative approach, enabling the I_{GAIN} to adapt dynamically to changing system conditions. While the methodology has been validated both on the IEEE test network and a representative Turkish Transmission System, it is scalable and can be adapted to other power networks by customizing the correlation analysis to system-specific parameters that influence I_{GAIN} behavior.

Beyond adaptive I_{GAIN} control, the AGC scheme integrates a dynamic reserve activation strategy that improves the deployment of automatic Frequency Restoration Reserves (FRR) in real-time. Using a Sequential Least Squares Quadratic Programming (SLSQP) optimization algorithm, this strategy ensures rapid and efficient reserve deployment following critical events such as system splitting. This approach not only enhances system resilience but also balances operational feasibility by aligning reserve activation with the specific needs of each split area.

The AGC framework has been rigorously tested and validated in a software-in-the-loop (SIL) environment using both the IEEE test network and Turkish Transmission System as representative models. The results demonstrate its robustness, practicality, and potential for real-world applications, providing a scalable and adaptive solution for modern power system challenges.

Furthermore, the proposed AGC methodology, with its real-time adaptability and compatibility with ENTSO-E operational modes, offers a framework that could inform future updates to ENTSO-E Load-Frequency Control and Reserves policies, particularly in managing control areas under splitting and reconnection conditions.

1.3 The Outline

This thesis is structured to provide a comprehensive understanding of the proposed AGC scheme and its applications.

Chapter 2 presents the background information necessary to understand the research. It begins with an overview of load-frequency control and AGC, explaining their role in power systems, followed by a discussion on power system splitting events in the ENTSO-E region. The chapter concludes with a literature review, summarizing relevant academic works.

Chapter 3 details the methodology employed in this study. It describes the proposed AGC scheme, introduces the splitting detection method, and explains the adaptive

control strategies and reserve optimization technique, highlighting the innovative aspects of the approach.

Chapter 4 focuses on modeling and scenario setup. It describes the simulation environment, the modeling of power systems using IEEE test networks and Turkish Transmission System data, and the development of simulation scenarios to evaluate the AGC's performance under various conditions.

Chapter 5 presents the simulation results, demonstrating the effectiveness of the proposed AGC scheme in addressing the challenges posed by power system splitting and validating its practical applicability.

Finally, Chapter 6 concludes the thesis by summarizing the key findings, discussing their implications, and outlining potential directions for future research.



CHAPTER 2

GENERAL BACKGROUND

2.1 Load Frequency Control and AGC

Load Frequency Control is a foundational mechanism in modern power system operation, responsible for maintaining the continuous balance between active power generation and load demand while stabilizing system frequency within acceptable limits [1]. In interconnected grids, LFC also ensures that scheduled tie-line power exchanges between control areas are upheld. Effective LFC is vital for avoiding cascading failures, equipment malfunctions, or large-scale blackouts due to frequency instability.

LFC operates within a hierarchical multi-layered control structure, as defined by international standards such as those from ENTSO-E, consisting of:

1. Frequency Containment Control (FCC) – Primary Frequency Control (PFC)
2. Frequency Restoration Control (FRC) – Secondary Frequency Control (SFC)
3. Replacement Reserve Activation – Tertiary Control
4. Time Control

Each layer contributes to the overall frequency regulation strategy by acting over different time scales and control objectives [2].

- Frequency Containment Control (Primary Control) provides the first stabilizing action within seconds of a disturbance. It is typically realized via decentralized governor response of generating units, which counteracts frequency deviation without reference to tie-line flows. However, FCC stabilizes the system only temporarily and cannot restore frequency to its nominal value.

- Frequency Restoration Control (Secondary Control), executed via AGC, aims to restore frequency to the nominal level (typically 50 Hz in ENTSO-E) and reestablish the scheduled tie-line exchanges between areas. Operating over a time window of approximately 10 seconds to 15 minutes, AGC plays a central role in coordinated system-wide frequency correction and is critical in multi-area power systems.
- Tertiary Control, also referred to as replacement reserve activation, is responsible for restoring reserve levels after FRC deployment and optimizing power dispatch from a market or operational efficiency perspective. It is typically manually activated and bridges the gap between real-time operations and economic dispatch.
- Time Control addresses long-term frequency deviations by correcting accumulated time errors to maintain synchronism across frequency-dependent devices and systems.

Figure 2.1 illustrates a typical system frequency trajectory in response to a sudden generation-load imbalance

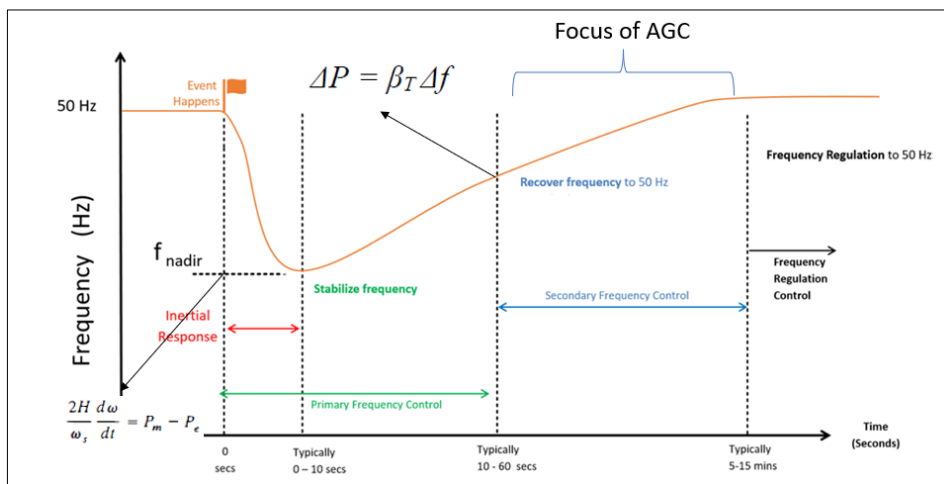


Figure 2.1. A typical frequency response following a disturbance

Figure 2.1 outlines the sequential activation of inertial response, primary control, and secondary control mechanisms. The diagram emphasizes that the focus of AGC lies in the secondary frequency control phase, where it facilitates recovery of system frequency and scheduled inter-area exchanges by processing Area Control Error (ACE) in real time.

The frequency response starts with an inertial reaction, a physical property of synchronous machines that resists sudden frequency changes. This is followed by primary frequency control, which stabilizes frequency without restoring it to nominal. Secondary control, led by AGC, acts to eliminate the remaining deviation and settle the system back to scheduled conditions.

In multi-area power systems, AGC ensures system stability by balancing generation and demand while maintaining scheduled power exchanges between interconnected areas. A key parameter in AGC operation is the ACE, which represents the imbalance in each control area. Mathematically, ACE is defined in (2.1).

$$ACE = \Delta P_{tie} + \beta \cdot \Delta f \quad (2.1)$$

where ΔP_{tie} is the tie-line power deviation (MW), representing the difference between the actual and scheduled power exchange with neighboring areas; β is frequency bias factor (MW/Hz), which reflects the control area's frequency sensitivity and load-frequency characteristics; Δf is the frequency deviation (Hz), indicating the deviation from the nominal system frequency (50 Hz in ENTSO-E).

The AGC system continuously monitors ACE and adjusts generator outputs accordingly to restore frequency stability and maintain scheduled tie-line flows. The control action in AGC is typically implemented using a PI controller, which modifies generator power setpoints based on ACE as in (2.2).

$$\Delta P_G = K_P \cdot ACE + K_I \int ACE dt \quad (2.2)$$

where ΔP_G is the adjustment in generation output (MW) for AGC-participating units, K_P is the proportional gain, providing an immediate response to ACE and K_I is the integral gain, eliminating steady-state errors over time.

This layered and responsive architecture enables AGC to ensure stable frequency restoration, efficient reserve utilization, and reliable tie-line power flow control under both normal and contingency conditions. However, its effectiveness heavily depends on well-calibrated control gains and sufficient frequency-responsive reserves, especially under system stress or splitting events, which challenges addressed in later sections of this study.

2.2 Splitting & AGC in ENTSO-E

Power system splitting refers to the division of a previously interconnected grid into two or more electrically isolated subsystems, often referred to as electrical islands. Such events may occur either intentionally, as a preventive action to safeguard system integrity, or unintentionally, because of equipment failures, line trips, operator errors, or large-scale disturbances. Regardless of the cause, the principal objective following a splitting event is to maintain system-wide operational stability, preserve frequency control within each islanded area, and prevent cascading failures that may lead to widespread blackouts [3].

Successful management of splitting events relies on correct detection and coordinated control actions, particularly in ensuring frequency stabilization and balancing generation-demand relationships within each separated subsystem. This challenge becomes significantly more complex when network separation occurs asymmetrically or under stressed operating conditions, such as low inertia or insufficient reserves in one of the islands.

ENTSO-E operates one of the largest and most complex synchronized power networks in the world, encompassing multiple countries and interconnected control areas. In recent years, this system has encountered increasing difficulties associated

with system separations and frequency instabilities. These challenges are primarily linked to the growing integration of renewable energy sources and the associated decline in system inertia.

In its 2021 Annual Report [4], ENTSO-E emphasized the adverse impact of reduced inertia on frequency stability in the Continental Europe synchronous area. This issue was attributed to the large-scale deployment of inverter-based renewable generation. Furthermore, the 2023 long-term frequency stability report [5] highlighted a continuing decline in the system's resilience to grid separations, indicating the need for improved operational strategies and more dynamic control mechanisms.

Several recent incidents reflect the increasing frequency and severity of system separation events. The Continental Europe system split in January 2021 [6], [7], the Iberian Peninsula separation in July 2021, and the regional disturbance in South-East Europe in June 2024 [8], [9] all presented significant operational challenges. These events revealed limitations in control coordination, frequency recovery, and resynchronization procedures under abnormal conditions.

One of the most specific and critical examples was the nationwide blackout in Turkey on March 31, 2015 [10], [11]. In this event, extreme operational stress, high power transfers, and the lack of a resilient islanding strategy resulted in the collapse of the entire grid. Unlike the previously mentioned cases, this incident did not allow for manageable island formation, exposing a significant weakness in the system's protection and control infrastructure. It also illustrated the importance of maintaining AGC functionality even in split or degraded operating states.

In response to these challenges, ENTSO-E has developed new technical guidelines and policies aimed at reinforcing system defense, restoration capabilities, and frequency regulation under both normal and disturbed conditions [12]. However, practical implementation remains limited, especially in terms of enabling AGC systems to remain active and adaptive during splitting and reconnection phases.

Historically, splitting events in the ENTSO-E synchronous area have been triggered by transmission outages, interconnection disruptions, and cascading failures. These events continue to pose serious threats to real-time system reliability. They also underscore the inadequacy of conventional AGC frameworks, many of which either transition to frozen mode or become inactive during topological changes. This loss of automatic frequency control during separation can delay recovery and increase the risk of system-wide instability.

These insights underscore the need for a more flexible and adaptive AGC architecture that can respond effectively to evolving grid conditions. Conventional AGC systems, which assume a unified network, are often unable to manage the dynamic challenges introduced by system separation. A modern AGC must be capable of detecting splits in real time, reconfiguring control areas accordingly, and maintaining independent load-frequency control within each island. Such adaptability is essential for enhancing system resilience and meeting the operational expectations of interconnected grids like ENTSO-E.

The following section presents a series of selected historical case studies that reflect these operational challenges, highlighting the need for AGC adaptability and extracting key lessons for the development of future frequency control strategies.

Continental Europe Split – January 8, 2021 [6]

The January 8, 2021, Continental Europe Split was one of the most significant power system separation events in recent history, affecting large portions of the ENTSO-E synchronous area. The incident resulted in the formation of two separate electrical islands as shown in Figure 2.2, with distinct frequency deviations and challenges. The primary cause of the event was a failure at the 400 kV Ernestinovo substation in Croatia, which triggered a cascade of disconnections along the South-East to North-West corridor of the Continental Europe power system as shown Figure 2.3.

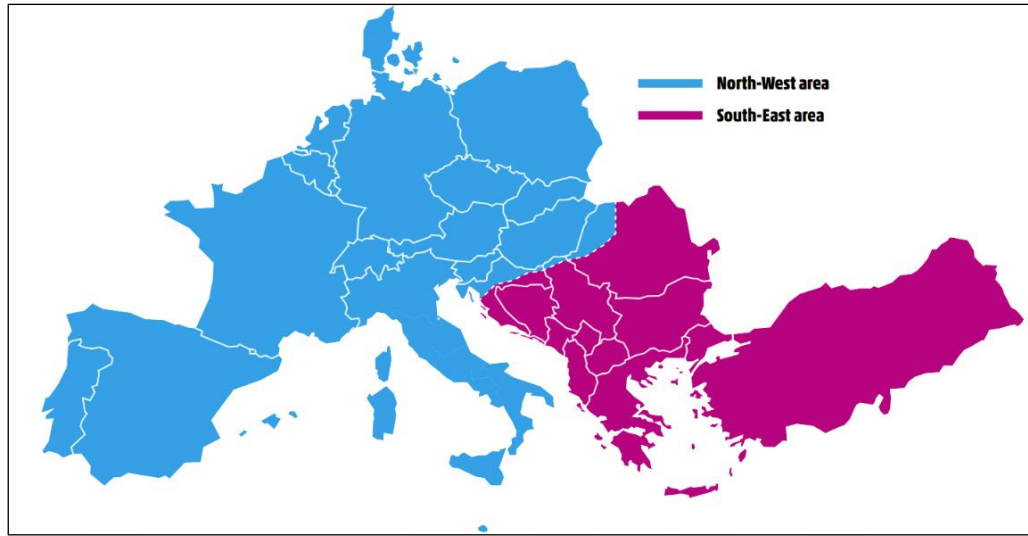


Figure 2.2. Two synchronous areas after the system split



Figure 2.3. The sequence of events causing the system split in January 2021

Figure 2.4 illustrates Phasor Measurement Unit (PMU) recordings from selected busbars during the sequence of events leading to the splitting. The frequency trends captured at multiple substations provide insight into how the grid split occurred. Mainly, the second event triggered a cascading separation between the North-West (blue) and South-East (red/orange/yellow) areas.

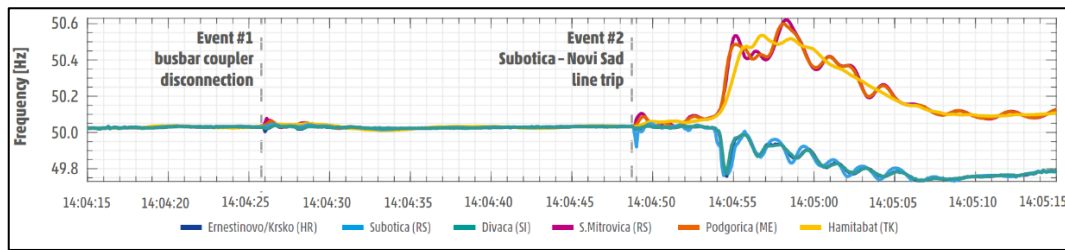


Figure 2.4. Frequencies at busbars during the event in January 2021

Figure 2.5 presents frequency measurements from both regions following the system separation. The South-East region experienced a sharp increase in frequency, peaking above 50.6 Hz before stabilizing around 50.2 Hz, indicating a generation surplus. In contrast, the North-West region saw a frequency drop to approximately 49.75 Hz, reflecting a generation deficit. Over time, both frequencies gradually stabilized, with the South-East remaining above nominal and the North-West below nominal. The figure also illustrates that the system reaches its steady-state conditions within approximately 30 seconds after the separation. At equilibrium, a frequency difference of approximately 350 mHz persists between the two regions.

The resynchronization process was carefully coordinated after the initial stabilization of the two separated regions. Following load shedding actions in the North-West and generation curtailments in the South-East, the frequency deviation between the areas was reduced, bringing them closer to the nominal 50 Hz. At 15:07:25 CET, the busbar coupler in Ernestinovo was switched off, initiating the synchronization sequence. Shortly after, at 15:08:20 CET, the overhead line Subotica 3 – Novi Sad 3 was reconnected, completing the resynchronization process. These switching actions caused short-lived transient frequency deviations, as seen in Figure 2.6 before the system frequencies in both regions stabilized. By 15:08 CET, synchronization was successfully achieved, fully restoring the Continental Europe Synchronous Area to normal operation.

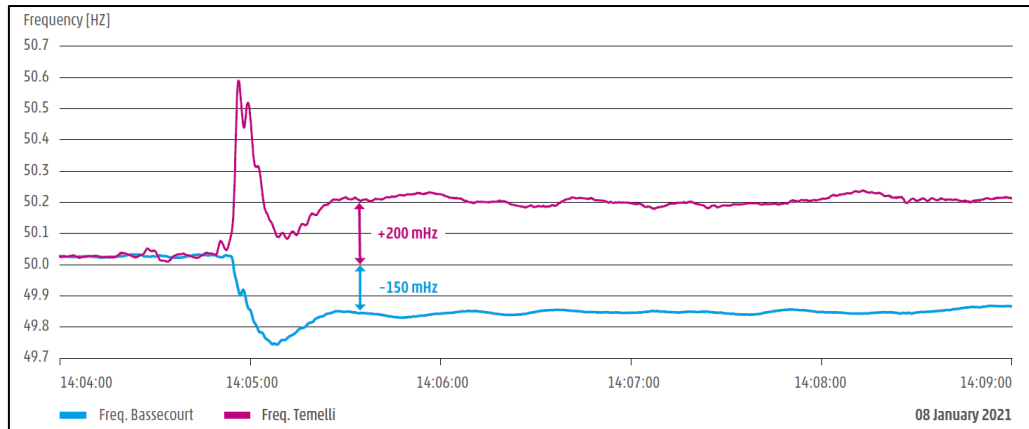


Figure 2.5. Area frequencies during the January 2021 event

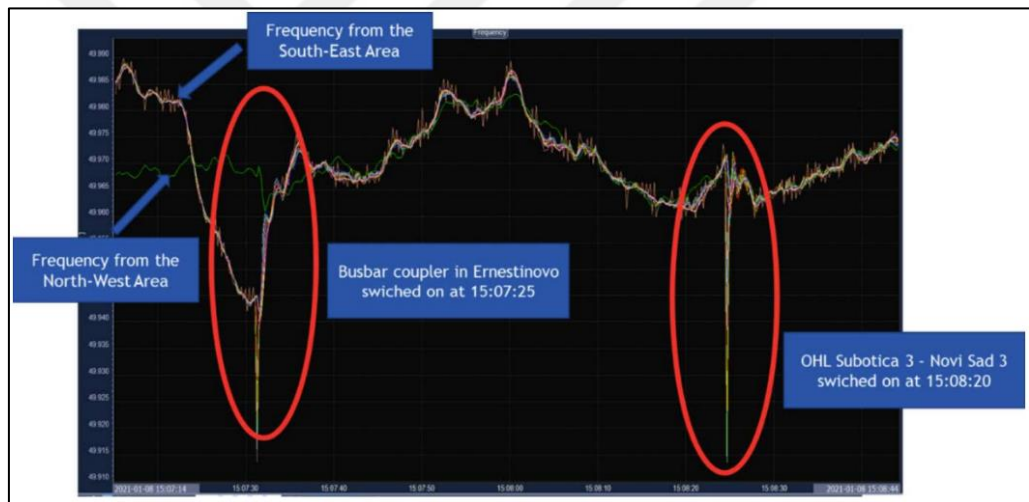


Figure 2.6. Frequency measurements during the resynchronization

This system split highlighted critical challenges in frequency control, AGC adaptability, and resynchronization strategies. The event underscored the importance of real-time splitting detection based on frequency measurements, as asynchronous frequency deviations between regions were key indicators of system separation. The incident also demonstrated the need for greater flexibility in AGC, as rigid transitions to frozen or stop mode in many TSOs limited automatic frequency restoration efforts.

The seamless operation of AGC during splitting remains a critical area for improvement, as the disruption exposed limitations in existing AGC schemes, particularly in handling isolated areas with sudden generation-demand imbalances. These lessons emphasize the necessity of an adaptive AGC approach that can dynamically adjust to grid conditions, ensuring stable frequency restoration and efficient resynchronization in future system separation scenarios.

Iberian Peninsula Separation – July 24, 2021 [8]

On July 24, 2021, at 16:36 CET, the Iberian Peninsula experienced a separation from the Continental Europe Synchronous Area due to a series of cascading trips of transmission lines, primarily initiated by a wildfire near the Baixas–Gaudière 400 kV lines in southern France (see Figure 2.7). Figure 2.8 provides an overview of the five main phases of the separation event. Before the event, the system operated under normal conditions with stable frequency. The separation was triggered by a wildfire near the Baixas–Gaudière 400 kV lines, leading to cascading line disconnections and the loss of synchronism between the Iberian Peninsula and Continental Europe. Following the split, automatic countermeasures, including frequency containment reserves and load-shedding, were activated to stabilize frequency deviations. Manual countermeasures, such as generation redispatch and load adjustments, were then implemented to restore system balance. Finally, at 17:09 CET, the Iberian Peninsula was resynchronized with Continental Europe, marking the successful restoration of normal operation after 33 minutes of separation.

This system split demonstrated that power system separation can occur even in a relatively small portion of the ENTSO-E region, emphasizing the necessity of adaptive AGC schemes capable of maintaining effective control during partial system separations.

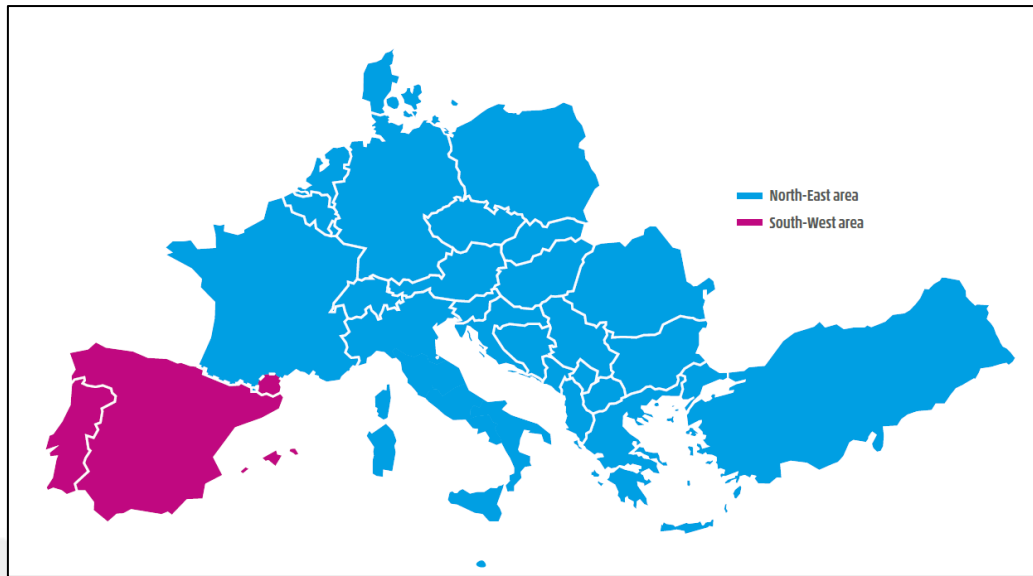


Figure 2.7. Two synchronous areas after the system split

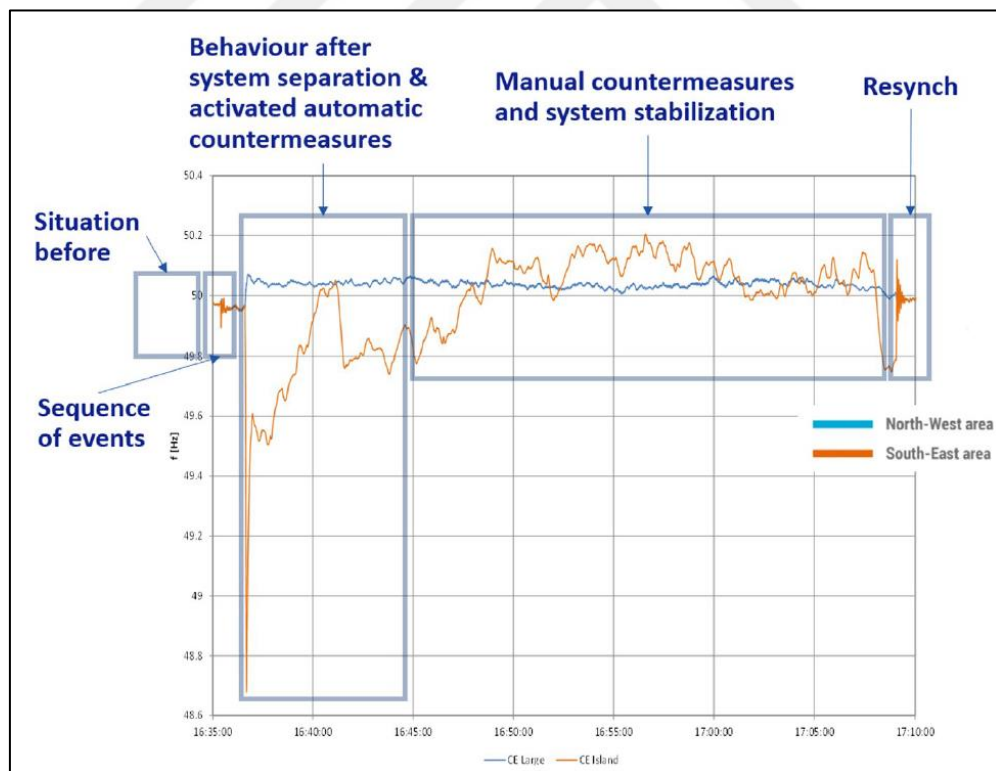


Figure 2.8. Frequency during phases of the system split

Turkey's Nationwide Blackout – March 31, 2015 [10]

The Turkish power system blackout on March 31, 2015, was one of the most severe electricity disruptions in the country's history, affecting nearly 80 out of 81 provinces and leaving millions without power for several hours. The outage originated from a failure in the 400 kV interconnected transmission network, leading to a cascade of frequency instability and grid separation as presented in Figure 2.9. The blackout was triggered by high power flows between Turkey's western and eastern regions, causing a failure in the grid's automatic protection and control systems. This led to splitting within the network, with some regions becoming islanded while others faced a complete loss of supply.

This event was significantly different from other splitting events within the ENTSO-E system, as it did not result in controlled islanding but instead led to a complete system collapse affecting nearly the entire country. The blackout might also reveal a critical weak point in the Turkish grid, which must be carefully considered in AGC operations and network security planning. This may highlight the importance of dynamic AGC strategies, where dynamic adaptation and intelligent reserve activation could play a key role in mitigating the impact of sudden grid separations.

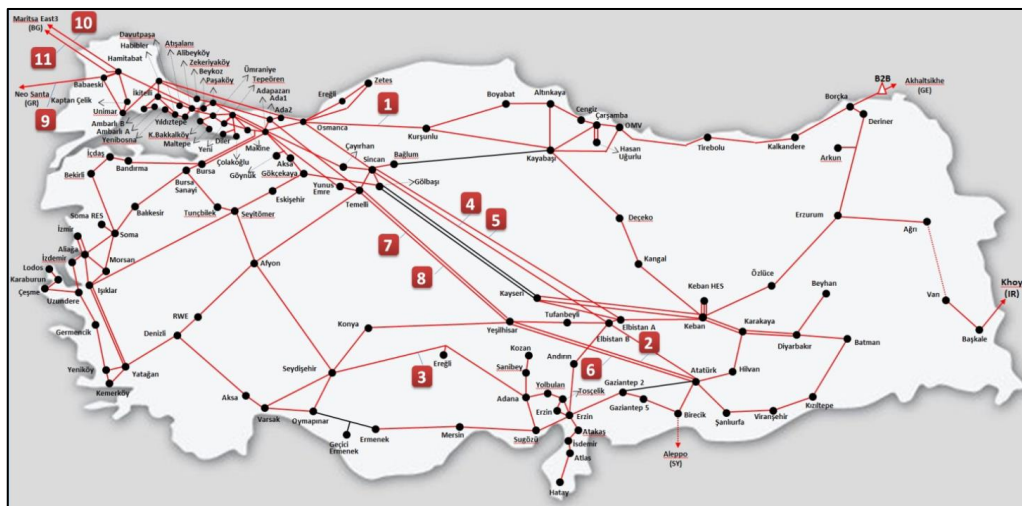


Figure 2.9. Sequence of events leading to the Turkish blackout

In summary, the Continental Europe separation and the Iberian Peninsula separation highlight critical challenges in AGC adaptability, real-time splitting detection, reserve activation, and resynchronization coordination. In both events, frequency deviations were key indicators of separation, yet there was no online splitting detection mechanism integrated with AGC. The rigid application of frozen or stop mode during these disturbances limited AGC's ability to correct frequency deviations, particularly in the South-East region during the January event and in the Spanish control block during the Iberian event. Furthermore, reserve activation was not fully efficient. The 2015 Turkish blackout further underscores the consequences of cascading failures and reveals potential weak points in the Turkish power system's ability to handle grid separation. These findings emphasize the need for an adaptive and flexible AGC approach that integrates real-time split detection based on generator coherency, dynamically adjusts AGC settings instead of freezing or disabling controllers, and enhances reserve activation efficiency. By addressing these limitations, a more resilient and efficient frequency control system can be developed for future separation and resynchronization scenarios, preventing both uncontrolled system collapses and inefficient frequency restoration efforts.

2.3 Literature Review

Numerous automatic generation control schemes and control techniques have been studied, implemented, and reviewed in the context of frequency regulation [13–15]. Traditionally, AGC systems have relied on PI controllers to reduce control errors and maintain system stability. However, to improve AGC adaptability in increasingly complex, multi-source, and deregulated power systems, various intelligent control methods have been recently introduced. For example, a novel cascade control design was proposed in [16], incorporating a serial Proportional-Integral-Derivative (PID) controller with an integrated filter. Kumar et al. [17] investigated an AGC scheme tailored for deregulated environments, using a Big Bang–Big Crunch optimized PID controller to manage load perturbation scenarios,

demonstrating improved performance over Imperialist Competitive Algorithm and Harmony Search algorithms in multi-area systems. Bevrani et al. [18] presented a Bayesian network-based multi-agent control scheme for AGC under high wind power penetration, offering enhanced flexibility, scalability, and robustness in uncertainty management.

Tan et al. [19] proposed a frequency-based control method with segmented frequency response values and a fuzzy Proportional-Derivative-Complementary-Integral controller to minimize overshoot, implemented alongside adaptive filter-based strategies in the hydropower-rich Southwest China Grid. A hybrid Particle Swarm Optimization (PSO) and Modified Sine Cosine Algorithm – based PID – Fuzzy – PID strategy was proposed in [20] to enhance frequency stability in a two-area power system with electric vehicle aggregators, combining swarm intelligence and sine-cosine-based search mechanisms for optimal controller tuning. Various Fuzzy Logic Controller techniques have also been applied to improve AGC performance, particularly in handling non-linear dynamics [21–22].

In addition, Artificial Neural Network (ANN) – based methods have become prominent in AGC applications, especially for addressing dynamic and non-linear system behavior where traditional controllers may fall short. Li and Chen [23] proposed a deep forest network-based AGC strategy, combining the real-time responsiveness of PI control with the adaptability of Discrete Fourier Transform – based approaches. Similarly, a Deep Forest Reinforcement Learning (DFRL) strategy for system state prediction and mode-dependent reinforcement learning was introduced in [24] to manage both emergency and normal operation states in large, interconnected power systems. An adaptive Model Predictive Control (MPC) approach to load frequency control in multi-area grids with high renewable penetration was presented in [25], demonstrating improved performance over conventional methods. Additional studies have explored MPC-based AGC schemes for both centralized and decentralized architectures in [26–28].

These approaches reflect a growing trend toward intelligent, adaptive, and learning-based AGC strategies that aim to improve frequency control under increasingly complex system conditions. Fuzzy logic and MPC techniques offer enhanced interpretability and accurate system modeling, making them suitable for structured and predictable environments. In contrast, deep learning-based methods, such as DFRL, provide high adaptability and improved decision-making in dynamic scenarios, but they often require substantial training data and computational resources, which can limit their practicality for real-time implementation.

In addition to adaptive control techniques within AGC, this research also emphasizes the importance of evaluating network splitting scenarios and ensuring that AGC systems remain functional and effective under such conditions. Numerous studies have explored network splitting and islanding detection in power systems, presenting a wide range of methodologies for identifying and managing such events. As highlighted in [29], post-fault remedial splitting detection methods can generally be classified into hybrid, analytical, numerical, heuristic, and meta-heuristic approaches. Lin et al. [30] proposed a Wide-Area Measurement System (WAMS)-based method employing similarity parameters to identify generator coherency, optimized using a weight determination process. Similarly, another WAMS-based technique utilized kernel principal component analysis combined with clustering analysis to detect coherency in systems with high levels of renewable integration [31].

Other approaches focus on electromechanical dynamics and frequency behavior. In [32], a method was introduced for identifying slow coherent generators, considering the strength and direction of electromechanical coupling between units. A projection pursuit technique was applied in [33] to identify coherent generator groups, using two indices to evaluate the relevance of each projection in forming critical and dominant clusters. Khalil et al. [34] proposed a novel method based on dynamic frequency deviations at bus level, which allows the identification of coherent generator zones in real time. A sensitivity analysis-based approach was described in [35], incorporating changes in frequency and angle differences to detect islanding

events using frequency disturbance recorder data in the North American power grid. A three-stage real-time splitting detection framework was outlined in [36], which involved defining generator domains using power flow tracing, initializing separation boundaries, and iteratively refining them. Pinceti and Vanti [37] presented a topology-based islanding detection method that does not rely on measurement data, thus offering a generic strategy applicable in systems with limited observability.

Although these studies provide valuable insights and solutions for identifying grid separations and coherent generator groups, they do not incorporate AGC functionality during or after such events. Moreover, a few studies have explored the interaction between AGC and splitting detection mechanisms under real-time operational constraints. Liu et al. [38] attempted to model AGC operation under islanding conditions and simulated frequency control response during partial system separation. In parallel, Bevrani et al. [39] emphasized the importance of intelligent AGC design under abnormal system conditions, laying foundational concepts relevant to adaptive AGC during splitting. Furthermore, decentralized control concepts, such as the one proposed by Molina-García et al. [40], illustrate how distributed resources could support frequency control, which becomes critical in islanded or weakly connected grids.

CHAPTER 3

THE METHODOLOGY

This chapter presents the methodological framework developed to design, implement, and validate an adaptive and flexible AGC scheme capable of maintaining continuous operation under both normal and splitting conditions. The proposed scheme aims to ensure robust load-frequency control and efficient reserve utilization in compliance with ENTSO-E operational standards. The methodology employs a PI control strategy that adapts to varying system conditions. Under normal operating conditions, a dynamic PI control approach is utilized, where the integrator gain is continuously adjusted based on real-time ACE and Area Control Signal (ACS). In contrast, during power system splitting scenarios, an adaptive PI control method is activated. This approach relies on a pre-calculated look-up table derived from correlation analysis, enabling the integrator gain to be adjusted according to system-specific parameters such as inertia or FRR. Additionally, the methodology incorporates a reserve activation strategy that replaces market-based activation with a system-aware optimization algorithm, enhancing frequency regulation during disturbances. The remainder of this chapter is structured as follows: Section 3.1 introduces the proposed AGC scheme, detailing its control operations and area management. Section 3.2 describes the adaptive control framework, covering both the dynamic PI control for normal conditions and the adaptive PI control for splitting conditions. Section 3.3 presents the improved reserve activation strategy designed to enhance response and stability during critical events.

3.1 The Proposed AGC Scheme

The proposed AGC scheme consists of two main stages: Area Management and AGC Control Operations, as illustrated in Figure 3.1. The Area Management stage is

responsible for processing user inputs and real-time system measurements, evaluating conditions that may necessitate the separation of the network, and determining whether to partition the algorithm into independent AGC control loops for each area. In contrast, the primary objective of the AGC Control Operations stage is to maintain system frequency at the predetermined setpoint and ensure that tie-line power flows match their scheduled values by adjusting the power outputs of generators within each control area. In the event of a system split, the AGC calculates ACE values for each separated area using newly defined control parameters, enabling efficient and autonomous management of frequency and power flows within the isolated regions. Although the area management stage logically precedes the control actions, this chapter firstly presents AGC Control Operations in order to first establish the core control logic that underpins the overall scheme.

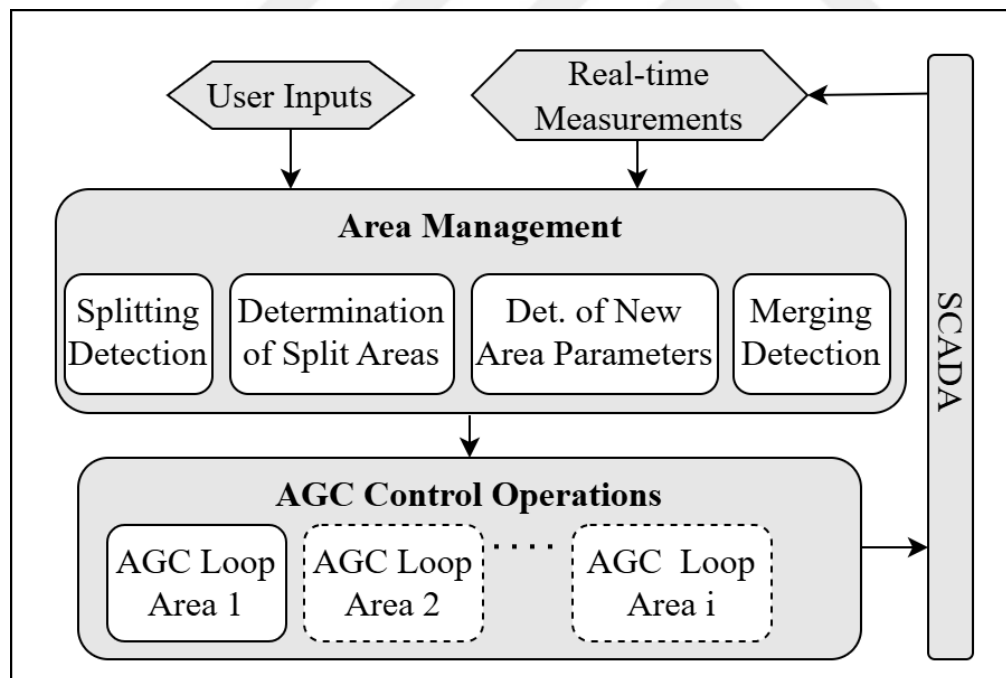


Figure 3.1. The proposed AGC scheme

3.1.1 AGC Control Operations

The general methodology for AGC control operations is illustrated in Figure 3.2, which presents the internal structure of each AGC loop, including state management, mode handling, ACE calculations, and setpoint delivery. Each AGC control loop is capable of operating under several distinct states, including STOP, ACTIVE, EMERGENCY, and FROZEN. These states represent different operational conditions and allow the AGC to adapt its behavior to real-time system requirements in accordance with ENTSO-E policies. For instance, the STOP state is activated either manually by the user or automatically when AGC operation becomes infeasible due to reasons such as insufficient reserve availability or continuous invalid measurement data. Similarly, the FROZEN state is typically triggered during topology changes, merging operations, or data inconsistencies (conditions under which AGC calculations must be temporarily frozen (uses the last calculated data)) to prevent incorrect control actions. A detailed description of all operational states and the conditions that trigger transitions between them is provided in Table 3.1.

Following state evaluation, the AGC proceeds with mode management, where different AGC modes define how the ACE should be computed during each control cycle. These operational modes are mostly aligned with the ENTSO-E Load-Frequency Control and Reserves Policy, ensuring compliance with continental European system requirements. This layered approach to control logic introduces flexibility in response to network dynamics. Once the ACE is determined, the system calculates the required power setpoints (P_{set}) for the participating generating units based on their assigned reserves, aiming to restore the ACE to zero. These setpoints are then delivered to the respective generators via the Supervisory Control and Data Acquisition (SCADA) interface, ensuring synchronized real-time operation across the control area.

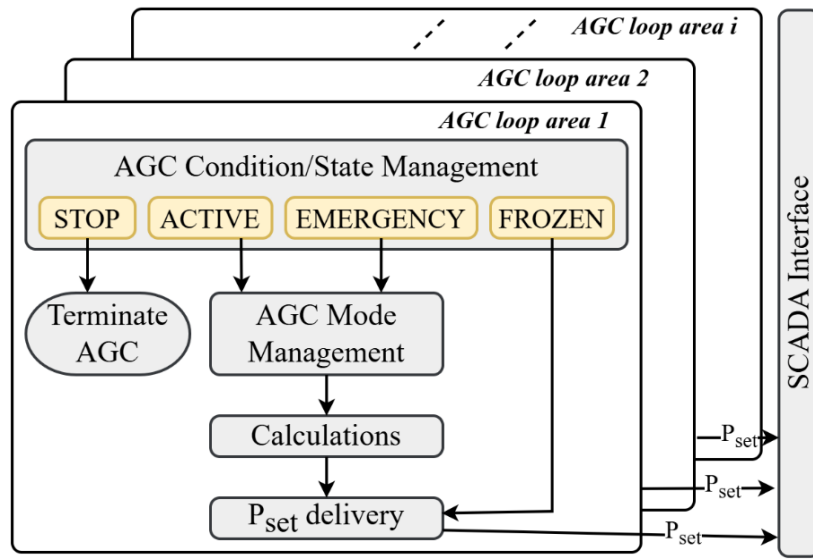


Figure 3.2. Details for AGC control loops

Table 3.1 State transitions of the AGC

Current State	New State	Condition
ACTIVE	EMERGENCY	ACE exceeds the second threshold limit
ACTIVE	FROZEN	Invalid measurements detected
ACTIVE	STOP	Operator input (user preference)
EMERGENCY	ACTIVE	ACE drops below the first threshold limit
EMERGENCY	STOP	ACE exceeds the third threshold limit
EMERGENCY	FROZEN	Invalid measurements detected
EMERGENCY	STOP	Operator input (user preference)
FROZEN	ACTIVE	Invalid measurements become valid before the timeout threshold
FROZEN	STOP	Invalid measurements persist beyond the time threshold
FROZEN	STOP	Operator input (user preference)
STOP	ACTIVE	Operator input (user preference)

The philosophy of the proposed AGC in splitting conditions is mainly based on independent ACE calculation in each control area. Although inputs for the ACE calculation may alter based on the operational mode, the generic calculation method (tie-line plus frequency) applied in the proposed algorithm can be given as in Eqs. (3.1), (3.2), and (3.3).

$$ACE_i = \Delta P_{tie,i} + \beta_i \cdot \Delta f_i \quad (3.1)$$

$$\Delta P_{tie,i} = \sum_{j=1}^{TL_i} (P_{sch,j} - P_{act,j})_i \quad (3.2)$$

$$\Delta f_i = f_{set,i} - f_{act,i} \quad (3.3)$$

In these equations, index i represents the area index. The term ACE_i denotes the control error for area i , computed as the sum of the total tie-line power deviation $\Delta P_{tie,i}$ and the frequency deviation Δf_i multiplied by the bias factor β_i . The tie line deviation $\Delta P_{tie,i}$ is calculated as the sum of the differences between scheduled power flows $P_{sch,j}$ and actual power flows $P_{act,j}$ across all TL_i tie-lines in area i . The frequency deviation Δf_i is the difference between the setpoint frequency $f_{set,i}$ and the actual frequency $f_{act,i}$.

The AGC operates as a closed-loop system that continuously drives the ACE value toward zero by adjusting generation in real time. The required generation adjustment is calculated using a PI control structure, as shown in Eq. (3.4).

$$P_{REQ,i} = P_{GAIN_i} \cdot ACE_i + \frac{1}{T_i} \int ACE_i dt \quad (3.4)$$

Here, $P_{REQ,i}$ represents the total required change in generation for area i , P_i is the proportional gain, and T_i is the integral time constant of the PI controller ($IGAIN^{-1}$).

After determining the total required generation adjustment, the AGC distributes this value among the available reserve units using pre-defined participation factors. This allocation is given by Eqs. (3.5) and (3.6).

$$P_{set,k,i} = P_{REQ,i} \cdot a_{k,i} \quad (3.5)$$

$$\sum_{k=1}^{R_i} a_{k,i} = 1 \quad (3.6)$$

In these expressions, k refers to the index of a generating unit in area i , $P_{set,k,i}$ is the power setpoint for unit k , $a_{k,i}$ is the participation factor of unit k , typically derived from ancillary market orders. The number of active reserve units in area i is denoted by R_i , and the sum of all participation factors must equal one to ensure correct proportional distribution.

Finally, the bias factor for each area is determined dynamically based on the installed capacity of the available generators. This ensures fair and accurate scaling of frequency response among areas, particularly during splitting scenarios. The calculation is given by Eq. (3.7):

$$\beta_i = \beta_{total} \cdot \frac{\sum_{k=1}^{R_i} P_{gen,k,i}}{\sum_{j=1}^N \sum_{k=1}^{R_j} P_{gen,k,j}} \quad (3.7)$$

In this equation, β_i is the bias factor assigned to area i , and β_{total} is the total bias factor of the entire interconnected system before split. The term $P_{gen,k,i}$ represents the installed capacity of generator k in area i , and R_i is the number of generators in area i . The denominator sums up the installed capacities of all generating units across all N areas formed after the system has split.

This proportional method ensures that larger areas with more installed generation capacity are assigned higher bias factors, thereby contributing more actively to frequency stabilization. It aligns with ENTSO-E recommendations for distributed frequency control and supports balanced ACE correction in a multi-area environment.

3.1.2 The Area Management

The Area Management stage serves as a critical decision-making layer within the proposed AGC architecture, enabling real-time structural adaptation of the control scheme during both normal operation and network separation events. In large-scale interconnected systems, such as those governed by ENTSO-E, disturbances or faults may lead to partial system islanding, rendering traditional centralized AGC approaches ineffective. To address this challenge, the Area Management module continuously monitors frequency measurements with the user-defined inputs to detect incoherencies among generator units, identify splitting, and dynamically partition the network into independently controlled AGC areas. Once areas are identified, the system verifies their operability based on active generation capacity and recalculates essential control parameters such as assigned frequencies, control modes, and bias factors for each region. Besides, the AGC parameters including efficient I_{GAIN} values and the updated reserve activation strategy are also set during this phase to ensure reliable control under the new system topology. Furthermore, the module enables merging of areas once synchronization conditions are met, transitioning the control scheme back to its centralized form. This flexible and autonomous design ensures that the AGC remains operational and compliant with ENTSO-E requirements under various system topologies. The full logic and operation flow of the Area Management are presented in Figure 3.3, encompassing four key sub-processes: Splitting Detection, Determination of Split Areas, Determination of New Area Parameters, and Merging Detection.

As shown in Figure 3.3, the area management process begins with Splitting Detection, where generator frequency measurements are evaluated for coherency. The frequency differences between adjacent generator pairs, $\Delta f_{\text{gen}_{k-1,k}}$, are computed and sorted. If any deviation exceeds a predefined threshold f_{thres} , the system considers this an indication of a potential network separation. Otherwise, the AGC continues in normal operation mode.

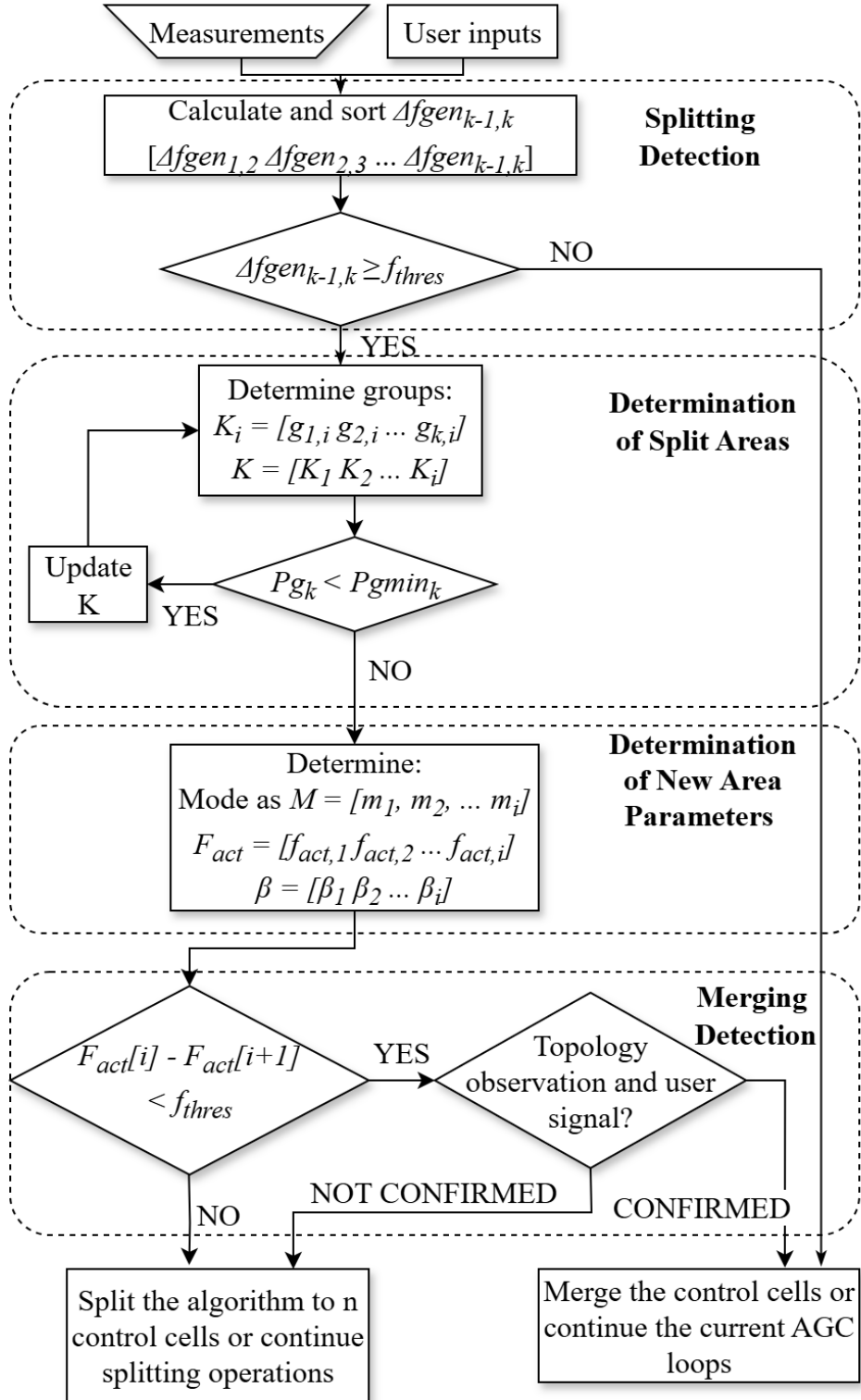


Figure 3.3. The flowchart of the area management

If a potential split is detected, the algorithm proceeds to the Determination of Split Areas. In this phase, generating units are evaluated into coherent groups $K_i = [g_{1,i} g_{2,i} \dots g_{k,i}]$, forming a complete area configuration $K = [K_1 K_2 \dots K_i]$. After initial grouping, the current generator dispatch Pg_k in each area is evaluated against a predefined minimum dispatch threshold $Pgmin_k$. If a generator's dispatch falls below this limit, it is considered operationally insufficient and excluded from the group and AGC process by updating the group set K . This step ensures that only sufficiently resourced areas are managed by the AGC algorithm.

Next, the Determination of New Area Parameters is performed for each valid control area. This involves assigning a control mode vector $M = [m_1 m_2 \dots m_i]$, selecting the frequency inputs $F_{act} = [f_{act,1} f_{act,2} \dots f_{act,i}]$ to be used for ACE calculations in the corresponding control area, and recalculating area-specific bias factors $\beta = [\beta_1 \beta_2 \dots \beta_i]$ based on the installed generation capacity. These parameters are essential to initialize independent PI-based AGC loops in each split area. Besides, I_{GAIN} values based on the look-up table and the updated reserve activation strategy are determined in this part.

Finally, the system enters the Merging Detection phase. It continuously monitors the frequency differences between adjacent areas. If the absolute difference between assigned frequencies of two areas $F_{act}[i] - F_{act}[i + 1]$ is less than the threshold f_{thres} , the system checks for additional confirmation such as operator input or automatic topology detection. If merging is confirmed, the previously separated AGC loops are recombined into a unified control loop. If merging is not confirmed, the algorithm maintains the independent loops with continually evaluating splitting conditions.

3.2 The Adaptive Control Approach

This section outlines the rationale and design of adaptive control approach, including two complementary and hybrid mechanisms: dynamic PI control, which operates

under normal conditions using real-time ACE response characteristics, and adaptive PI control, which is specifically utilized for system separation scenarios using a pre-calculated gain look-up table derived from system parameters.

3.2.1 Dynamic PI Control

Traditional PI controllers in AGC typically operate with fixed parameters, which may not be adequate for handling the increasingly dynamic behavior of modern power systems. To address this, a dynamic PI control strategy is introduced in the proposed AGC scheme, in which the I_{GAIN} is adaptively adjusted in real-time based on normal operating conditions.

The dynamic I_{GAIN} approach adjusts the gain value as a function of the difference between the ACE and ACS within each AGC control cycle. This relationship enables the controller to fine-tune its responsiveness depending on the system's current area error. The proposed method defines the I_{GAIN} adaptation using an interpolation-based framework as described in Eqs. (3.8), (3.9) and (3.10):

$$Y = [y_1, y_2, \dots, y_d]^T \quad (3.8)$$

$$V = [v_1, v_2, \dots, v_d]^T \quad (3.9)$$

$$I_{GAIN}^* = func_{int}(ACE^*, ACS^*) \quad (3.10)$$

Here, Y is the vector of known 2D input coordinates, where each $y_d = (ACE, ACS)$ represents a pair of data points obtained from prior simulations or system knowledge, and V contains the corresponding predefined I_{GAIN} values. In each AGC loop, a new operating point (ACE^*, ACS^*) is identified, and the interpolating function $func_{int}$ estimates the appropriate control gain I_{GAIN}^* for that point based on the surrounding values in Y and V . Linear interpolation is used to provide a smooth and computationally efficient gain update across the control space.

This model-free adaptive control approach offers several advantages over traditional fixed-gain or optimization-based controllers. By using the interpolation method described in [41], the need for explicit system modeling is eliminated, making the approach highly flexible and well-suited for real-world systems characterized by uncertainty and variability. Moreover, unlike computationally intensive optimization routines, the proposed method enables fast, real-time adaptation of control parameters with minimal computational overhead. As a result, the AGC system becomes more responsive and robust across a wide range of operating scenarios, including normal operation, contingency response, and early phases of system splitting. However, the determination of suitable (ACE, ACS) input pairs for dynamic gain tuning remains a significant challenge, especially considering the infinitely many possible splitting scenarios and system configurations for real and large power systems. To address this limitation, a more systematic and scalable adaptive PI control approach is introduced in the following section for splitting conditions.

3.2.2 Adaptive PI Control

While the dynamic PI control method offers a practical solution under normal operating conditions, its effectiveness is significantly reduced in the context of power system splitting especially for larger networks. The core challenge lies in the difficulty of identifying and correlating appropriate boundary points for different splitting cases. Since each separation results in unique area configurations and dynamic behaviors, the ACE-ACS relationship used for tuning the dynamic I_{GAIN} may become unreliable. As a result, the dynamic method lacks generalizability and cannot guarantee stable or effective performance across varying islanding scenarios.

To address this limitation, a more structured and scenario-based adaptive PI control methodology is developed. This approach aims to generalize the I_{GAIN} tuning process using pre-analyzed grid characteristics and real-time adaptive control logic. The full methodology is outlined as in six steps:

- Step 1: Analyze the corresponding power system and identify a minimum set of representative splitting scenarios that capture realistic and impactful network separations.
- Step 2: For each scenario, determine the key network parameters, such as Total Load, FRR, Total Inertia (H), and Total Inertia Contribution ($\sum H \cdot P$).
- Step 3: Simulate each scenario under various initial ACE values and determine the effective I_{GAIN} for each case using a heuristic trial-and-error approach. The selection is based on criteria such as minimal overshoot, fast settling time, and ACE convergence within ENTSO-E-compliant limits.
- Step 4: Perform a correlation analysis to evaluate the linear relationships between I_{GAIN} values and the recorded network parameters. The aim is to find the most correlated parameter.
- Step 5: Construct a two-dimensional look-up table to be used in splitting conditions using ACE and the selected network parameter from the correlation analysis as inputs, with corresponding I_{GAIN} values as outputs.
- Step 6: Perform a bilinear interpolation to estimate an appropriate I_{GAIN} if the current values do not exactly match a table entry, ensuring a smooth and accurate control response even under unlisted operating points.

Details of each step are given in the following paragraphs.

Step 1 – Selection of representative splitting scenarios

The first step of the adaptive PI control methodology involves analyzing the power system to determine representative and realistic splitting scenarios. This step lays the foundation for constructing a lookup-based adaptive AGC strategy, as the effectiveness of the method depends on diversity and plausibility of the scenario set.

To achieve generalization and ensure broad applicability, the scenario selection is guided by both practical grid behavior and established literature on coherency, islanding, and cascading failures. Some key studies were used to structure this analysis and identify typical conditions under which system separation may occur:

- **Coherency Identification and Islanding:** Zhang et al. [42] emphasize the importance of real-time coherency analysis for designing reliable islanding strategies. Their work highlights that traditional static methods are insufficient for modern, dynamic grids particularly those with significant renewable integration. The recommendation to group generators based on dynamic coherency behavior under varying operating conditions directly informs the spatial definition of balanced and stable islands.
- **Topological Weaknesses in the Turkish Grid:** Schäfer and Yalcin [43] model the Turkish power system and identify structural vulnerabilities, particularly in systems with centralized generation and limited east-west transfer capacity. These findings directly support the definition of Scenario 1, which reflects the seasonal power transfer stress from Eastern hydro resources.
- **Low-Inertia Challenges in Small Islands:** Kock et al. [44] examine frequency deviations in small, isolated islands and emphasize the difficulty of maintaining stability with limited control and reserve capacity. This insight motivates Scenario 3, which isolates a weak, under-resourced area to evaluate AGC performance under severe imbalance conditions.

Based on these studies and a review of the Turkish Transmission System's structural and operational characteristics, three primary splitting scenarios are initially established:

1. **High east-to-west transfer with weak transmission corridor (Scenario 1)** – Representing seasonal hydro-driven power export and east-west congestion risk.
2. **Balanced split with similar generator and inertia distribution (Scenario 2)** – Serving as a benchmark to assess controller performance under stable and coherent conditions.

3. **Small-area isolation with minimal control resources (Scenario 3)** –
Simulating a highly asymmetric separation with limited inertia and reserve capacity.

Each of these scenarios reflects a distinct operating condition, control challenge, and system behavior. Besides splitting, there is a base scenario that represents the network operating, with no splitting, where the AGC controls the entire grid as normal operation mode (frequency + tie-line control). Together, they help to provide a comprehensive testbed for developing and validating the proposed adaptive AGC scheme under realistic separation conditions.

Step 2 – Determination of network parameters for each scenario

Once the representative scenarios are defined, the next step is to systematically extract and record the relevant network parameters for each area involved. These parameters capture the dynamic and structural characteristics of the post-splitting system and form the input dataset for identifying effective I_{GAIN} parameters in the following steps. For each scenario and corresponding control area, the following key metrics are recorded:

- Number of Total Units and AGC-Controlled Units: Reflects the scale and controllability of the generation portfolio.
- Total Installed Capacity (MW) and Total Load (MW): Indicate the generation-load balance within each area.
- Available Frequency Restoration Reserves (FRR): Determines the flexibility available for ACE correction.
- Total Inertia Contribution ($H \cdot P$, in $\text{GW} \cdot \text{s}$): Represents the product of inertia and rated power, capturing the area's ability to resist frequency deviations.
- Average Inertia (H , in seconds): Represents the system's energy storage in rotating mass and is used to assess dynamic performance.

These values are summarized in Table 3.2, covering the base (non-splitting) case as well as three splitting scenarios, each comprising two independently controlled

areas. These metrics directly influence the system's frequency stability, control responsiveness, and reserve deployment capability, which are critical in identifying the relationship between system parameters and I_{GAIN} values required for stable AGC performance. They also form the basis of the correlation and interpolation strategy detailed in subsequent steps.

Table 3.2. Network parameters for scenarios

Scenarios	# of total units	# of AGC units	Total Capacity (MW)	Total Load (MW)	Total FRR (MW)	Total H-P (GW·s)	Total Inertia (s)
NoSplit-Base	120	104	43977.3	21938	1612.0	253.7	5.769
ENTSO-E side (Area-1)							
Split-Scn-1	78	66	30024.4	13253	896.9	179.6	5.982
Split-Scn-2	53	47	20390.5	10306	668.1	123.2	6.046
Split-Scn-3	113	97	42536.0	20860	1504.2	246.2	5.789
Isolated (Area-2)							
Split-Scn-1	42	38	13952.9	8685	715.1	74.1	5.311
Split-Scn-2	67	57	23586.8	11632	943.9	130.4	5.529
Split-Scn-3	7	7	1441.3	1078	107.8	74.8	5.189

Step 3 – Determination of effective I_{GAIN} values

In this step, effective I_{GAIN} values are systematically determined for each splitting scenario and ACE level using a structured heuristic procedure. The primary objective is to identify gain values that enable fast and stable ACE recovery while avoiding overshoot or oscillatory behavior, which is particularly important under the altered dynamic conditions introduced by system separation.

Given the complexity and nonlinearity of AGC performance in large-scale power systems, a trial-and-error approach is adopted, as detailed modeling is often

impractical for real-world applications [45]. For each scenario and associated ACE level, I_{GAIN} is iteratively tuned through a stepwise process until a satisfactory dynamic response is achieved. The following procedure outlines the applied heuristic algorithm:

0. Disable the merging functionality by setting the frequency difference threshold to zero and initiate the predefined splitting event for the corresponding scenario.
1. Introduce a recurring stepwise ACE disturbance every 15 minutes, applied both independently and simultaneously to each control area. This setup creates a consistent testing environment with repeatable error injections.
2. Initialize I_{GAIN} to a base value, typically derived from the non-splitting (reference) condition.
3. After each disturbance, assess the system's ACE response:
 - a. If an overshoot (or oscillations) is observed, decrease I_{GAIN} by 0.005 and wait for the next disturbance cycle.
 - b. If the response is overshoot-free, increase I_{GAIN} by 0.005 and re-assess.
4. Upon detecting a reversal in the I_{GAIN} adjustment direction (i.e., switching from increasing to decreasing or vice versa), the step size is reduced to 0.001 to enable fine-tuning with sufficiently high resolution.
5. During this refined adjustment phase, the last overshoot-free setting is recorded as the effective and acceptable I_{GAIN} for the specific ACE level and scenario.

This method ensures that the selected gain is sufficiently aggressive to provide responsiveness while remaining conservative enough to prevent instability. Performance is evaluated based on key control metrics such as settling time, damping characteristics, and the elimination of overshoot in the ACE response. The resulting effective I_{GAIN} values are subsequently used to populate the scenario-based look-up table for real-time adaptive control during AGC operation.

Step 4 – Correlation analysis

After determining the effective I_{GAIN} values for each splitting scenario and ACE level, the next step is to understand how these gains are influenced by the underlying network conditions. To determine the network parameters that have the strongest influence on the calculated I_{GAIN} values, a correlation matrix using Pearson correlation coefficients is computed [46]. Pearson correlation is chosen for its simplicity and effectiveness in identifying linear relationships between network parameters and I_{GAIN} values. The correlation was determined as in Eq. (3.11).

$$\rho_{I_{GAIN}, X} = \frac{cov(I_{GAIN}, X)}{\sigma_{I_{GAIN}} \sigma_X} \quad (3.11)$$

where $\rho_{I_{GAIN}, X}$ is the correlation coefficient between I_{GAIN} and network parameter X , $cov(I_{GAIN}, X)$ represents the covariance between the effective I_{GAIN} values and the parameter X and $\sigma_{I_{GAIN}}$ and σ_X are the standard deviations of I_{GAIN} and the parameter X , respectively.

The primary objective of this study is to obtain more effective I_{GAIN} values following network splitting events, based on the prevailing system conditions at the time of separation. To achieve this, it is necessary to identify a network parameter that shows strong correlation with I_{GAIN} and is also measurable in real time. Among several possible candidates, four parameters were selected for analysis due to their relevance to system dynamics and practical observability: Total Load, Frequency Restoration Reserve (FRR), Total Inertia Contribution ($\sum H \cdot P$), and Average Inertia (H). Table 3.3 shows the Pearson correlation coefficients between the optimal I_{GAIN} values and the network parameters.

The aim of this step is to establish a correlation-based methodology that enables adaptive I_{GAIN} selection during future splitting events, thereby improving control performance. As shown in Table 3.3, the correlation analysis reveals that in Area-1, which remains connected to the ENTSO-E network, Total Inertia Contribution ($\sum H \cdot P$) exhibits the strongest and most consistent negative correlation with I_{GAIN} . In

contrast, in Area-2, which operates in island mode, Average Inertia (H) shows the highest negative correlation with I_{GAIN} .

To further assess the possible effect of ENTSO-E side regarding the inertia, additional correlation analyses were conducted including ENTSO-E generators. These analyses showed that while $\sum H \cdot P$ remained strongly correlated with I_{GAIN} , the average inertia values became nearly identical across different splitting scenarios due to the large dominance of ENTSO-E units (e.g., 5.894, 5.893, 5.869 seconds), resulting in low sensitivity and poor discriminative power. Although a positive correlation was still observed, the lack of variation in H limited its practical utility (see Appendix A).

Therefore, for methodological consistency and practical implementation, $\sum H \cdot P$ was chosen as the common input for I_{GAIN} estimation in both areas. Even though it is not the most dominant driver in Area-2, it still yields acceptable and stable results and enables a unified framework for real-time control adaptation. Moreover, since ENTSO-E units are not under the operational control of the Turkish AGC, excluding them from the calculation ensures that the gain estimation remains representative of the controllable system.

From a control theory perspective, this approach is well-grounded. System inertia buffers frequency deviations by slowing the rate of change of frequency (RoCoF), allowing lower I_{GAIN} values to restore ACE without causing instability, in line with established load-frequency control principles [1], [47]. Furthermore, in high-inertia systems with strong generation and grid strength, slower frequency dynamics may cause ACE to persist longer, leading to excessive integral accumulation if I_{GAIN} is not properly reduced. This may result in overshoot during ACE correction, highlighting the importance of I_{GAIN} tuning in such conditions and reinforcing the observed negative correlation between $\sum H \cdot P$ and I_{GAIN} in this study.

Table 3.3. The correlation table

	Area-1				Area-2			
ACE Levels (MW)	600	480	280	140	130	100	80	60
Total Load (MW)	-0,868	-0,893	-0,962	-0,987	-0,874	-0,959	-0,924	-0,920
FRR (MW)	-0,862	-0,887	-0,959	-0,985	-0,772	-0,892	-0,840	-0,840
$\Sigma H \cdot P$ (MW·s)	-0,989	-0,964	-0,997	-0,999	-0,887	-0,966	-0,933	-0,930
H (sec)	0,856	0,882	0,956	0,982	-0,964	-0,998	-0,987	-0,990

Step 5 – Construction of the Look-up table

Following the correlation analysis, a two-dimensional look-up table is constructed to assign effective I_{GAIN} values based on Total Inertia Contribution and the initial ACE level. This table forms the core of the proposed adaptive AGC strategy, enabling the controller to dynamically adjust its gain settings in response to real-time system conditions, especially after splitting events. Table 3.4 shows the look-up table for effective I_{GAIN} parameters based on Total Inertia Contribution and ACE.

Table 3.4 is populated using the effective I_{GAIN} values previously identified through simulation (Step 3). Total Inertia Contribution is selected as the single network parameter for constructing the look-up table across all areas and scenarios. Each table entry corresponds to a unique combination of ACE level and $\Sigma H \cdot P$, mapping these input pairs to an effective I_{GAIN} value that demonstrated satisfactory AGC performance during offline testing.

Table 3.4. The look-up table for Area-1 and Area-2

$\Sigma H \cdot P$ (MW·s)	ACE (MW)	I_{GAIN}	$\Sigma H \cdot P$ (MW·s)	ACE (MW)	I_{GAIN}
Area-1			Area-2		
120,000	600	0.027	7,500	130	0.066
120,000	480	0.03	7,500	100	0.088
120,000	280	0.035	7,500	80	0.099
120,000	140	0.04	7,500	60	0.107
180,000	600	0.017	75,000	130	0.065
180,000	480	0.02	75,000	100	0.083
180,000	280	0.03	75,000	80	0.096
180,000	140	0.038	75,000	60	0.104
250,000	600	0.013	130,000	130	0.056
250,000	480	0.015	130,000	100	0.072
250,000	280	0.025	130,000	80	0.085
250,000	140	0.035	130,000	60	0.093

During a system splitting event, the proposed AGC scheme dynamically determines the appropriate I_{GAIN} using the look-up table. As soon as the split is detected, two key values are calculated for each resulting control area: ACE value at the moment of splitting and the Total Inertia Contribution of the area. These two parameters serve as the input coordinates to access the lookup table populated with effective I_{GAIN} values obtained through offline analysis. If the exact pair is not found in the table, a bilinear interpolation is applied (as explained in the final step) to compute the most suitable I_{GAIN} for the given conditions. This ensures that each isolated area continues operating with an integral gain specifically tailored to its real-time state, enabling faster ACE correction and enhanced frequency regulation during the most critical post-splitting period.

Step 6 – The Usage of I_{GAIN}

As a final step, the corresponding I_{GAIN} value is selected and used from the lookup table. If the values fall between table entries, the algorithm performs bilinear interpolation [48] to estimate the near-effective I_{GAIN} , ensuring a smooth and accurate control response. However, in cases where the target values lie outside the bounds of the table (i.e., extrapolation is required), the methodology is slightly adapted as a two-step linear extrapolation, first along the ACE axis for each fixed total inertia contribution level, and then across $\sum H \cdot P$ values. This alternative approach better preserves the expected control behavior under extreme conditions and avoids the limitations of direct bilinear extrapolation in edge regions.

This adaptive interpolation strategy enables the AGC system to maintain an effective ACE response across a wide range of system conditions, including varying network topologies and splitting scenarios encountered in real-world applications. The formulation of bilinear interpolation used to compute the interpolated point I_{GAIN} (C, A) is provided in Eq (3.12).

$$\begin{aligned} I_{\text{GAIN}}(C, A) = & I_{11} \cdot \frac{(C_2 - C)(A_2 - A)}{(C_2 - C_1)(A_2 - A_1)} + I_{12} \cdot \frac{(C_2 - C)(A - A_1)}{(C_2 - C_1)(A_2 - A_1)} \\ & + I_{21} \cdot \frac{(C - C_1)(A_2 - A)}{(C_2 - C_1)(A_2 - A_1)} + I_{22} \cdot \frac{(C - C_1)(A - A_1)}{(C_2 - C_1)(A_2 - A_1)} \end{aligned} \quad (3.12)$$

Here, C denotes the current Total Inertia Contribution and A is the current ACE. The algorithm first identifies the four surrounding grid points in the table: (C_1, A_1) , (C_1, A_2) , (C_2, A_1) , and (C_2, A_2) , along with their corresponding I_{GAIN} values: I_{11} , I_{12} , I_{21} , and I_{22} . The interpolated gain $I_{\text{GAIN}}(C, A)$ is then calculated.

3.3 The Reserve Activation Strategy

Lastly, this study introduces an improved reserve activation strategy specifically tailored for grid splitting conditions. Utilizing the SLSQP method [49], reserve

activation is enhanced within each AGC control loop to ensure the efficient deployment of automatic FRR. The primary objective of the strategy is to maximize the area under the production curve, enabling selective and gradual activation of reserves across multiple generating units within a defined time horizon. In this study, the term "optimal reserve activation" refers to the solution obtained using the SLSQP method, which efficiently solves the defined problem under given constraints. While alternative methods were not benchmarked, the SLSQP-based activation provides a feasible and effective schedule that adheres to operational requirements and improves AGC performance.

This optimization framework accounts for several critical constraints, including generator ramp rate limits, minimum and maximum power outputs, and the minimum required time intervals between successive reserve activations. By identifying the best activation time points and rate adjustments, the model produces a dynamic reserve activation schedule, allowing the AGC system to manage unit outputs in real time. This enhances ACE performance for each separated area, effectively supporting the system during grid splitting and reconnection events. The formulation is given in Eqs. (3.13), (3.14), (3.15), and (3.16).

$$\min - \int_{t_0}^{t_f} \sum_{k=1}^R P_k(t) dt \quad (3.13)$$

$$P_{min,k} \leq P_k(t) \leq P_{max,k}, \quad \forall k \text{ in } R \quad (3.14)$$

$$\left| \frac{dP_k(t)}{dt} \right| \leq Ramp_k, \quad \forall k \text{ in } R \quad (3.15)$$

$$t_{k,j+1} - t_{k,j} \geq \Delta t_{min}, \quad \forall k, j \quad (3.16)$$

In this part, $P(t)$ is the total production from AGC units as a function of time, t_0 is the initial time of the SLSQP, and t_f is the final time. $P_{min,k}$ and $P_{max,k}$ are the minimum and maximum power output limits for unit k , respectively. $Ramp_k$ is the

ramp rate limit for unit k . $t_{k,j}$ represents the time of the j^{th} activation for unit k , and Δt_{min} is the minimum time interval between reserve activations.





CHAPTER 4

MODELLING AND SCENARIOS

This chapter presents the modelling framework and simulation scenarios developed to validate the AGC scheme described in Chapter 3. The scenarios are designed to evaluate the performance of the AGC strategy under both normal and disturbed conditions, with a particular focus on network splitting and reconnection events. Two different test systems are utilized: a modified IEEE 9-bus system and a representative Turkish transmission network. This setup enables a comprehensive performance assessment of the proposed control strategies across diverse system topologies and operational challenges, using the SIL test environment developed in this study.

4.1 The Simulation and Testing Environment

To validate the proposed AGC strategy, a comprehensive SIL simulation environment was developed, which integrates four key interfaces: A Python-based platform for both developing and executing the proposed AGC algorithm; a power system analysis tool (DIgSILENT PowerFactoryTM) for conducting real-time dynamic Root Mean Square (RMS) simulations and modelling; a Graphical User Interface (GUI) for facilitating user interaction, control configuration, and scenario management; and an Open Platform Communication (OPC) interface to enable synchronized, real-time data exchange between all system components, as illustrated in Figure 4.1. This integrated setup ensures accurate, closed loop testing of the AGC under realistic operating conditions, supporting repeatable assessments across a wide range of scenarios.

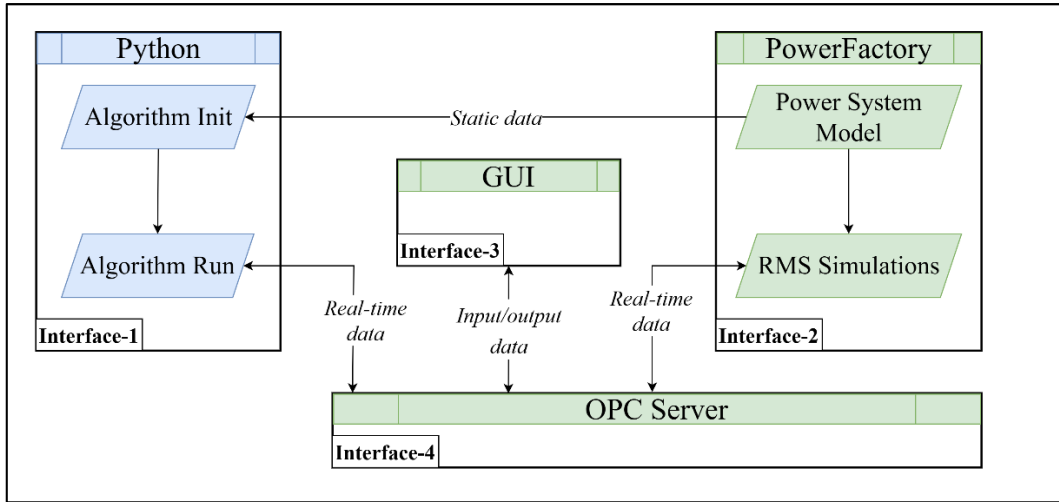


Figure 4.1. The structure of the simulation and testing environment

The overall process begins with the transfer of static power system data from PowerFactory™ to the Python, with some pre-processing and formatting. All static system data are prepared as Comma-Separated Value (CSV) files and loaded via Interface-1, enabling flexible integration and customization for various test systems. The following input files are used to initialize the AGC algorithm (see Appendix B for details):

- **Generator Definition File:** Contains the AGC status, reserve capacities, base generation values, minimum and maximum active power limits, and ramp rate constraints for each generator unit participating in AGC.
- **Line Definition File:** Provides the list of transmission lines, including names, breaker information, flow directions, and power flow measurements.
- **Busbar Definition File:** Includes busbar identifiers, names, and tags for system visualization and control mapping.
- **Generator Daily Schedule Program File:** Specifies daily schedule of generators (15-min time interval) in terms of base power, FCR and FRR.

Once initialized, time-domain RMS simulations are launched within PowerFactory™ through Interface-2, simulating system dynamics over time. In

parallel, the Python-based AGC algorithm continuously exchanges real-time measurement and control data with PowerFactory™ via the OPC interface (Interface-4). The GUI (Interface-3) serves as a supervisory layer, allowing the operator to adjust control loop intervals, switch between control modes, and modify reserve settings during simulation runs.

This modular and real-time SIL environment enables thorough testing of AGC performance across a wide range of system configurations, disturbances, and splitting conditions. It serves as a flexible, scalable, and ENTSO-E-compliant testbed for validating the effectiveness of the proposed control framework.

4.2 Modelling

To evaluate the proposed AGC strategy under various system complexities and operating conditions, two distinct test networks were developed and implemented in the simulation platform: A modified IEEE 9-bus system and a representative Turkish transmission network. These systems serve different validation purposes:

- The IEEE test network is primarily used to internally verify the simulation environment and to test the basic control logic of the developed AGC scheme under simplified and controlled conditions.
- The Turkish system supports a more realistic and comprehensive assessment of the AGC framework, including dynamic area control and adaptive I_{GAIN} tuning under system splitting and reconnection scenarios.

This approach allows for a staged validation of the AGC described in Chapter 3.

4.2.1 The Nine-Bus IEEE Test Network

The IEEE test network, as shown in Figure 4.2, was modeled in PowerFactory™, incorporating essential static and dynamic elements. A key modification involves the addition of an adjacent external system, modeled as a dynamic generator with its

own PI-based AGC. This external grid represents tie-line coordination and allows for emulation of adjacent load-frequency control behaviors during steady-state and disturbed conditions.

The proposed AGC is implemented on the main grid comprising three synchronous generators (G1, G2, and G3) all of which are governed by the AGC scheme. Given that Automatic Voltage Regulators (AVRs) and Power System Stabilizers (PSSs) have minimal impact on frequency control, only dynamic governor models are considered in the simulations. Each generator actively participates in FCC, thereby contributing to the provision of FCR. The grid includes three different types of generators (Power Plants (PP)): Hydro, gas, and thermal. Priority levels are assigned to these generator types with the aim of observing the stepwise engagement of different generator groups during control actions. The parameters of the IEEE test network utilized in the study are presented in Table 4.1.

The setup with the IEEE test network is mainly used to verify the correct implementation of control loops, reserve-sharing logic, tie-line regulation, and the dynamic I_{GAIN} mechanism introduced in Section 3.2.1.

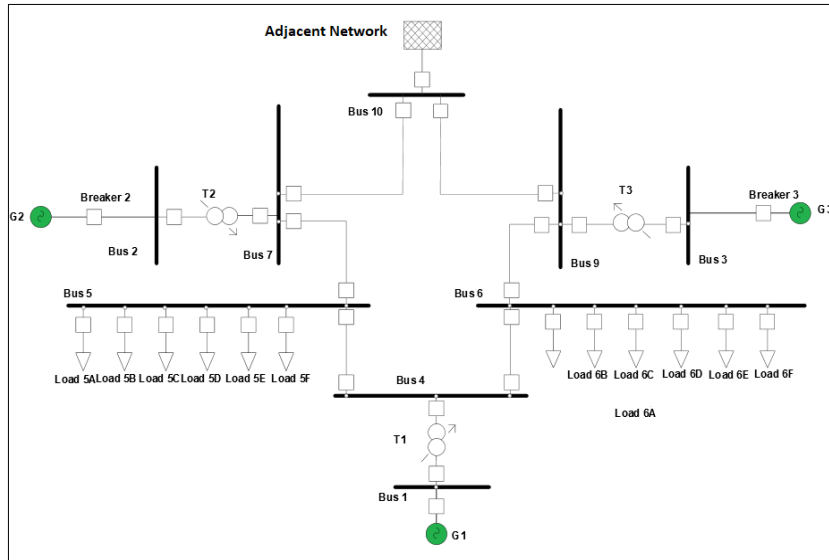


Figure 4.2. Single-line diagram of the IEEE test network

Table 4.1. Network parameters for the IEEE test network

	<i>Type</i>	<i>Base P</i>	<i>FCR</i>	<i>FRR</i>	<i>Priority</i>
G ₁	Hydro PP	120 MW	24 MW	24 MW	1st
G ₂	CCPP	80 MW	16 MW	16 MW	2nd
G ₃	Thermal PP	50 MW	10 MW	10 MW	3rd

4.2.2 The Representative Turkish Transmission System

The dynamic model of Turkish transmission network, shown in Figure 4.3, was modeled in PowerFactory™, integrated with a simplified ENTSO-E model to simulate realistic tie-line behavior. This system was designed to evaluate the AGC scheme under real-world operational complexity, including more complex splitting conditions, frequency stability challenges, and adaptive control strategies. To balance detail and computational efficiency, the model includes the following assumptions:

- All units and loads operate at the 400 kV level.
- The simulations generally assume a 22 GW total load dispatch.
- 104 generator units actively participate in AGC and PFC.
- The remaining units are modeled as aggregated equivalents per region.
- Generic governor models are used for AGC units.
- AVRs and PSSs are excluded to focus solely on active power control.
- The ENTSO-E side is represented by a single equivalent unit placed at Maritsa (Bulgaria), featuring both primary and secondary control.

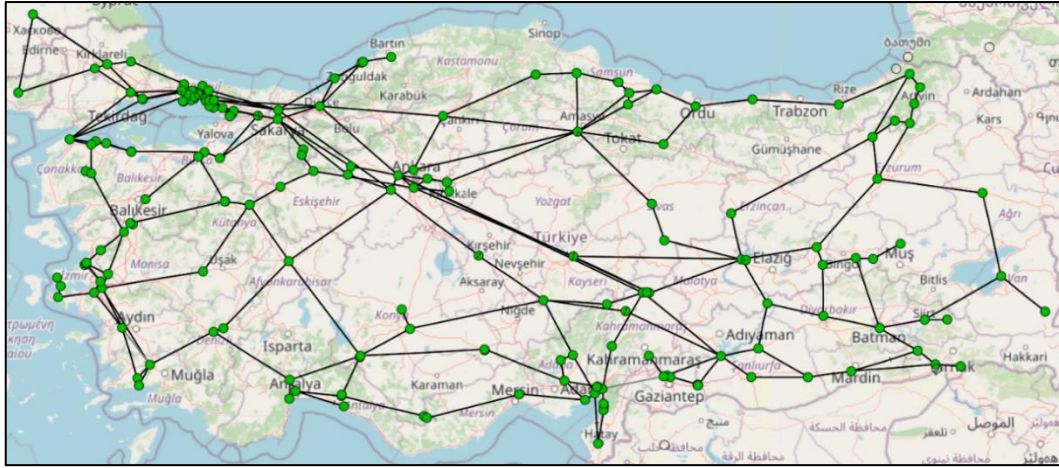


Figure 4.3. Representative Turkish Transmission System

4.3 The Simulation Scenarios

To evaluate the effectiveness of the proposed AGC scheme under various grid conditions, four simulation scenarios are designed and implemented including also a sensitivity analysis. Each scenario consists of multiple cases that reflect different operating states, such as normal operation, load disturbances, and controlled system splitting events. These scenarios are executed using both the IEEE 9-bus test system and a representative and simplified model of the Turkish Transmission System.

Throughout all scenarios, the AGC operates with a default control cycle of 4 seconds, configurable between 1 and 5 seconds to comply with ENTSO-E operational standards. During each control loop, the algorithm processes real-time measurements of frequency, active power output, and tie-line power flow. Based on the configuration of each case, it applies either a dynamic or adaptive I_{GAIN} control strategy to regulate the ACE and ensure frequency stability.

In splitting-related scenarios based on the Turkish Transmission System, specific conditions are applied to determine valid system separations and reconnections. While ENTSO-E generally considers frequency differences exceeding 0.2 Hz as an

indicator of splitting, and below 0.1 Hz as a condition for merging based on previous events [6], this study adopts stricter thresholds of ± 0.02 Hz for splitting and ± 0.01 Hz for merging to enforce more precise event modeling. Additionally, a two-cycle delay (8 seconds) is applied before confirming any splitting action, ensuring robust detection by filtering out transient frequency fluctuations.

4.3.1 Scenario 1 – Validation of Basic Functionalities

This scenario is designed to validate the consistency and correctness of the proposed AGC scheme and the overall simulation platform using the modified IEEE 9-bus test network. It aims to evaluate whether the proposed AGC performs as expected under both nominal and disturbed operating conditions, including a simple system splitting and reconnection events. The scenario consists of three cases, each focusing on a distinct aspect of operational performance.

Case 1: Normal Operation with Load Increase

In this case, the AGC is tested under nominal operating conditions. The consumption values are set to 400 MW for the external grid and 250 MW for the main grid. Tie-line power flow is initialized to -65 MW, representing an import to the main grid. During the simulation, additional static loads are introduced into the main grid. The objective is to verify that the AGC responds appropriately by adjusting generator outputs in accordance with their reserve contribution priorities and restoring the ACE to zero. This test confirms the correct implementation of the PI control logic and reserve dispatch sequence under standard conditions.

Case 2: Splitting and Merging

This case examines the performance of the AGC during a splitting event followed by a reconnection. The network is divided into two areas as shown in Figure 4.4. Area-1, which includes generator G2 and remains synchronized with the external grid, and Area-2, which becomes an isolated system. Following the split, the AGC changes the operational mode of Area-2 to sole frequency control mode and keeps

Area-1 in the tie-line plus frequency control mode. This case verifies the algorithm's ability to detect the splitting, reconfigure control loops accordingly, and maintain stable ACE values in both areas. It also assesses the AGC's capability to re-merge the two areas into a unified control structure once the synchronization is re-established.

Case 3: Load Change Response under Splitting

Building upon the previous case, Case 3 focuses on evaluating the AGC response to dynamic load changes while the system is in split. After the network is divided into two control areas, a step load change is applied to Area-2 (the isolated zone). This case tests the flexibility of the AGC in handling disturbances when operating under islanded conditions. The AGC is expected to maintain frequency stability and quickly restore ACE by reallocating reserves within the isolated control area.

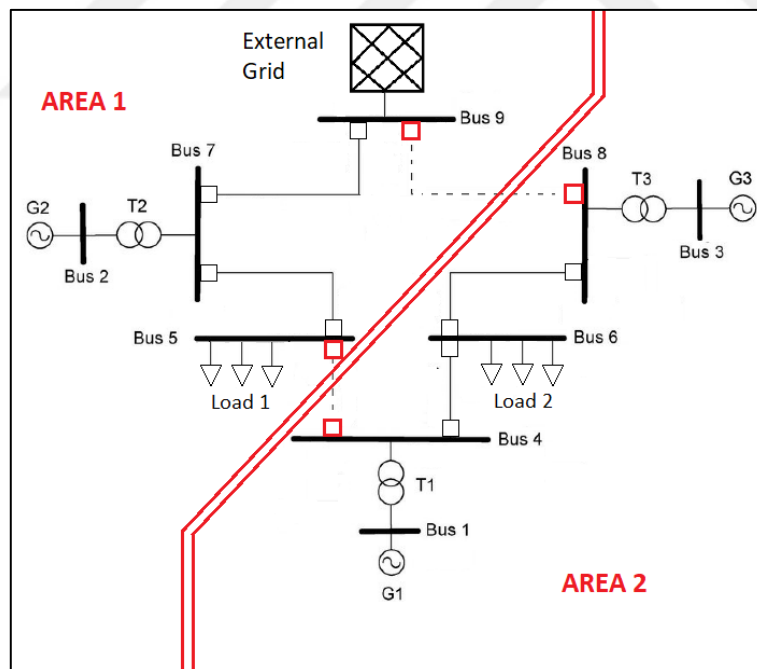


Figure 4.4. The splitting event at the 9-bus IEEE test network

4.3.2 Scenario 2 – Dynamic Control Evaluation on the IEEE Network

Scenario 2 focuses on evaluating the dynamic PI control methodology described in Chapter 3.2.1 for the modified IEEE 9-bus test network. The behavior of the proposed approach is assessed under both normal and splitting conditions. The key objective is to compare the performance of conventional (with fixed integral gain) and dynamic (with dynamic I_{GAIN}) PI control in various operating states. This scenario is composed of five cases that collectively assess the flexibility, robustness, and performance improvement introduced by dynamic control strategies.

Case 1: Static PI Control under Load Disturbance

This baseline case evaluates the AGC's performance under a 50 MW load disturbance while using a fixed integral gain. The case is intended to benchmark the system's frequency response and ACE behavior using conventional PI control. The ACE response time, overshoot, and settling characteristics provide reference metrics for subsequent comparisons.

Case 2: Dynamic PI Control under Load Disturbance

In this case, the same 50 MW load disturbance is applied, but the AGC employs a dynamic PI controller. I_{GAIN} is dynamically adjusted in real-time using a pre-calculated boundary table (see Table 4.2) constructed from ACE and ACS values based on heuristic approaches. The boundary range for ACE and ACS is set to ± 100 MW, considering the system's total available FRR of 50 MW. Based on these boundaries, I_{GAIN} values are iteratively tuned for each control area to improve ACE performance across all scenarios. Figure 4.5 presents 3D heat maps of I_{GAIN} values, showing their relationship with ACE - ACS pairs derived from the boundary values provided in Table 4.2. This case demonstrates the improvement in control responsiveness when compared to the static approach in Case 1.

Case 3: Static PI Control under Network Splitting

Here, a network splitting event is introduced to evaluate the AGC's response with a static I_{GAIN} value. The network is separated into two control areas, and the AGC continues to operate in a fixed parameter for both areas. The performance is analyzed in terms of the ACE stabilization and frequency recovery in each isolated zone.

Case 4: Dynamic PI Control under Network Splitting

In this case, the AGC employs dynamic I_{GAIN} values during network splitting events, with each area operating independently. As in Case 2, the integral gains are drawn from Table 4.2 defined for an ACE/ACS range of ± 100 MW. This range, again, is selected to align with the available FRR capacity, ensuring a wide enough control window to support stability in each area. The simulation assesses whether dynamic control enhances ACE recovery speed and reduces oscillations compared to the static control used in Case 3.

Case 5: Enhanced Boundary Set Application

The final case applies alternative boundary tables constructed through a simple iterative tuning process aimed specifically at improving ACE clearance efficiency under network splitting conditions. In contrast to previous cases, the original boundary table is replaced with two more efficient tables, each tailored for one of the split areas. This case demonstrates the adaptability and scalability of the proposed dynamic control framework when system-specific characteristics are mostly known after splitting. By assigning more efficient I_{GAIN} values independently to each area, the AGC can respond more aggressively to frequency deviations and ACE fluctuations. This approach is particularly useful when the topological structure of the grid is simple and can be identified in real time following a disturbance. As illustrated in Table 4.3 and Table 4.4, these revised boundary sets are found to enhance AGC performance by applying control gains better suited to each area's operating conditions, ultimately achieving faster frequency restoration.

Table 4.2. Boundary parameters for IEEE network (Case 2 & Case 4)

ACE vs ACS	-100	0	100
-100	0.025	0.04	0.05
0	0.025	0.025	0.025
100	0.05	0.04	0.025

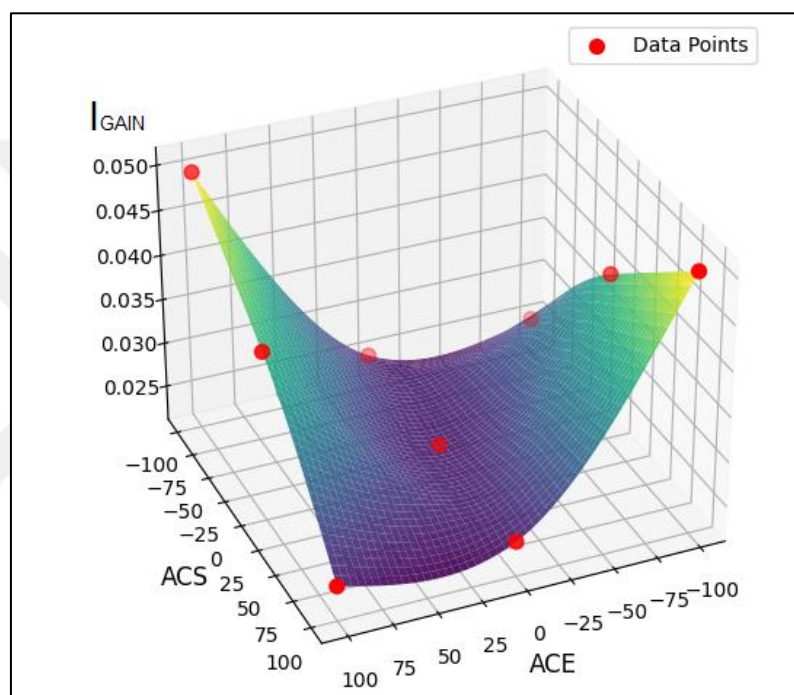


Figure 4.5. 3D heat maps of I_{GAIN} for the IEEE test network

Table 4.3. Boundary parameters for IEEE network (Area 1, Case 5)

ACE vs ACS	-100	0	100
-100	0.04	0.055	0.065
0	0.04	0.04	0.04
100	0.065	0.055	0.04

Table 4.4. Boundary Parameters for IEEE network (Area 2, Case 5)

ACE vs ACS	-100	0	100
-100	0.075	0.09	0.1
0	0.075	0.075	0.075
100	0.1	0.09	0.075

4.3.3 Scenario 3 – Dynamic Control Evaluation on the Turkish System

Scenario 3 mirrors the structure and intent of Scenario 2, but the evaluation is conducted on the dynamic model of the Turkish Transmission System. The primary aim is to validate the applicability, adaptability, and effectiveness of the proposed dynamic PI control method under more realistic, large-scale grid conditions. As in the previous scenario, five cases are analyzed, comparing conventional and dynamic AGC approaches under both normal operation and network splitting events.

The Turkish system model includes larger-scale generation and demand values, along with increased complexity in network topology. Therefore, this scenario also tests the scalability and computational feasibility of the dynamic gain adjustment strategy in more practical settings.

Case 1: Static PI Control under Load Disturbance

A 902 MW load disturbance is introduced to the system, and the AGC operates using a static I_{GAIN} . This baseline case evaluates the ACE and frequency response under fixed control parameters, serving as a reference for the impact of adaptive control.

Case 2: Dynamic PI Control under Load Disturbance

The same disturbance as in Case 1 is used, but the AGC employs a dynamic PI control strategy. The integral gain is adapted in real time using the boundary table (see Table 4.5) defined for the Turkish system, with ACE and ACS values ranging within ± 2000 MW to accommodate the higher reserve capacity. Figure 4.6 presents

3D heat maps of I_{GAIN} values, showing their relationship with ACE - ACS pairs derived from Table 4.5. This case demonstrates the improved dynamic response and faster ACE clearance achieved through gain adaptation.

Case 3: Static PI Control under Network Splitting

In this case, the Turkish system undergoes a controlled splitting event. The AGC continues to use fixed I_{GAIN} values, and the resulting ACE trends and frequency profiles in each area are monitored. The limitations of static control under large disturbances and reduced system inertia are highlighted.

Case 4: Dynamic PI Control under Network Splitting

This case applies the adaptive gain methodology to each separated area after splitting. The I_{GAIN} values are selected dynamically based on pre-established ACE/ACS boundaries that account for system size and available FRR. The goal is to assess the effectiveness of dynamic control in managing two independent control areas and maintaining stability across both.

Case 5: Enhanced Boundary Set Application

The final case explores the application of more efficient, scenario-specific boundary tables for each area following a network split. These customized boundary sets are developed through simple iterative tuning methods, with the objective of enabling more aggressive and responsive control strategies tailored to the distinct operational characteristics of each region. However, due to the large scale and increased complexity of the Turkish Transmission System, applying this methodology across the entire network is challenging. Identifying the optimal boundary sets for all possible splitting configurations becomes computationally intensive and may not be feasible in real-time applications. As such, a single and more efficient representative boundary set has been selected for demonstration purposes in this case.

While this test confirms the conceptual benefit of tailored dynamic gain adaptation post-splitting, it also highlights the practical limitations of exhaustive boundary optimization in large-scale grids. Therefore, this case serves as a transitional step

toward Scenario 4, where a more generalized and scalable approach to adaptive gain setting is proposed using system-level correlation analysis and pre-defined look-up tables based on critical network parameters.

Table 4.5. Boundary parameters for the Turkish System (Case 2 & Case 4)

ACE vs ACS	-2000	0	2000
-2000	0.015	0.03	0.04
0	0.015	0.015	0.015
2000	0.04	0.03	0.015

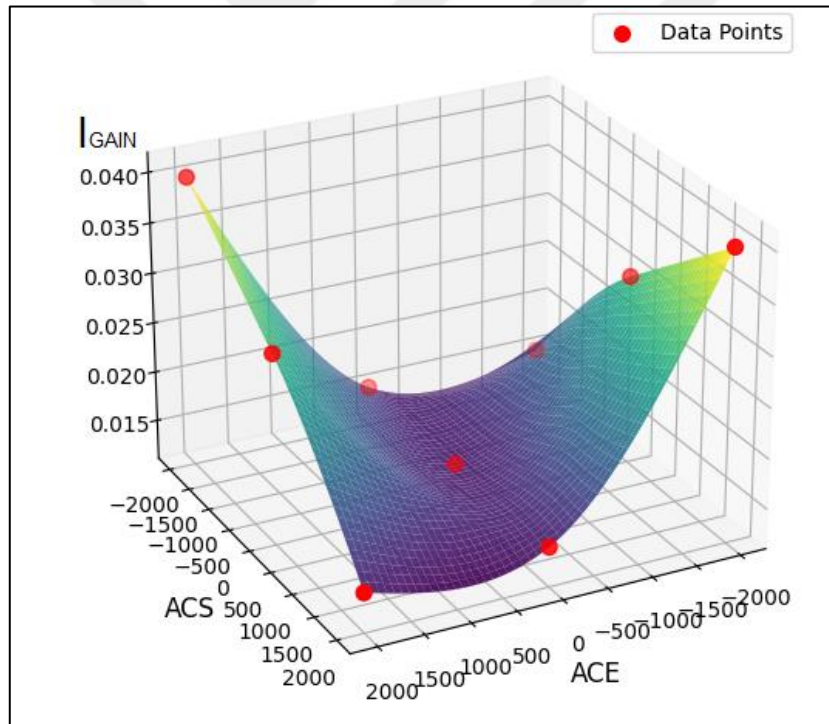


Figure 4.6. 3D heat maps of I_{GAIN} for the Turkish System

4.3.4 Scenario 4 – Adaptive Methodology on the Turkish System

Scenario 4 implements the full adaptive AGC methodology described in Chapter 3.2.2, with a focus on adaptive I_{GAIN} calculation using a correlation-based look-up table. The objective is to validate the proposed method under realistic splitting conditions and demonstrate its effectiveness in enhancing ACE and frequency control performance. This scenario includes one base case and five distinct splitting cases, selected to represent a spectrum of operational challenges that may arise during system separation events.

In addition to performance validation, Cases 1, 2, and 3 were used to derive the correlation between I_{GAIN} and key system parameters such as total inertia contribution, as presented earlier in the methodology section. However, the main purpose of this scenario is not the derivation of those relationships, but rather the practical demonstration of the adaptive control benefits achieved through their implementation by also adding two more Cases as 4 and 5.

Case 0: Base Case – No Splitting

This case represents the normal operating mode of the Turkish system, where the entire grid is managed as a single control area. The AGC operates using traditional tie-line and frequency control mode. This case serves as a performance benchmark, illustrating the system's ACE response under undisturbed conditions with conventional control.

Case 1: Historical Event-Based Splitting – Turkish Blackout Analogue

In this case, the system is split into two areas as shown in Figure 4.7 replicating the conditions of the 2015 Turkish blackout, but modeled as a controlled and recoverable event. Area 1 (ENTSO-E side) remains synchronized with the external grid, Area 2 becomes isolated, forming a disconnected subnetwork. Unlike the historical event where system-wide collapse occurred, this case investigates how the proposed AGC could have managed the event through adaptive island control. The AGC

autonomously reconfigures operational modes and applies dynamically tuned I_{GAIN} values based on area-specific parameters such as total inertia contribution. This test illustrates the method's potential to maintain system stability and continuity during major disturbances that, in practice, led to full blackouts.



Figure 4.7. Scenario 4: Splitting Case 1

Case 2: Balanced Split

Case 2, presented in Figure 4.8, introduces a more symmetrical grid separation, where the two areas are relatively balanced in terms of generation units and available reserves. This configuration presents a more neutral operating challenge, offering a suitable test case for validating the correlation-based I_{GAIN} tuning method across both areas simultaneously. The ACE and frequency performance of each area is monitored to assess the responsiveness and fairness of adaptive control actions.

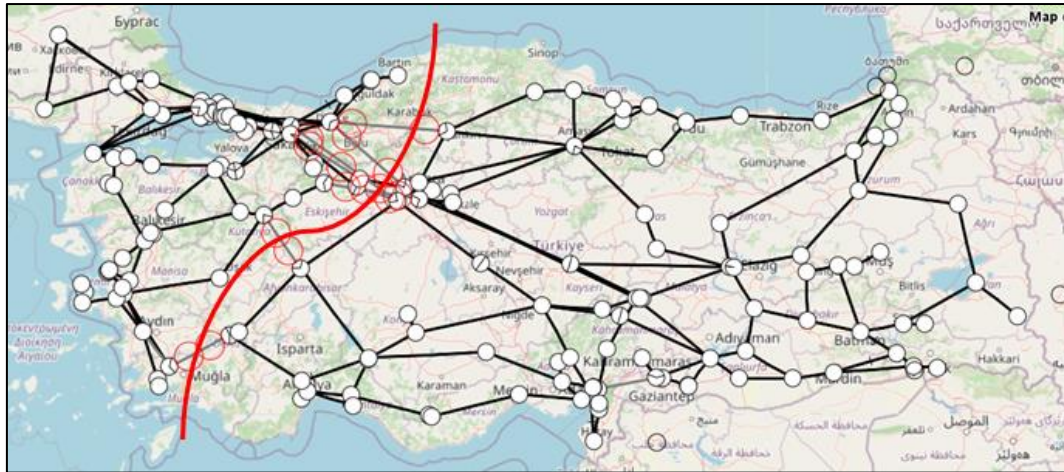


Figure 4.8. Scenario 4: Splitting Case 2

Case 3: Small-Area Islanding (ENTSO-E Dominant)

This case simulates a resource-constrained islanding event, where most of the generation capacity and inertia remain on the ENTSO-E side (Area 1), while Area 2 is reduced to a small, isolated subnetwork with minimal inertia and reserve margin. This configuration represents an extreme challenge for frequency regulation in Area 2. The test serves to evaluate the adaptive AGC's ability to scale down its control effort and still deliver acceptable performance under severely stressed conditions.



Figure 4.9. Scenario 4: Splitting Case 3

Case 4: Small-Area Islanding (Deficient FRR)

This case builds upon the conditions in Case 3 but introduces a significant constraint in terms of FRR. While the topology and inertia of the small island area remain similar to Case 3, its available FRR is deliberately reduced in accordance with the initial ACE observed after the splitting event. The objective is to evaluate the performance of the adaptive AGC scheme under severely constrained reserve conditions. This configuration enables the analysis of the AGC's capability to maintain ACE control when the reserve margin is insufficient to support effective frequency regulation, thus reflecting operational challenges faced in under-resourced islanded systems.

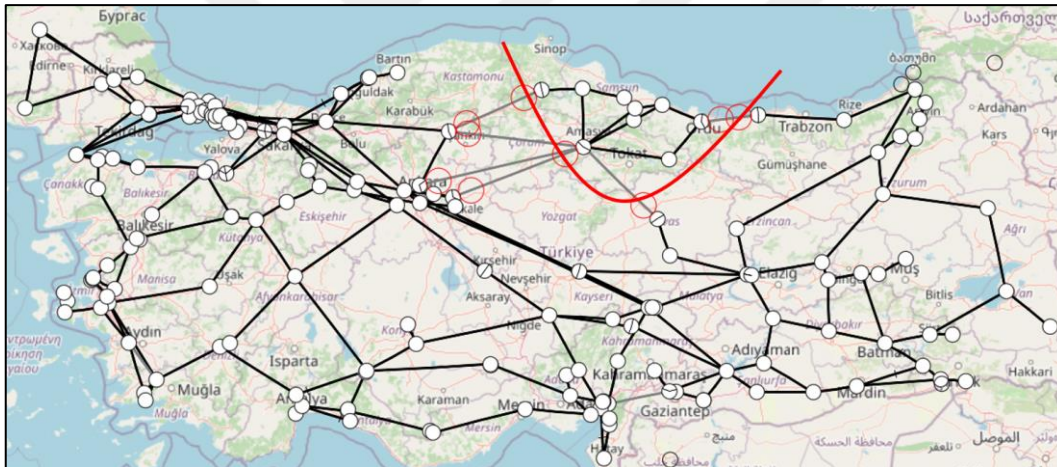


Figure 4.10. Scenario 4: Splitting Case 4

Case 5: Splitting with an ACE Limit Violation at One Area

This case evaluates the performance of the proposed AGC scheme under an asymmetrical ACE condition in which one of the separated areas exceeds critical ACE thresholds immediately after splitting. Specifically, the ACE in one area triggers an automatic transition of the AGC state to STOP in accordance with the

operational logic defined in Chapter 3. While AGC operations are halted in the violating area, the algorithm continues to manage the other area independently and effectively. This case demonstrates the resilience of the proposed methodology, which allows partial AGC functionality to persist and stabilize the grid where feasible, rather than suspending control operations system-wide.

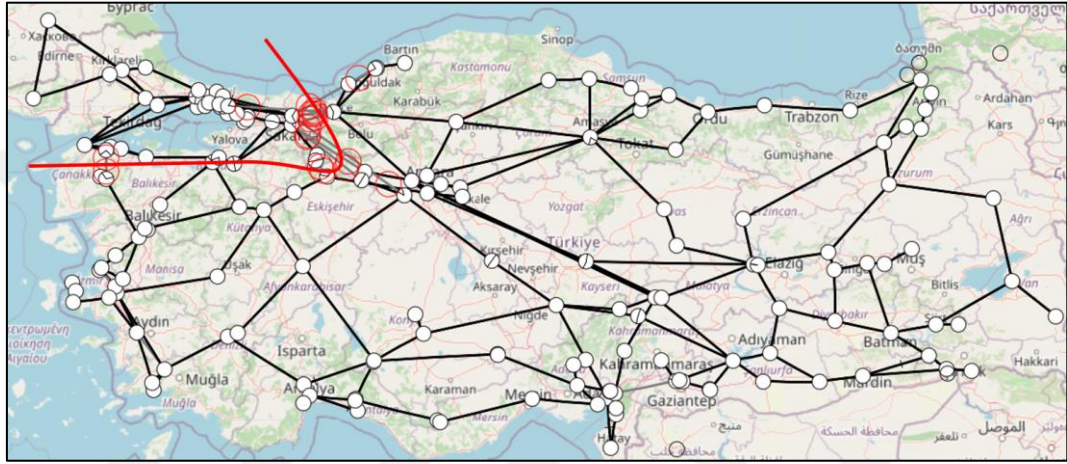


Figure 4.11. Scenario 4: Splitting Case 5

Table 4.6 provides a comprehensive summary of the operating conditions and key parameters for all cases defined under Scenario 4. This scenario is specifically designed to reflect various splitting conditions and assess the adaptability and robustness of the proposed AGC methodology. The table highlights differences in system parameters such as total inertia contribution, load-generation balance, and available FRR across base and sensitivity cases. Corresponding observations on I_{GAIN} adjustments and ACE performance are noted, demonstrating how the adaptive control scheme dynamically responds to changing conditions.

Table 4.6. Summary of Scenario 4

Scenarios	# of total units	# of AGC units	Total Capacity (MW)	Total Load (MW)	Total FRR (MW)	Total H·P (MW·s)	Total Inertia (s)
Case 0	120	104	43977.3	21938	1612.0	253,700	5.769
ENTSO-E side (Area-1)							
Case 1	78	66	30024.4	13253	896.9	179,600	5.982
Case 2	53	47	20390.5	10306	668.1	123,200	6.046
Case 3	113	97	42536.0	20860	1504.2	246,200	5.789
Case 4	111	96	41736.5	21031	1522.4	241,500	5.788
Case 5	26	23	11679.0	4935	430.6	70,800	6.058
Isolated (Area-2)							
Case 1	42	38	13952.9	8685	715.1	74,100	5.311
Case 2	67	57	23586.8	11632	943.9	130,400	5.529
Case 3	7	7	1441.3	1078	107.8	74,800	5.189
Case 4	9	8	2240.8	907	89.6	12,200	5.422
Case 5	94	81	32298.3	17003	1181.4	182,900	5.666

4.3.5 Sensitivity Analysis

To assess the robustness of the proposed AGC methodology under practical operating uncertainties, a series of sensitivity analyses are conducted based on Scenario 4 – Case 1. This scenario, which emulates the 2015 Turkish blackout conditions under a controlled splitting event, serves as the baseline configuration for all sensitivity cases. The goal is to evaluate how the adaptive I_{GAIN} mechanism and the AGC scheme respond to variations in system characteristics, including inertia, dispatch profiles, available reserves, and ACE levels. The following four sensitivity cases are examined:

Sensitivity Case 1: Reduced Inertia and Dispatch in Both Areas

In this case, both Area-1 and Area-2 experience reduced total inertia and generation dispatch. The available FRR remains unchanged.

Sensitivity Case 2: Localized Inertia Reduction in Area-2

Here, only Area-2 undergoes a reduction in inertia and dispatch, while Area-1 retains its base case parameters.

Sensitivity Case 3: Reduced FRR in Area-2

In this case, the total inertia and ACE values are preserved, but the available FRR in Area-2 decreased from 715.1 MW to 579.4 MW. Despite this reduction, ACE regulation remains within acceptable limits.

Sensitivity Case 4: Asymmetric Generation Shift

This case investigates the impact of shifting 1000 MW of generation capacity from Area-2 to Area-1, creating an imbalanced ACE condition immediately after splitting.



CHAPTER 5

SIMULATION RESULTS

This chapter presents a comprehensive evaluation of the proposed AGC scheme under various operational scenarios. Simulations are performed on two distinct network models: The IEEE 9-bus test system and a representative Turkish Transmission System. Results are structured scenario-by-scenario, each consisting of multiple cases reflecting specific system configurations.

The simulation results are organized across four main scenarios. Scenario 1 serves to validate the fundamental control logic of the AGC scheme, including its ability to detect system splitting, operate independently across separated areas, and coordinate reconnection. Scenario 2 and Scenario 3 evaluate the performance of static and dynamic PI controllers under load disturbances and splitting, applied respectively to the IEEE and Turkish networks. Scenario 4 demonstrates the implementation of the adaptive PI control methodology based on a pre-constructed look-up table on the Turkish System. In addition, a sensitivity analysis is conducted to examine the robustness of the proposed control logic in the face of changes in system inertia, reserve capacities, and dispatch. Finally, an evaluation on scalability and detection dynamics of the proposed system is presented to further assess the generalizability of sub-region identification and the responsiveness of splitting detection mechanism.

5.1 Simulation Results for Scenario 1

Section 5.1 presents the simulation results for Scenario 1, which aims to validate the fundamental functionalities of the proposed AGC scheme using the IEEE 9-bus test system. This scenario includes three cases that assess the AGC's response under normal operation, during a controlled network splitting and reconnection event, and in the presence of load disturbances under split conditions.

5.1.1 Results for Case 1

In this case, a total load of 50 MW is added to the main grid at Bus 6 to evaluate the response of the proposed AGC within the SIL environment. As illustrated in Figure 5.1, immediately after the load is introduced at time t_0 , G1 (belonging to the 1st reserve group) increases its active power output up to its maximum reserve capacity. This response is directed by the P_{set} control signals, depicted in black in the figure, which are generated by the AGC. Once G1 reaches its limit, the algorithm sequentially activates the remaining reserve groups: G2 (2nd group) at time t_1 and G3 (3rd group) at time t_2 . By the end of the control action at t_3 , all necessary active power reserves have been deployed, resulting in the ACE value being reduced to zero, as expected. This case verifies the AGC algorithm's correct implementation of the PI control structure and reserve-sharing logic in a normal operational setting.

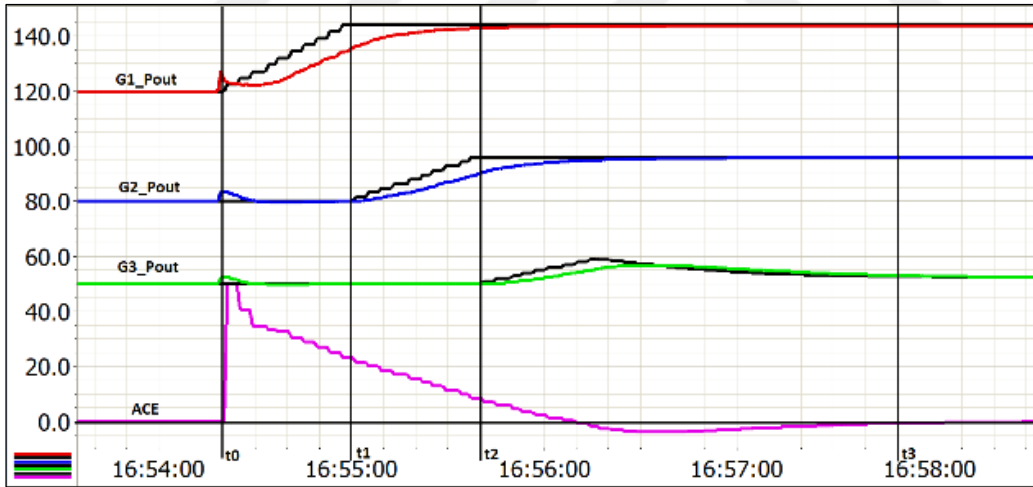


Figure 5.1. Scenario 1 – Case 1: Generator P outputs and ACE value in MW

Overall, Case 1 demonstrates the validity of the proposed AGC scheme as well as the operational consistency of the SIL environment. While not all possible test combinations such as varying loading conditions, control modes, state transitions,

and control cycle lengths are explicitly presented, each has been tested and verified through similar procedures throughout this study.

5.1.2 Results for Case 2

In Case 2, the test network is subjected to a composite disturbance involving simultaneous short-circuit faults on the lines between Bus 4–Bus 5 and Bus 8–Bus 9, resulting in a network split into two electrically isolated areas, as depicted in Figure 4.4. The resulting dynamics of frequency, ACE, and generator outputs are shown in Figures 5.2, 5.3, and 5.4, respectively.

As shown in Figure 5.2, the fault occurring at t_0 causes a loss of synchronism between generators and triggers the splitting of the main grid into two areas. At t_1 , the AGC algorithm detects the event and confirms the split. It then initiates two parallel AGC control loops as AGC Loop Area-1 and AGC Loop Area-2. Area-1 remains connected to the external grid and operates in a tie-line plus frequency control mode, whereas Area-2 becomes an isolated sub-network, transitions to only frequency control mode.

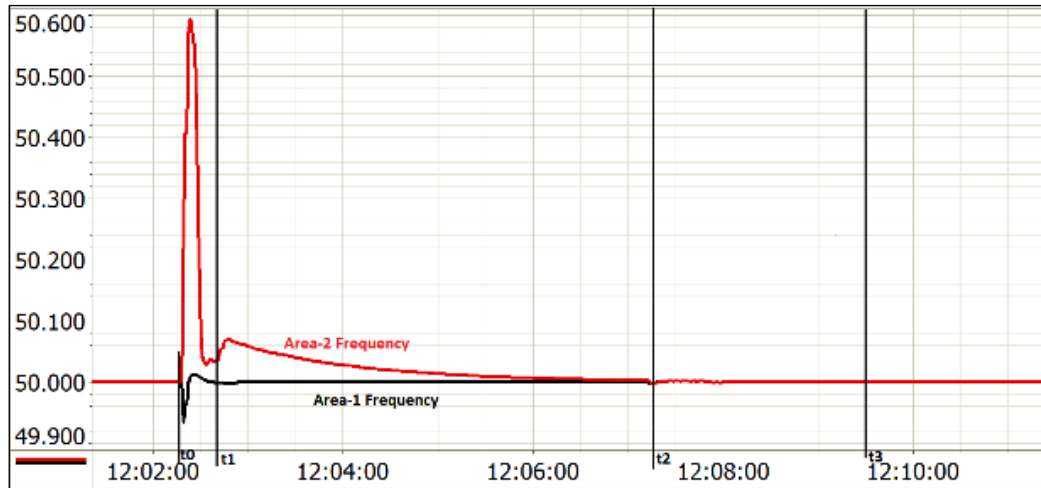


Figure 5.2. Scenario 1 – Case 2: Frequency curves

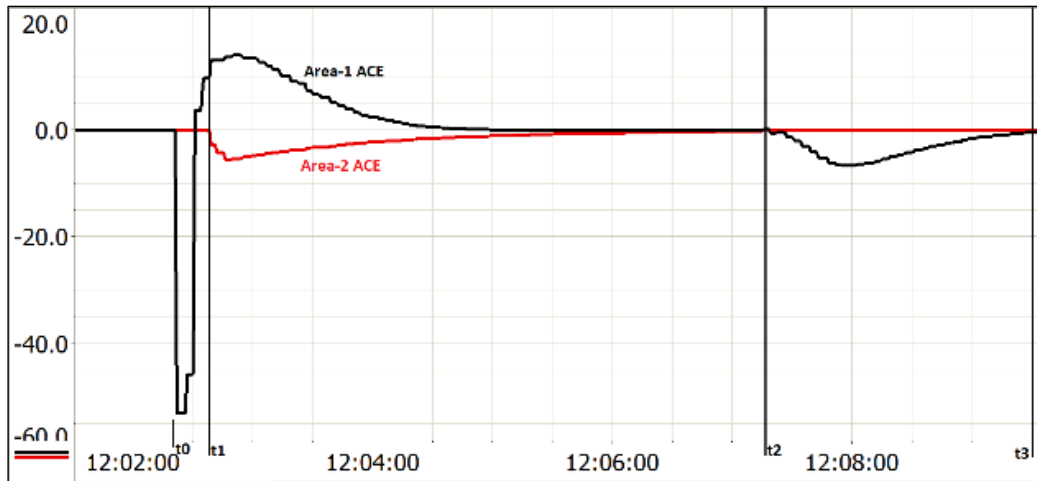


Figure 5.3. Scenario 1 – Case 2: ACE values in MW

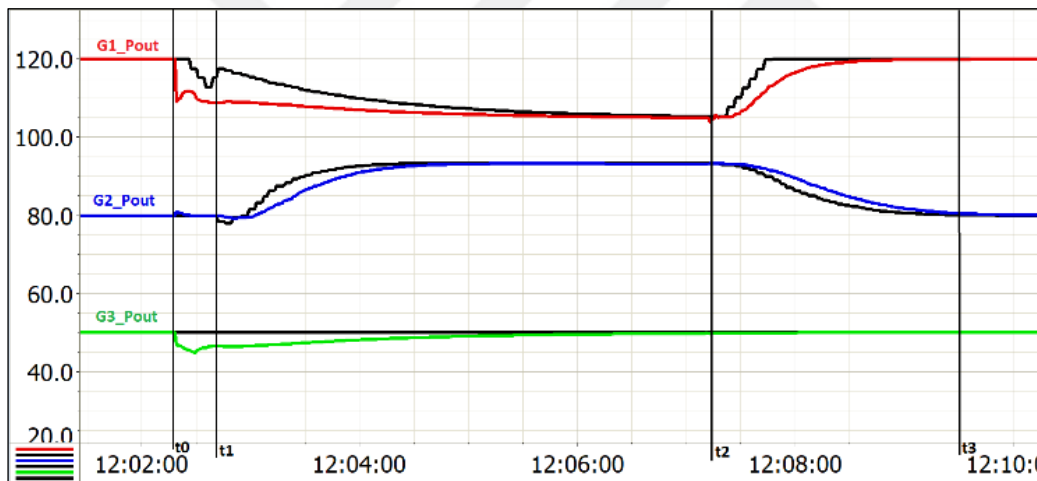


Figure 5.4. Scenario 1 – Case 2: Generator P outputs in MW

Figures 5.3 and 5.4 show that Area-1 experiences a positive ACE, prompting G2 to increase generation and eliminate the deviation. In contrast, Area-2 displays a negative ACE, requiring a reduction in generation starting with G1 (due to its higher priority) until the ACE_2 value is eliminated. At t_2 , the splitting condition ends, and synchronization between the areas is re-established. The algorithm detects this and

reconfigures AGC management into a single control area. During the transition from t_2 to t_3 , G1 re-assumes reserve duties from G2, in line with its prioritization. However, this reserve reallocation process can be streamlined by adjusting generator priorities, thereby avoiding unnecessary control operations.

5.1.3 Results for Case 3

Case 3 analyzes the AGC's ability to manage load disturbances under splitting conditions. Specifically, a load of 10 MW is added to Area-2 after the network has split, allowing for a comparison between the conventional AGC systems lacking splitting awareness (see Figure 5.5) and the proposed AGC (see Figure 5.6).

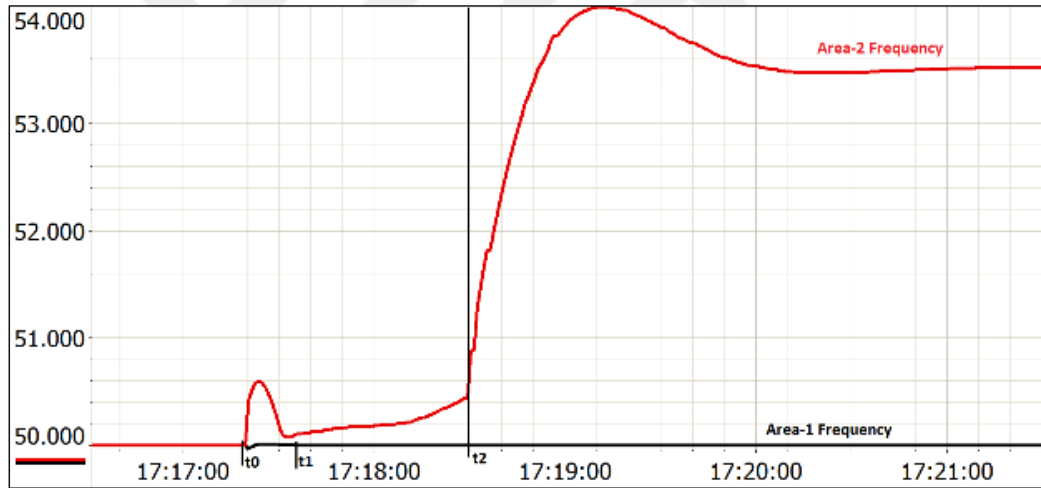


Figure 5.5. Scenario 1 – Case 3: The frequency without splitting management

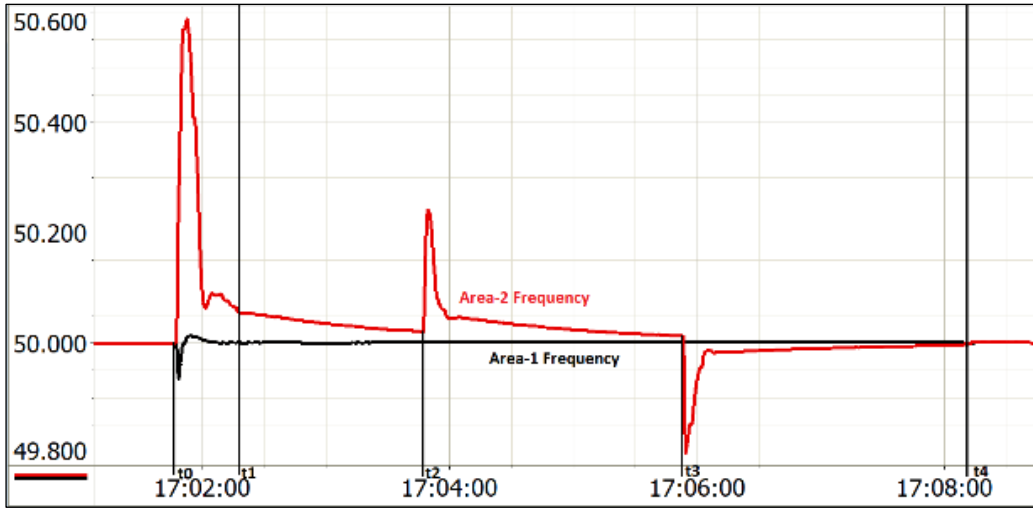


Figure 5.6. Scenario 1 – Case 3: The frequency with the proposed AGC

Figure 5.5 demonstrates the behavior of Area-2 under a conventional AGC system that lacks splitting detection. After the split at t_0 , the frequency in Area-2 initially rises modestly, but without any corrective AGC action. A total load of 10 MW load removal at t_2 results in unmitigated frequency increase. The frequency eventually reaches to 54 Hz, surpassing the protection threshold (52.5 Hz), at which point protection relays would remove G1 and G3, causing a blackout in Area-2.

In contrast, Figure 5.6 illustrates the response of the proposed AGC. Upon detecting the split at t_1 , the algorithm initiates independent control for both areas, simultaneously. After the 10 MW load is removed at t_2 , the frequency momentarily spikes to around 50.25 Hz but is rapidly stabilized. When the load is reconnected at t_3 , frequency stability is again maintained. Finally, when the system is resynchronized at t_4 , the AGC transitions seamlessly to unified operation.

This case highlights the robustness of the proposed AGC scheme in handling both load disturbances and re-synchronization events under splitting conditions. It demonstrates superior adaptability and reliability compared to traditional AGC approaches that do not support area-wise dynamic reconfiguration.

5.2 Simulation Results for Scenario 2

This section presents the simulation results of Scenario 2, which focuses on evaluating the impact of dynamic versus static PI control under varying operational conditions using the IEEE 9-bus test network. To assess control performance, two key metrics are employed in this scenario. The first is the ACE recovery time, which measures the duration required for the ACE to return within defined limits following a disturbance. The second is the ACE overshoot, indicating whether and to what extent the ACE exceeds acceptable bounds before settling. These indicators provide insight into the responsiveness and damping behavior of the control strategy.

Performance thresholds are established with reference to ENTSO-E standards and adapted to the scale of the IEEE test system. For load disturbance cases, an ACE limit of ± 7.5 MW is applied, representing a Level-1 threshold that corresponds to the standard ACE margin defined for TSOs. This value is derived by proportionally scaling the official Turkish system threshold (± 375 MW) according to the total system size of the IEEE 9-bus network. For network splitting scenarios, a more stringent threshold of ± 2 MW is adopted to represent the acceptable ACE settlement value. This conservative limit reflects the tighter ACE stability requirements expected in splitting conditions. These thresholds are visualized as dashed lines in the ACE plots, and time axes are marked in 10-second intervals.

The results are structured case-by-case, beginning with load disturbance events and progressing to controlled splitting scenarios. Each case includes visual and quantitative analysis of ACE trajectories offering a detailed comparison between conventional static control and the proposed dynamic gain adjustment methodology.

Case 1 (Figure 5.7) and Case 2 (Figure 5.8) evaluate normal network operations under a 50 MW load disturbance, where Case 1 employs a static I_{GAIN} value of 0.025, identified as the most effective gain for the IEEE test grid, while Case 2 applies a dynamic I_{GAIN} based on the data points in Table 4.2. Case 3 (Figure 5.9) and Case 4 (Figure 5.10) analyze the AGC performance under splitting conditions, comparing

the effects of regular (static I_{GAIN}) and dynamic I_{GAIN} control. Finally, Case 5 (Figure 5.11) investigates a splitting scenario using more efficient, area-specific parameter sets (Table 4.3 for Area-1 and Table 4.4 for Area-2), allowing further evaluation of the adaptability and scalability of the dynamic gain adjustment strategy.

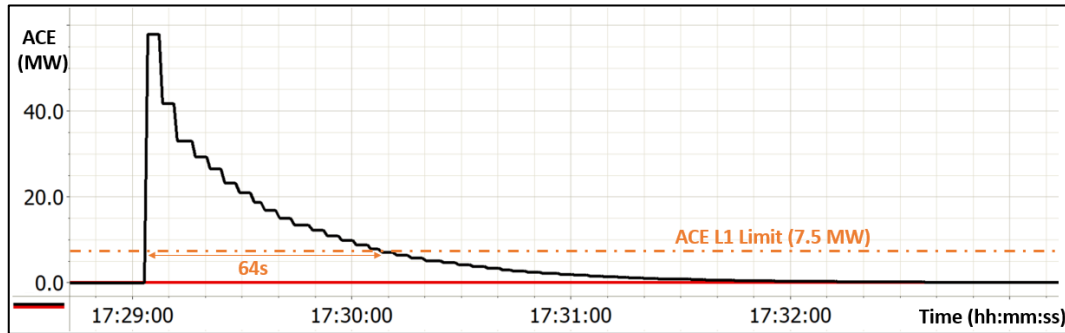


Figure 5.7. Scenario 2 – Case 1: ACE after 50 MW disturbance (static I_{GAIN})

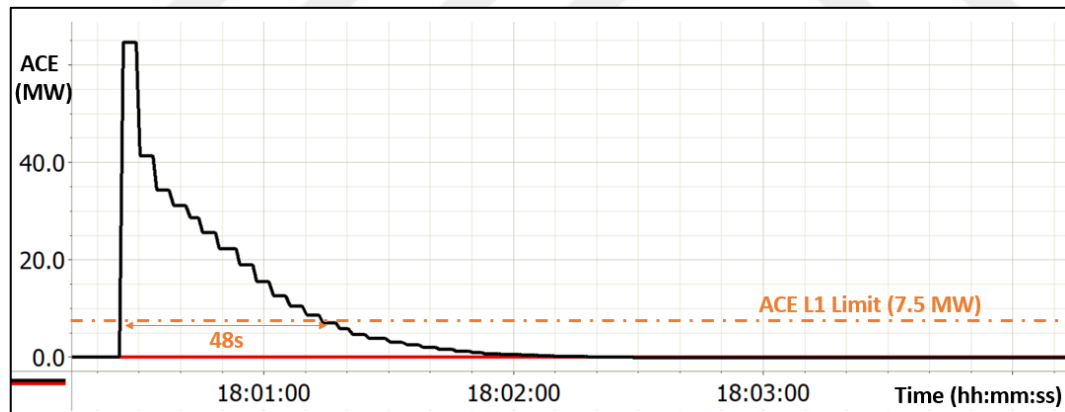


Figure 5.8. Scenario 2 – Case 2: ACE after 50 MW disturbance (dynamic I_{GAIN})

The key finding from the comparison of Case 1 and Case 2 is that the ACE performance can be significantly improved by implementing a dynamic I_{GAIN} within the AGC control loop. As illustrated in Figures 5.7 and 5.8, the application of

dynamic I_{GAIN} in Case 2 leads to a more effective ACE response compared to the static gain configuration used in Case 1. The dynamically adjusted gain enables faster corrective action without introducing any control violation.

Specifically, the dynamic gain adaptation allows the controller to respond proportionally to the magnitude and nature of the disturbance, resulting in improved ACE settling time. In contrast, the fixed I_{GAIN} in Case 1, although functional, exhibits a relatively slower response and less efficient damping behavior. These findings confirm the advantage of dynamic gain tuning in achieving precise and stable load-frequency control, particularly under normal operational conditions.

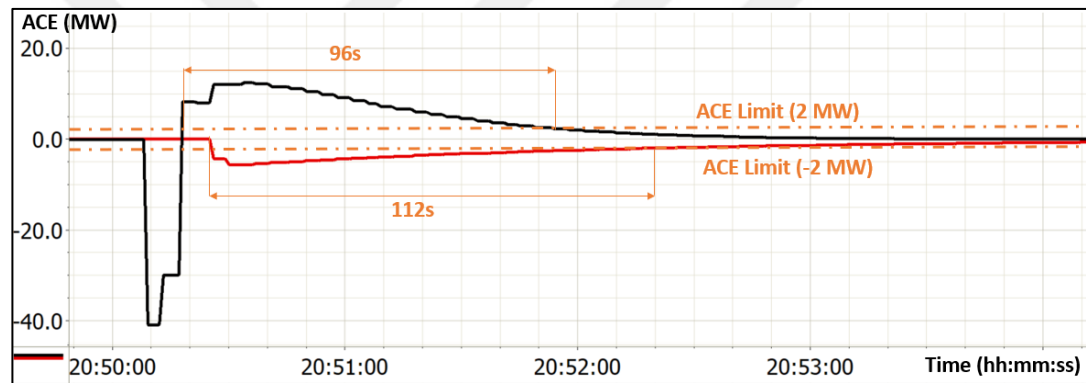


Figure 5.9. Scenario 2 – Case 3: Splitting with static I_{GAIN}

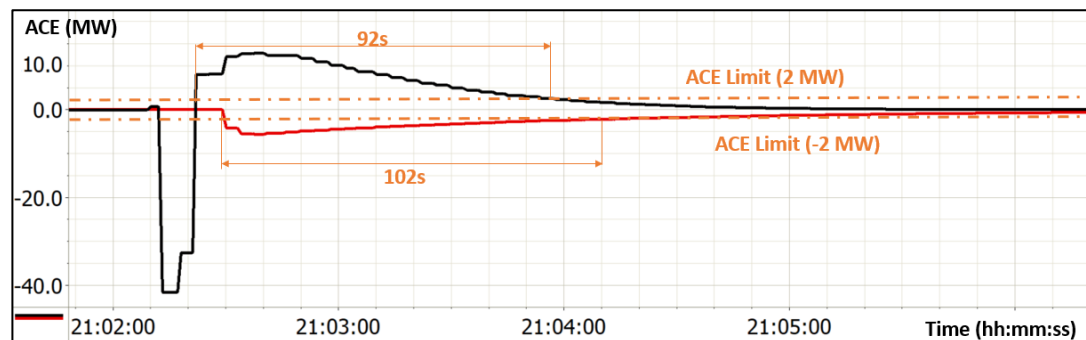


Figure 5.10. Scenario 2 – Case 4: Splitting with dynamic I_{GAIN}

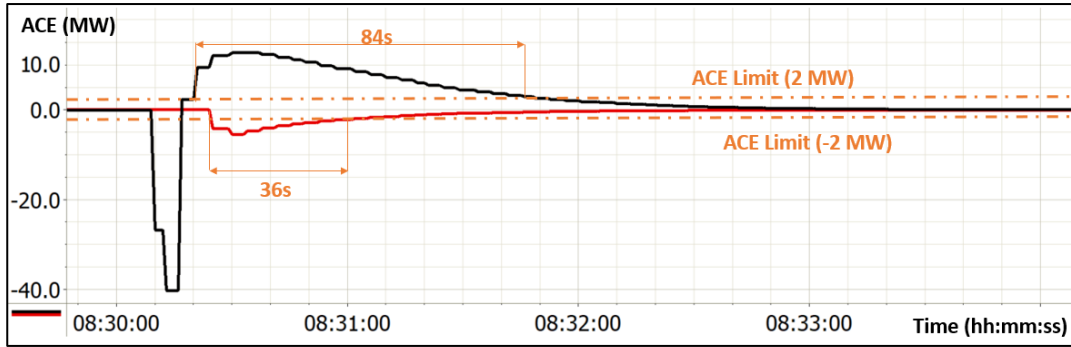


Figure 5.11. Scenario 2 – Case 5: Splitting with improved I_{GAIN} data points

Figures 5.9 and 5.10 show that applying a dynamic integrator gain yields a modest improvement in AGC performance under network splitting conditions. While dynamic I_{GAIN} reduces ACE and ACS rates in each area, the gains remain limited due to its reliance on generalized boundary conditions rather than area-specific tuning. To overcome this limitation, the proposed AGC framework incorporates a topology-dependent dynamic I_{GAIN} strategy. Since the splitting points are known before the event, this approach assigns each control area a predefined set of gain values tailored to its operational characteristics, using parameters from Table 4.3 for Area-1 and Table 4.4 for Area-2. These values better match each area's dynamic response following a split.

Figure 5.11 demonstrates the effectiveness of this adaptive scheme, showing notable improvements in ACE response and overall control performance compared to previous cases. By aligning the I_{GAIN} values with the known topological and dynamic characteristics of each area, the proposed method enhances damping and significantly accelerates ACE recovery following a splitting event.

Table 5.1 presents a comparative summary of control performance across all five cases analyzed in Scenario 2. The results confirm the progressive improvements achieved through the integration of I_{GAIN} -based (dynamic) strategies. Case 1, which uses a static I_{GAIN} value, serves as the baseline with an ACE recovery time of 64 seconds. Case 2 demonstrates the benefit of dynamic gain adjustment, reducing the

recovery time to 48 seconds. Under network splitting conditions, Case 3 maintains recovery times of 96 and 112 seconds for Area-1 and Area-2, respectively, using static I_{GAIN} . Case 4 offers a modest improvement, reducing these times to 92 and 102 seconds with dynamic gain tuning. The most significant performance enhancement is observed in Case 5, where area-specific dynamic I_{GAIN} parameters are employed. This configuration yields the fastest ACE recovery, with 84 seconds for Area-1 and just 36 seconds for Area-2, indicating a substantial improvement in the latter. Notably, no ACE overshoots are observed in any of the cases. These results underscore the effectiveness and scalability of the proposed dynamic AGC approaches for both interconnected and split system conditions in the IEEE test system.

Table 5.1. Performance summary of Scenario 2

Metric / Case	<i>Case 1</i>	<i>Case 2</i>	<i>Case 3</i>	<i>Case 4</i>	<i>Case 5</i>
Area-1 recovery time (s)	64 s	48 s	96 s	92 s	84 s
Area-1 overshoot	No	No	No	No	No
Area-2 recovery time (s)	-	-	112 s	102 s	36 s
Area-2 overshoot	-	-	No	No	No

5.3 Simulation Results for Scenario 3

Scenario 3 extends the evaluation of the dynamic PI control approach to a larger and more complex system. The objective is to assess the scalability, applicability, and effectiveness of dynamic I_{GAIN} control under both load disturbance and network splitting conditions in a real-world grid setting. Similar to Scenario 2, five cases are considered to compare static and dynamic control strategies.

Two key performance indicators are used throughout this scenario: ACE recovery time and ACE overshoot. These metrics provide a quantitative basis for evaluating the damping behavior and responsiveness of the AGC. The acceptable ACE threshold is set at ± 375 MW for normal operation, reflecting the Level-1 ENTSO-E criterion for the Turkish system. In splitting conditions, a stricter threshold of ± 20 MW is applied to represent the acceptable ACE settlement value. These limits are shown in ACE plots as dashed lines, and time axes are marked in 10-second intervals.

Case 1 (Figure 5.12) and Case 2 (Figure 5.13) assess system performance under a 902 MW load disturbance, comparing static and dynamic PI control configurations. In Case 1, the integral gain is fixed at 0.015, while Case 2 employs dynamic I_{GAIN} adjustment using the boundary values defined in Table 4.5. Case 3 (Figure 5.14) and Case 4 (Figure 5.15) evaluate AGC behavior under network splitting conditions, contrasting fixed-gain and dynamic-gain control strategies. In Case 5 (Figure 5.16), the study attempts to implement more efficient boundary sets tailored to the post-splitting areas. However, due to the scale and topological complexity of the Turkish Transmission System, it is not straightforward to identify the most effective parameter sets for each area, making this case a transitional step toward more structured adaptive gain tuning.

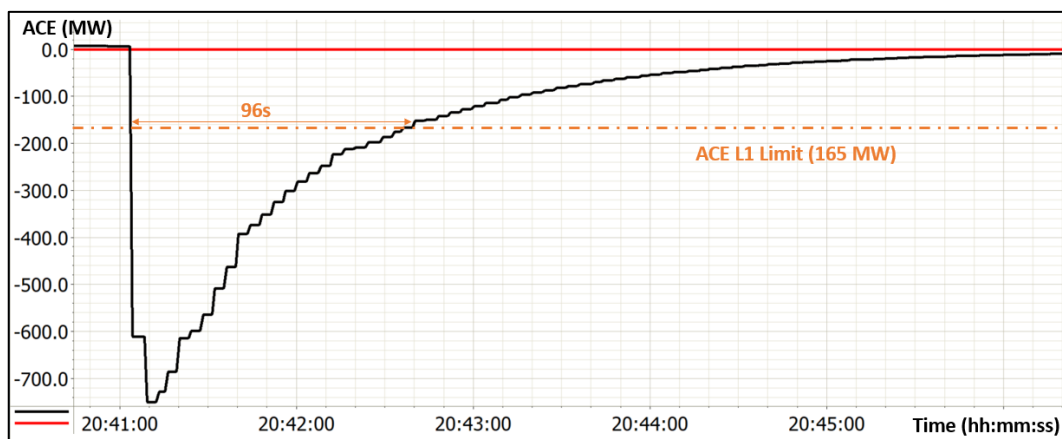


Figure 5.12. Scenario 3 – Case 1: ACE after 902 MW disturbance (static)

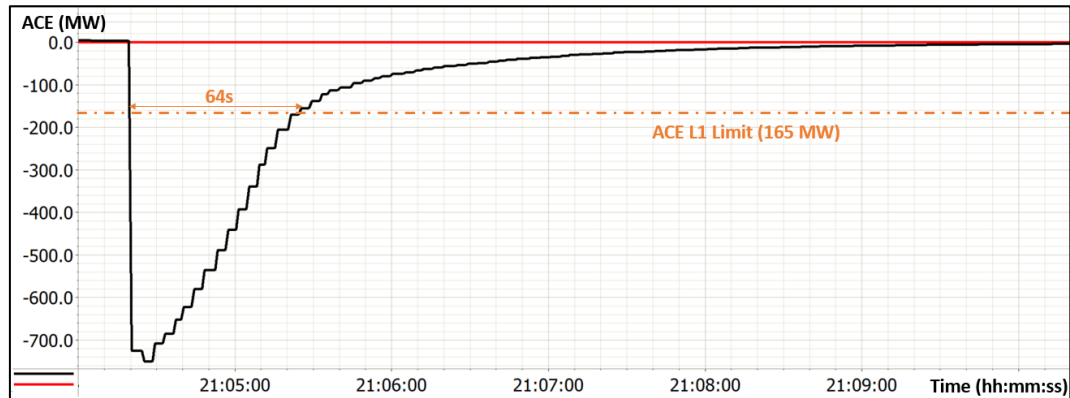


Figure 5.13. Scenario 3 – Case 2: ACE after 902 MW disturbance (dynamic)

Consistent with the results observed in Scenario 2, the findings from Case 1 and Case 2 demonstrate that the performance of the ACE during normal operations can be improved by implementing a dynamic I_{GAIN} strategy. In Case 1, the AGC successfully responds to the 902 MW load disturbance but exhibits slower ACE recovery. In contrast, Case 2, which applies dynamic gain adjustment using the boundary values from Table 4.5, achieves a faster and more stable ACE response.

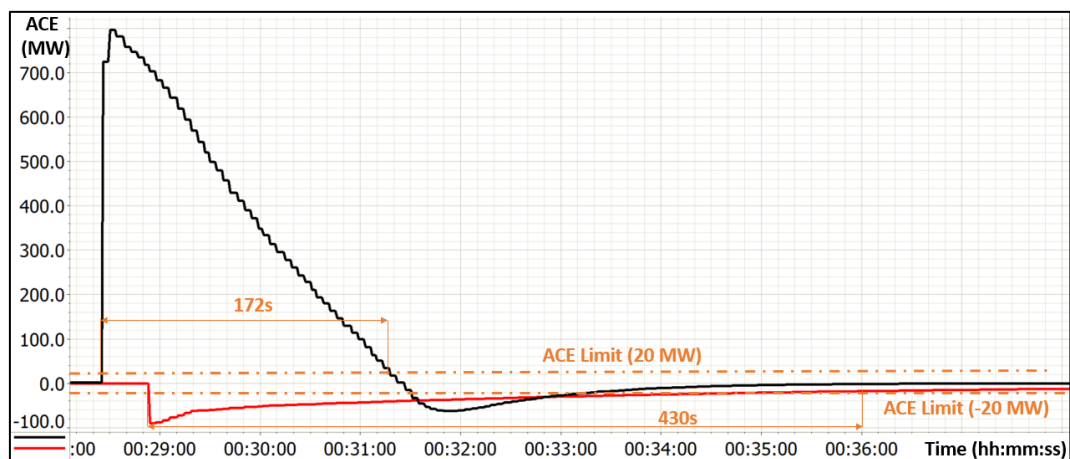


Figure 5.14. Scenario 3 – Case 3: Splitting with static I_{GAIN}

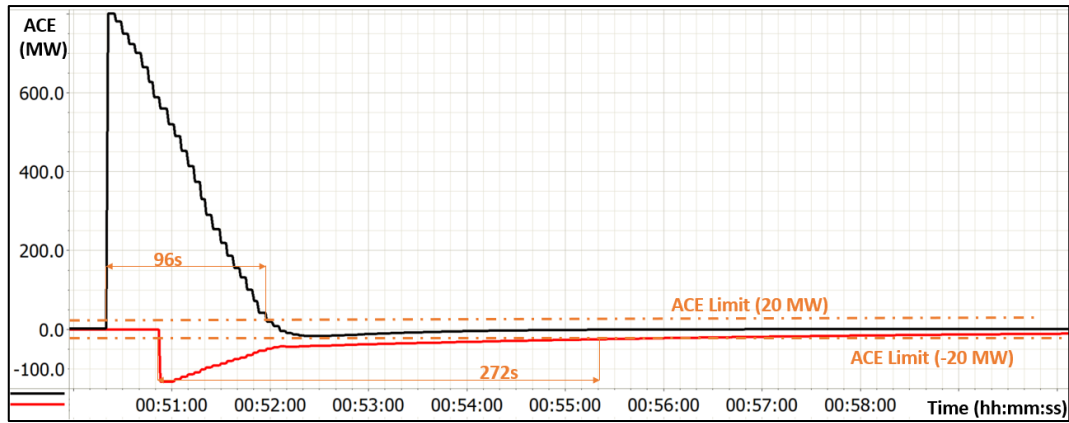


Figure 5.15. Scenario 3 – Case 4: Splitting with dynamic I_{GAIN}

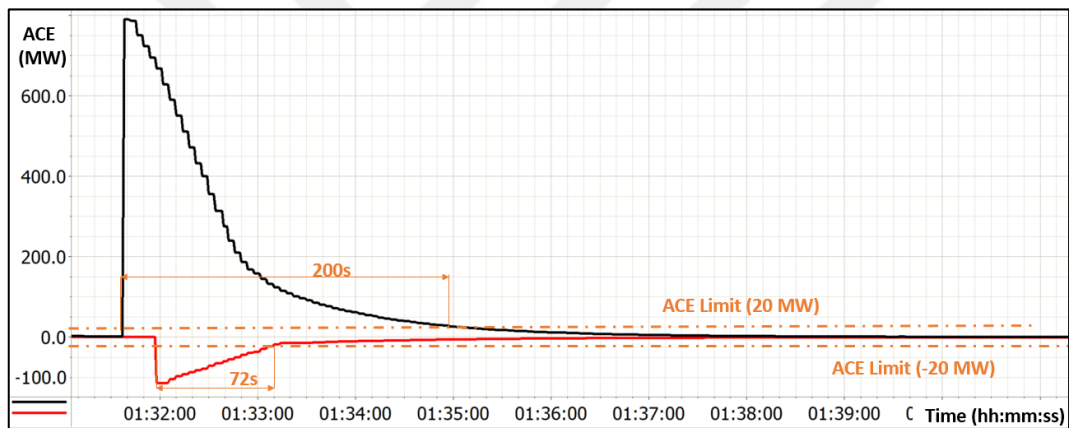


Figure 5.16. Scenario 3 – Case 5: Splitting with improved I_{GAIN} data points

As illustrated in Figures 5.14 and 5.15, the application of a dynamic I_{GAIN} improves AGC performance following system splitting. Compared to static gain configuration, dynamic control results in faster ACE recovery and improved frequency response in both areas. However, both cases still exhibit some overshoot in control actions, indicating the need for further tuning. To mitigate this, a revised set of I_{GAIN} parameters was manually derived and applied in Case 5, specifically tailored for the conditions observed after network separation. As shown in Figure 5.16, these

updated values significantly enhance AGC performance, particularly in the islanded area, where more aggressive control settings lead to faster stabilization and improved ACE tracking. The results highlight that even in complex, large-scale networks, assigning more effective and scenario-specific control parameters to each area can yield substantial improvements in system response and frequency stability.

Table 5.2 summarizes the ACE recovery performance across all five cases in Scenario 3. The results clearly demonstrate the benefit of dynamic gain adjustment in large-scale systems. In Case 1, the ACE recovery time is 96 seconds. Case 2, which applies dynamic I_{GAIN} using the boundary values in Table 4.5, reduces the recovery time to 64 seconds. Under splitting conditions, Case 3 records recovery times of 172 seconds for Area-1 and 430 seconds for Area-2 using static gains. Case 4 improves these times to 96 and 272 seconds, respectively, by introducing dynamic gain control. The most notable improvement is observed in Case 5, where more aggressive, area-specific I_{GAIN} values yield a recovery time of 200 seconds for Area-1 and a significantly reduced 72 seconds for Area-2. Although some overshoots were observed in Cases 3 and 4, Case 5 achieves a better balance between responsiveness and stability. These findings validate the effectiveness of the proposed dynamic control strategy in improving AGC performance in complex transmission networks where the splitting topology is known in advance.

Table 5.2. Performance summary of Scenario 3

Metric / Case	<i>Case 1</i>	<i>Case 2</i>	<i>Case 3</i>	<i>Case 4</i>	<i>Case 5</i>
Area-1 recovery time (s)	96 s	64 s	172 s	96 s	200 s
Area-1 overshoot	No	No	Yes	Yes	No
Area-2 recovery time (s)	-	-	430 s	272 s	72 s
Area-2 overshoot	-	-	No	No	No

5.4 Simulation Results for Scenario 4

Scenario 4 implements the full adaptive AGC methodology introduced in Section 3.2.2. The primary objective is to validate the operational effectiveness of the proposed scheme under realistic system separation events, demonstrating how adaptive I_{GAIN} control and effective reserve activation jointly contribute to improved ACE regulation and frequency stability. The simulation framework is based on the Turkish Transmission System model and includes five distinct splitting cases, each selected to represent a range of topological and operational challenges that may arise during unplanned or controlled islanding events.

System performance is evaluated using four ACE-based thresholds defined by ENTSO-E [12]. The Normal Operation Band (± 20 MW) corresponds to a 10 mHz deviation applied to the TEİAŞ bias factor (2000 MW/Hz) and represents the acceptable and nominal ACE settling band. The Level-1 (± 170 MW) and Level-2 (± 320 MW) thresholds are derived from TEİAŞ's historical ACE performance metrics averaged over the past eight years. The Critical Impact Level (± 375 MW) serves as a system-wide alert threshold from ENTSO-E, triggering coordination with the Regional Coordination Center (RCC) and the application of emergency measures. These thresholds are marked with dashed horizontal lines in the simulation plots to support visual performance assessment.

The results are structured case by case, focusing on the ACE and frequency responses in each control area during splitting and merging periods. They illustrate the effectiveness of the proposed AGC scheme in maintaining control continuity, adapting to varying system conditions, and supporting stable reintegration. In this scenario, in all cases, the network is divided into two areas: Area-1, representing the ENTSO-E side, remains connected to the external grid and operates in tie-line and frequency control mode; Area-2, representing the isolated side, becomes separated from the Continental Europe synchronous area and operates independently in frequency control mode. The x-axis represents time, divided into key phases: t_0 marks the start of the splitting event, t_1 indicates the beginning of independent area

operations, t_2 represents the point where the two areas reconnect, and t_3 shows the re-stabilization of the unified system with market-based reserve arrangements.

5.4.1 Result for Case 1

Case 1 evaluates the performance of the proposed AGC scheme during a grid-splitting and reconnection event, as illustrated in Figures 5.17 to 5.21. The analysis compares ACE behavior under three configurations: Case 1a, which employs a static I_{GAIN} together with conventional market-based reserve activation; Case 1b, which maintains the static I_{GAIN} but applies the reserve activation strategy formulated using the SLSQP method; and Case 1c, which integrates adaptive I_{GAIN} with the same SLSQP-based reserve activation. This comparison enables a clear assessment of how both the reserve scheduling approach and gain adaptation influence AGC effectiveness during system separation and re-synchronization. The reserve activation in Cases 1b and 1c is referred to as “optimal” within the scope defined in Section 3.3, where the SLSQP algorithm is used to compute a feasible solution that satisfies operational constraints.

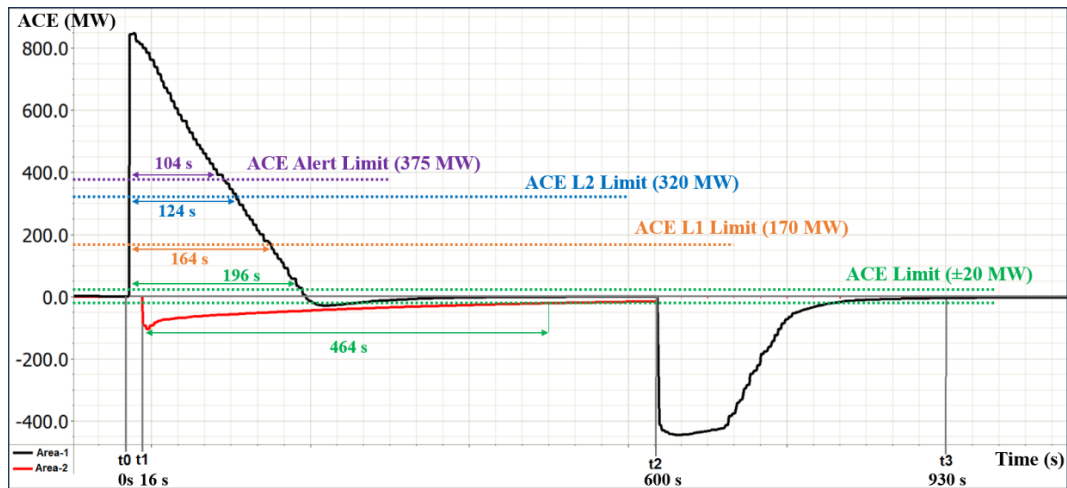


Figure 5.17. Scenario 4 – Case 1a: ACE values (static I_{GAIN} & regular FRR)

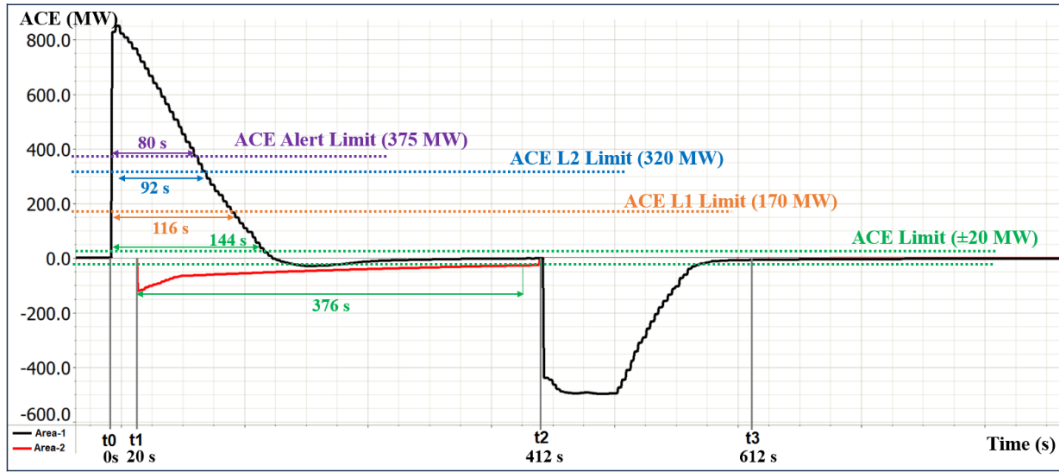


Figure 5.18. Scenario 4 – Case 1b: ACE values (static I_{GAIN} & improved FRR)

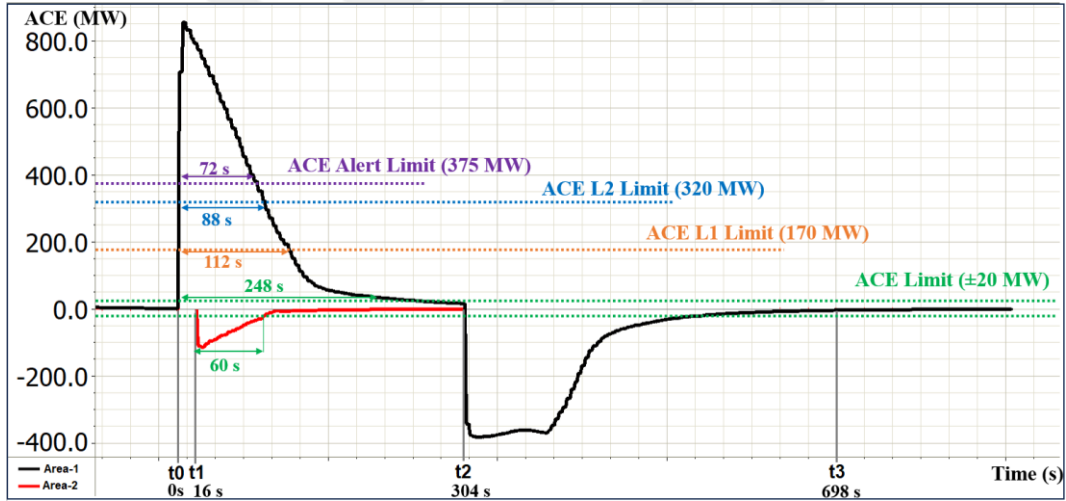


Figure 5.19. Scenario 4 – Case 1c: ACE (adaptive I_{GAIN} & improved FRR)

Figures 5.17, 5.18, and 5.19 illustrate the ACE responses for Case 1a, Case 1b, and Case 1c, respectively. In all cases, ACE for Area-2 becomes active at t_1 following system separation and disappears after merging at t_2 . During the splitting phase, Case 1c demonstrates the most effective ACE stabilization in both areas. The combination of adaptive I_{GAIN} and improved reserve scheduling results in faster ACE convergence

and smoother transitions. In comparison, Case 1a exhibits the slowest ACE recovery, indicating the limited responsiveness of static gain control combined with conventional market-based reserve deployment. Case 1b shows moderate improvement due to more efficient reserve utilization but remains less effective than the adaptive gain strategy in Case 1c. These findings highlight the added value of combining gain adaptivity with constraint-aware reserve activation for improved AGC performance during system separation and reintegration.

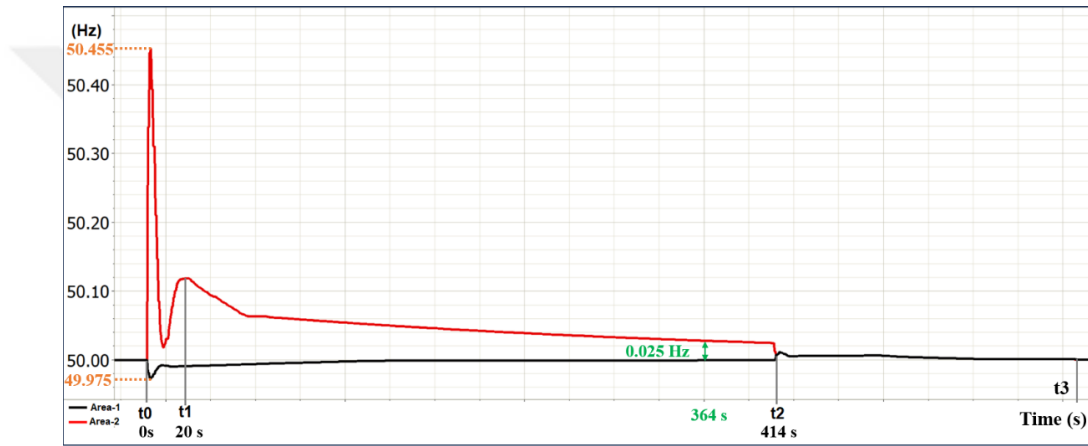


Figure 5.20. Scenario 4 – Case 1b: Frequency (static I_{GAIN} & improved FRR)

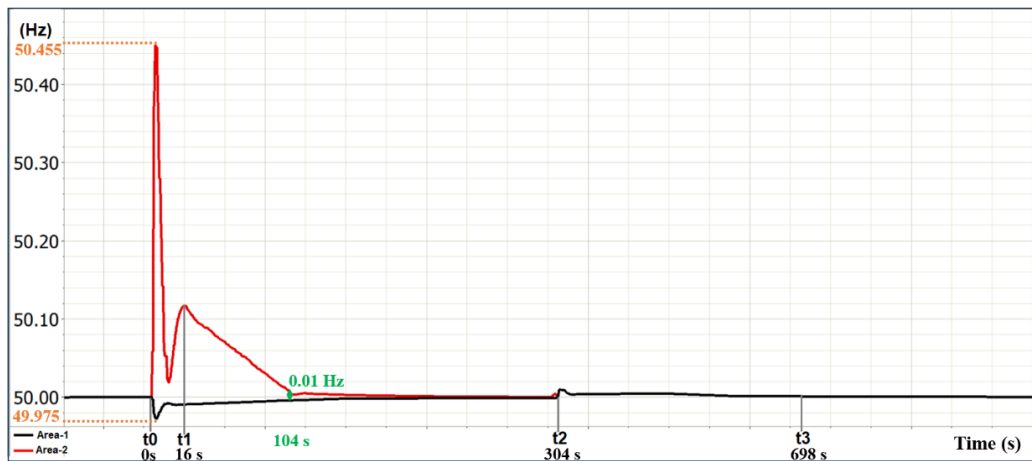


Figure 5.21. Scenario 4 – Case 1c: Frequency (dynamic I_{GAIN} & improved FRR)

Figures 5.20 and 5.21 illustrate the frequency behavior of the two control areas before, during, and after the splitting event for Case 1b and Case 1c, respectively. In both cases, Area-2 experiences significant frequency deviation immediately following separation. However, the adaptive control scheme in Case 1c demonstrates significantly faster stabilization toward nominal frequency compared to the static control in Case 1b. This accelerated recovery allows the merging process at t_2 to be initiated earlier or with a smaller inter-area frequency deviation, resulting in a smoother and more stable reconnection. These results highlight the advantages of adaptive I_{GAIN} in enhancing frequency regulation during critical post-splitting intervals and reducing the time required to restore interconnected system operation.

5.4.2 Result for Case 2

Case 2 examines the performance of the proposed AGC scheme during a grid-splitting and merging event under a different system configuration, as illustrated in Figures 5.22 and 5.23. Similar to Case 1, the network is divided into two control areas: Area-1 and Area-2. This case focuses on comparing ACE responses under two configurations: Case 2a, which applies a static I_{GAIN} in combination with the SLSQP-based reserve activation strategy, and Case 2b, which incorporates an adaptive I_{GAIN} with the same reserve activation method. The configuration involving market-based reserve activation is excluded from this case, as results from Case 1 confirmed its limited contribution to ACE performance improvement.

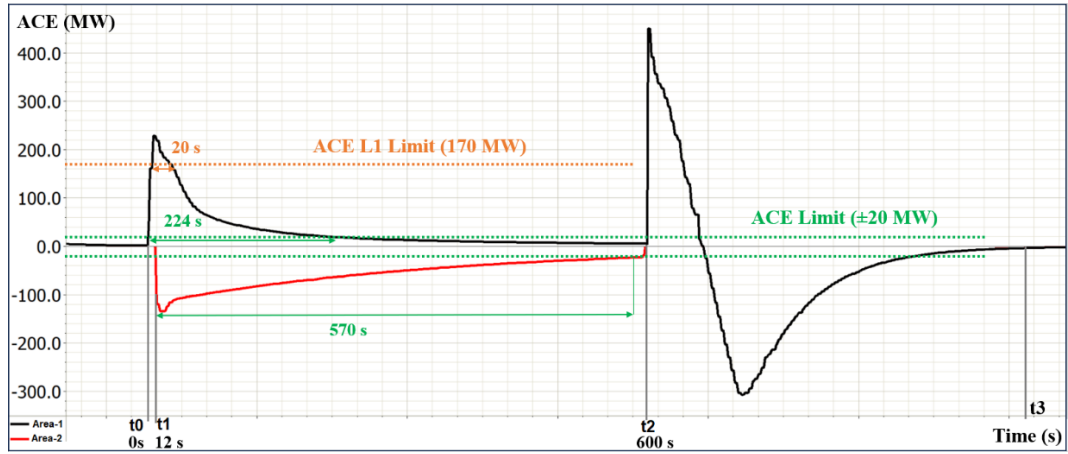


Figure 5.22. Scenario 4 – Case 2a: ACE (static I_{GAIN} & improved FRR)

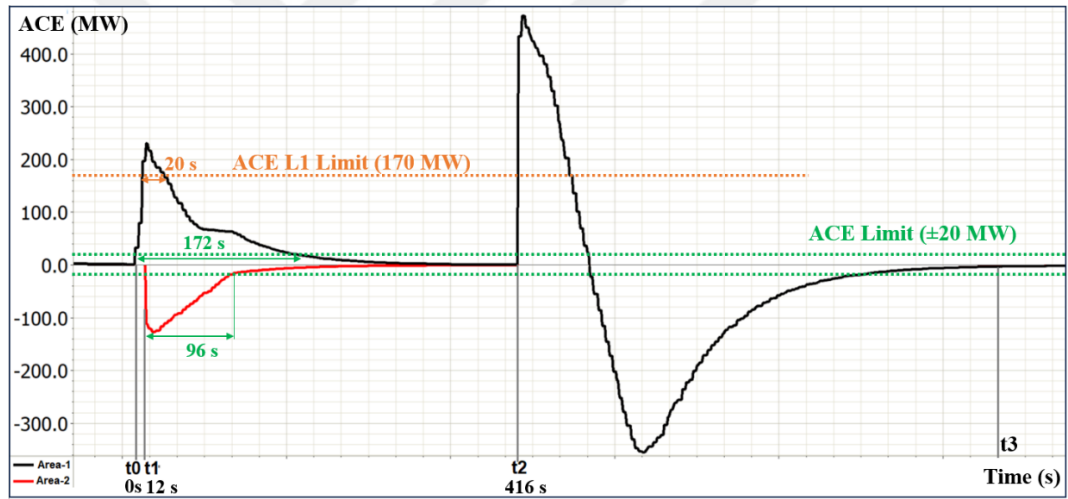


Figure 5.23. Scenario 4 – Case 2b: ACE (dynamic I_{GAIN} & improved FRR)

Figures 5.22 and 5.23 present the ACE trends for Case 2a and Case 2b, respectively. During the splitting phase, the application of adaptive I_{GAIN} in Case 2b results in significantly improved ACE stabilization for Area-2, characterized by faster recovery and smoother transitions relative to the static I_{GAIN} configuration in Case 2a. This enhanced control performance facilitates earlier merging and contributes to more efficient system re-stabilization. In contrast, improvements in Area-1 are more

limited, as ACE levels in that area were already low at the onset of separation. Following the merging phase, the AGC successfully redistributes the reserve responsibilities to the participating units, restoring them to their pre-event configurations and compensating for the control burden experienced during the separation interval.

5.4.3 Results for Case 3

Case 3 evaluates the performance of the proposed AGC scheme during an additional grid-splitting and merging event, as illustrated in Figures 5.24 and 5.25. This scenario, similar to Case 2, compares ACE responses under two configurations: Case 3a, which utilizes a static I_{GAIN} combined with the SLSQP-based reserve activation strategy, and Case 3b, which incorporates an adaptive I_{GAIN} with the same reserve activation method. As in previous cases, the configuration involving market-based reserve activation is excluded due to its minimal contribution to ACE correction, as demonstrated earlier in Case 1.

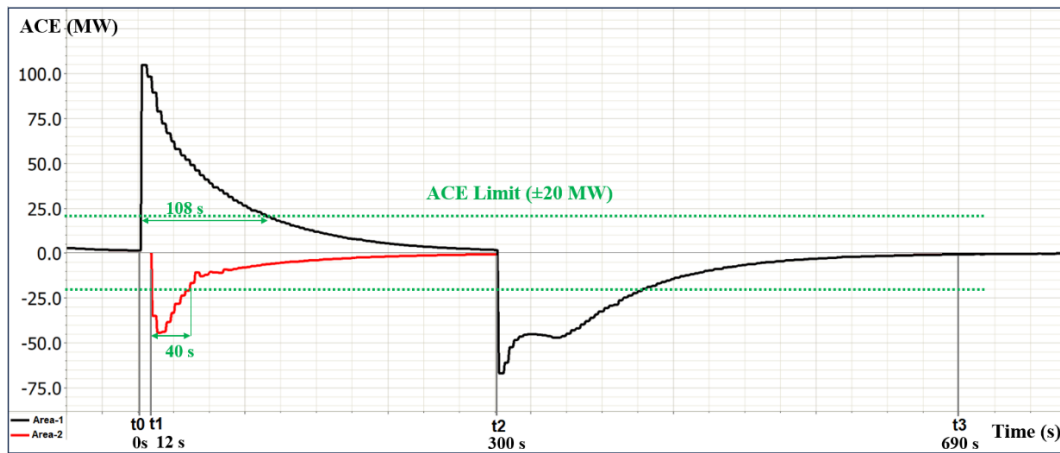


Figure 5.24. Scenario 4 – Case 3a: ACE (static I_{GAIN} & improved FRR)

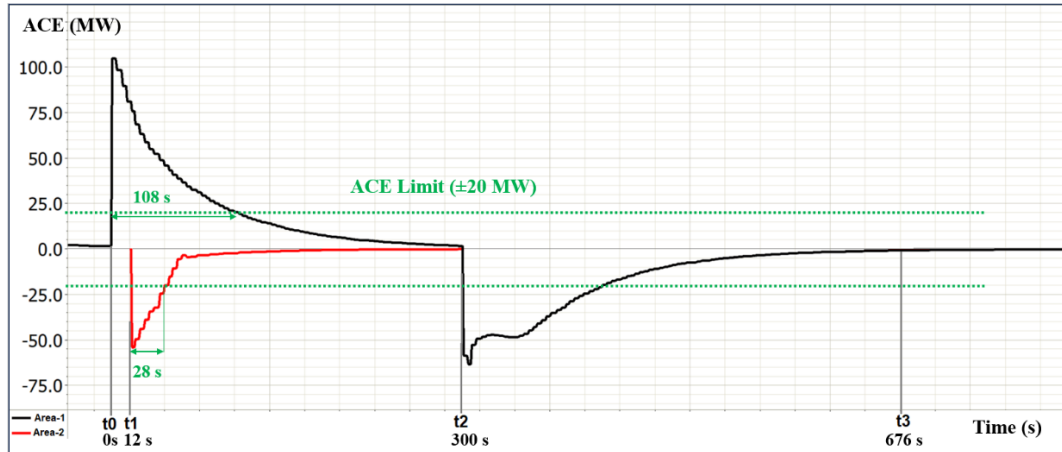


Figure 5.25. Scenario 4 – Case 3b: ACE (dynamic I_{GAIN} & improved FRR)

Figures 5.24 and 5.25 illustrate the ACE trends for Case 3a and Case 3b, respectively. During the splitting phase, the use of adaptive I_{GAIN} in Case 3b results in more pronounced improvements in ACE stabilization for Area-2, enabling a faster recovery and facilitating earlier system merging. In contrast, the impact on Area-1 remains limited, largely due to its already low ACE level at the start of the separation. As depicted in the figures, the merging process yields minimal ACE correction, primarily because the splitting scenario involves a significantly smaller control area in comparison to the other.

5.4.4 Results for Case 4

Case 4 investigates the performance of the proposed AGC scheme during a grid-splitting event involving small-area islanding with limited FRR. This case is particularly challenging due to the under-resourced control capability of the island area. Two configurations are analyzed: Case 4a and Case 4b. The objective is to assess how adaptive control improves ACE and frequency stabilization under severe reserve constraints. Figures 5.26 and 5.27 present the ACE trends, while Figures 5.28 and 5.29 illustrate the frequency responses for Case 4a and Case 4b, respectively.

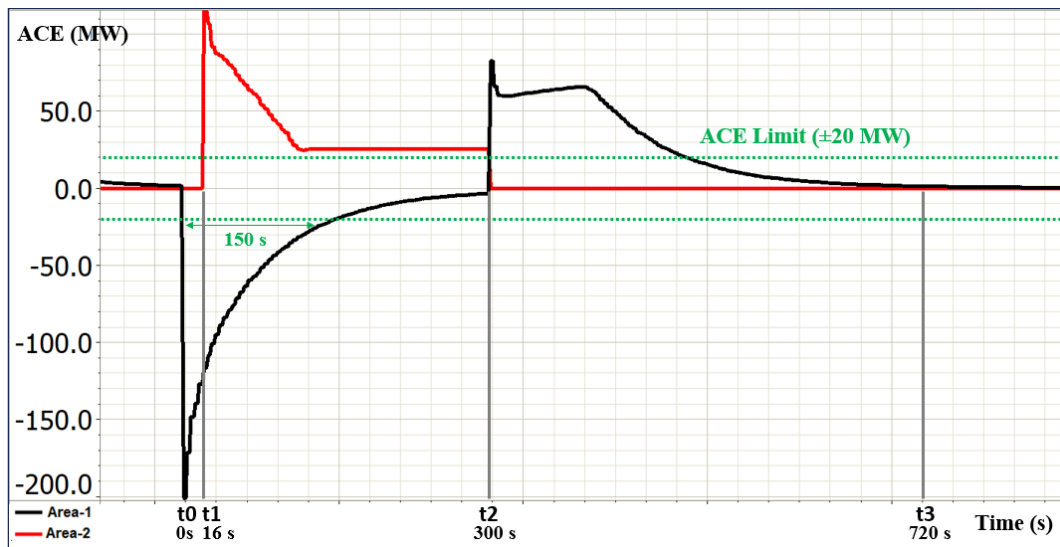


Figure 5.26. Scenario 4 – Case 4a: ACE (static I_{GAIN} & improved FRR)

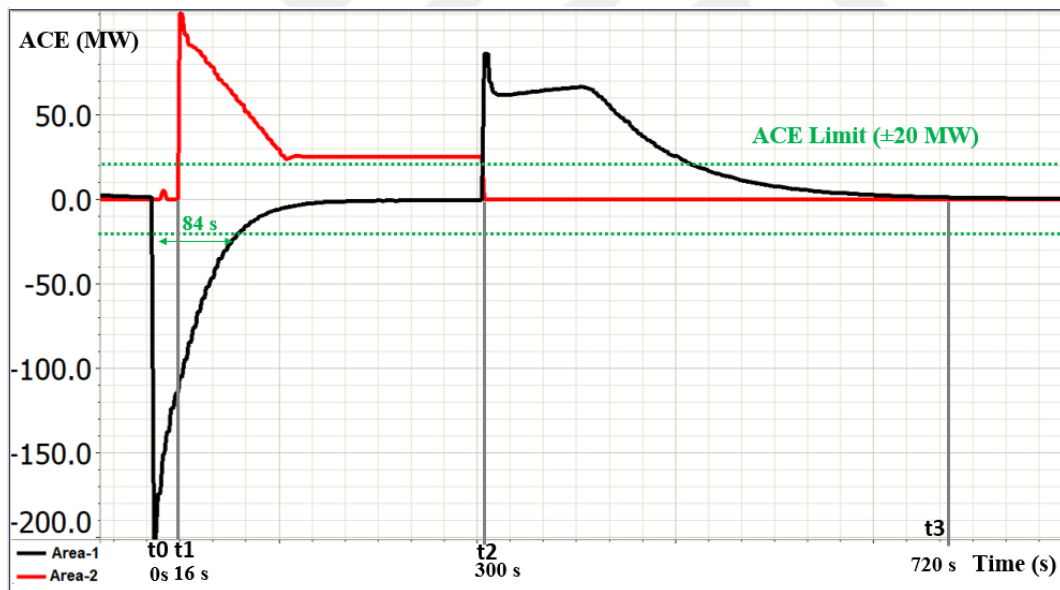


Figure 5.27. Scenario 4 – Case 4b: ACE (dynamic I_{GAIN} & improved FRR)

Figures 5.26 and 5.27 show the ACE trends for Case 4a and Case 4b, respectively. Unlike previous cases, this case exhibits opposing ACE signs in the two areas due to

system imbalance: Area-1 experiences a generation surplus, while Area-2 operates under a generation deficit. The adaptive methodology in Case 4b proves highly effective for Area-1, where the I_{GAIN} is calculated based on total inertia contribution and initial ACE using bilinear interpolation. As a result, ACE in Area-1 converges rapidly within acceptable limits. However, in Area-2, the lack of sufficient FRR prevents full ACE correction, and the value stabilizes at a persistent positive offset of approximately around +25 MW. This outcome highlights the effectiveness of the adaptive strategy when sufficient reserves are available, while also exposing the limitations of frequency regulation under severe reserve constraints.

Figures 5.28 and 5.29 present the frequency trajectories for Case 4a and Case 4b. In both cases, the frequency in Area-2 drops sharply to around 49.0 Hz following the splitting event and later stabilizes near 49.95 Hz, without fully recovering to the nominal 50 Hz. Although the adaptive I_{GAIN} methodology was implemented, its impact in Area-2 remains limited. This constrained response can be attributed to a combination of factors such as insufficient FRR volume and slow ramping characteristics.

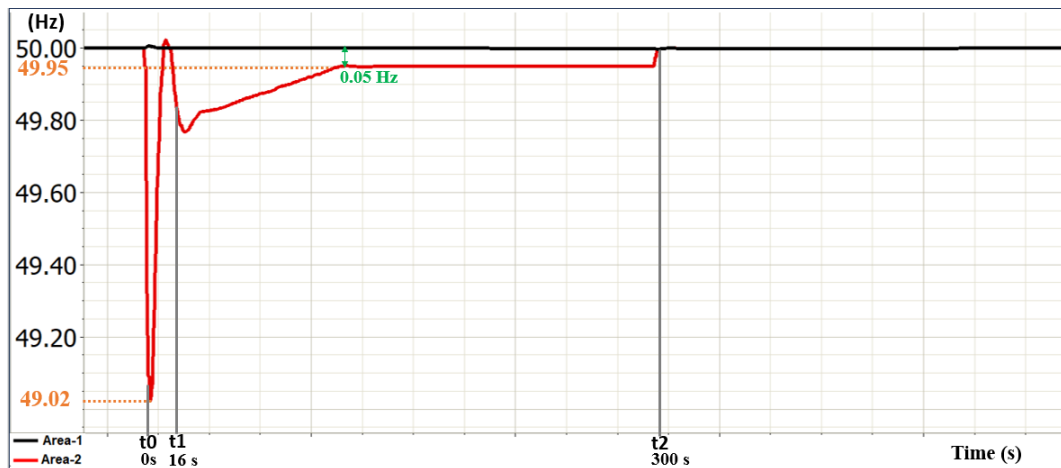


Figure 5.28. Scenario 4 – Case 4a: Frequency (static I_{GAIN} & improved FRR)

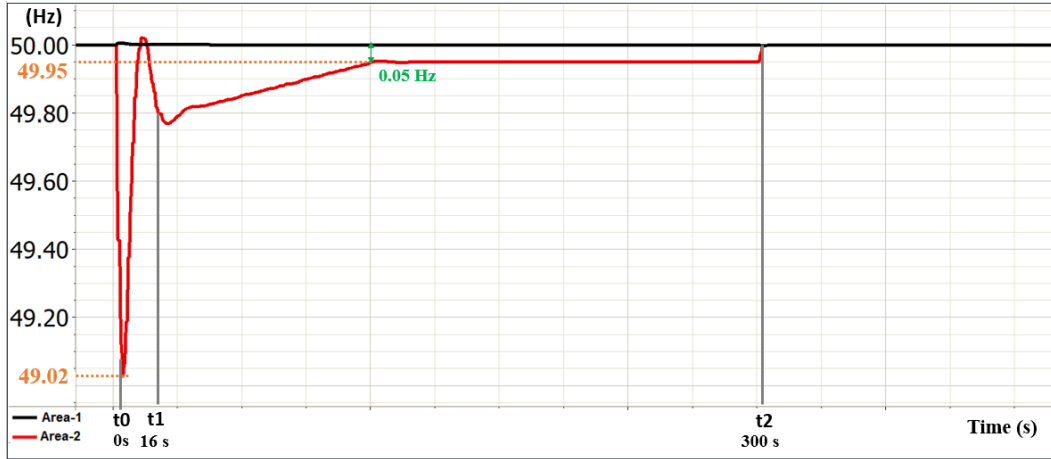


Figure 5.29. Scenario 4 – Case 4b: Frequency (dynamic I_{GAIN} & improved FRR)

5.4.5 Results for Case 5

Case 5 analyzes a grid-splitting event in which one area violates the ACE threshold and enters STOP mode, while the other remains controllable. Two configurations are evaluated: Case 5a with static I_{GAIN} , and Case 5b with adaptive I_{GAIN} , both using optimal reserve activation.

Figure 5.30 presents the ACE trends for Case 5, where static I_{GAIN} is used in combination with improved reserve activation. The splitting event occurs at t_0 , and by t_1 (after three control loops, or 12 seconds), Area-1, which is connected to the ENTSO-E system, exceeds the ACE STOP threshold of +1200 MW. Unlike previous cases, this triggers the automatic deactivation of AGC for Area-1 in accordance with real-world TSO operational logic, placing it into STOP state. However, at t_2 , the AGC detects stable conditions in Area-2 and transitions it into single-area frequency control mode, allowing independent regulation. Despite this, due to the use of a static I_{GAIN} in Case 5, ACE correction in Area-2 is slow and suboptimal, with values remaining above the acceptable ± 20 MW band for the remainder of the observation period.

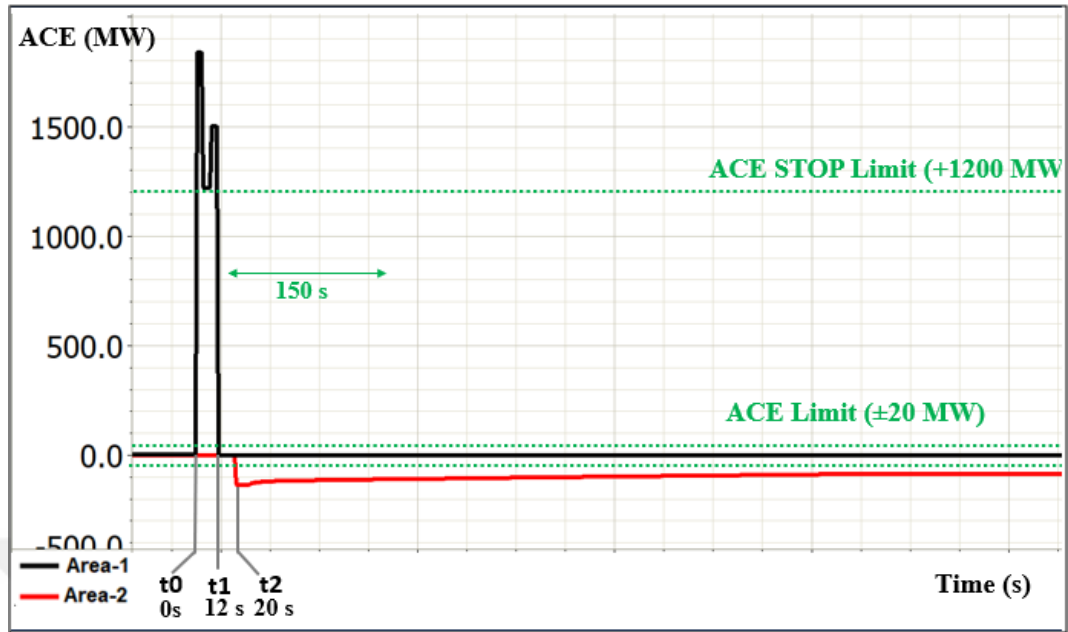


Figure 5.30. Scenario 4 – Case 5: ACE values (static I_{GAIN} & improved FRR)

In this Case, although the simulation output for the adaptive configuration could not be retained due to a critical hardware failure in the SIL environment, real-time observations indicated a clear improvement in ACE regulation in Area-2 when adaptive I_{GAIN} was employed. The adaptively tuned integrator gain enabled faster convergence and better ACE damping, enhancing local frequency control even as Area-1 remained in STOP state. These results underscore the capability of the proposed adaptive AGC scheme to maintain control continuity and improve stability under asymmetric separation scenarios where only part of the system remains within controllable limits.

5.4.6 Performance Comparison for Scenario 4

This section presents a comparative and quantitative evaluation of the proposed AGC scheme across Cases 1 to 4 in Scenario 4. Case 5 is excluded due to its distinct objective of demonstrating AGC continuity when one area enters STOP mode. The

analysis is based on ENTSO-E-compliant ACE recovery thresholds (± 375 MW, ± 320 MW, ± 170 MW, ± 20 MW), frequency convergence metrics, overshoot behavior, and merging times. The results are summarized in Table 5.3.

Table 5.3. Performance comparison of Scenario 4

Metric / Case	<i>Case 1a</i>	<i>Case 1b</i>	<i>Case 1c</i>	<i>Case 2a</i>	<i>Case 2b</i>	<i>Case 3a</i>	<i>Case 3b</i>	<i>Case 4a</i>	<i>Case 4b</i>
Splitting detection (t1-t0)	12-16 s	16-20 s	12-16 s	12-16 s	8-12 s	8-12 s	12-16 s	12-16 s	12-16 s
Time under Splitting (t2-t1)	584 s	392 s	288 s	588 s	404 s	288 s	288 s	288 s	288 s
Return to normal (t3-t2)	330 s	200 s	394 s	330 s	520 s	390 s	420 s	420 s	420 s
Area-1 ACE recovery (under 375MW)	104 s	80 s	72 s	-	-	-	-	-	-
Area-1 ACE recovery (under 320MW)	124 s	92 s	88 s	-	-	-	-	-	-
Area-1 ACE recovery (under 170MW)	164 s	116 s	112 s	20 s	20 s	-	-	-	-
Area-1 ACE recovery (into 20MW band)	196 s	144 s	248 s	224 s	172 s	108 s	108 s	150 s	84 s
Area-2 ACE recovery (into 20MW band)	464 s	376 s	60 s	570 s	96 s	40 s	28 s	-	-
Area-1 Overshoot	-30 MW	-25 MW	-	-	-	-	-	-	-
Area-2 Overshoot	-	-	-	-	-	-	-	-	-
Delta for merging f	0.025 Hz	0.025 Hz	0.01 Hz	0.025 Hz	0.01 Hz	0.01 Hz	0.01 Hz	0.04 Hz	0.04 Hz
Time to target merging f delta	584 s	344 s	88 s	588 s	112 s	60 s	36 s	300 s	300 s

As shown in Table 5.3, the adaptive AGC scheme consistently improves system performance across multiple dimensions. In Case 4, Area-2 ACE recovery within the ± 20 MW threshold improves from 150 seconds (Case 4a) to 84 seconds (Case 4b), a 44% reduction in recovery time. However, this improvement in Area-2 remains almost the same due to the lack of FRR. While the adaptive I_{GAIN} method enhances control responsiveness, its impact in Area-2 is constrained by reserve limitations.

Earlier cases further illustrate the method's impact. For instance, in Case 1, Area-2 ACE recovery time drops from 464 seconds (Case 1a) to 60 seconds (Case 1c), an 87% improvement with adaptive I_{GAIN} and improved reserve activation. Similarly, the time to reach the frequency merging threshold (e.g., $\Delta f = 0.01$ Hz) decreases from 584 s in the baseline static case to 88 s under adaptive control, demonstrating faster system resynchronization. In Cases 2 and 3, similar trends are observed, with frequency convergence times dropping to as low as 36 seconds (Case 3b).

Overshoot behavior also confirms the advantage of adaptive control. While Case 1a exhibits an overshoot of 30 MW in Area-1 and 25 MW in Case 1b, all adaptive configurations (Cases 1c, 2b, 3b, 4b) show no overshoot, contributing to smoother and more stable system transitions.

Collectively, these results validate the proposed adaptive AGC framework. It delivers faster ACE and frequency stabilization, eliminates overshoots, and supports secure grid operation during splitting and merging events, while remaining compliant with ENTSO-E performance criteria. The adaptive I_{GAIN} mechanism, supported by real-time correlation to system parameters, proves effective across a wide range of network conditions and separation scenarios.

5.5 Results for Sensitivity Analysis

To assess the robustness, scalability and sensitivity of the proposed adaptive AGC scheme, four sensitivity cases were evaluated using Scenario 4 – Case 1 as the reference. These analyses explore how variations in system-wide and local

conditions influence AGC performance, particularly the behavior of the I_{GAIN} lookup-based control under changes in total inertia contribution, load/generation levels, total FRR capacity, and dispatch configurations.

In Sensitivity Case 1 (see. Figure 5.31), both total inertia contribution and load-generation levels were reduced in Area-1 and Area-2. Area-1's total inertia contribution decreased from 180,000 to 162,000 MW·s, and Area-2's from 75,000 to 69,500 MW·s. Corresponding load-generation levels dropped from 13,253 MW to 11,200 MW in Area-1 and from 8,685 MW to 7,358 MW in Area-2. As expected, based on the established correlation between total inertia contribution and I_{GAIN} , the adaptive controller responded by increasing the I_{GAIN} values in both areas: from 0.0108 to 0.0136 in Area-1 and from 0.06 to 0.07 in Area-2.

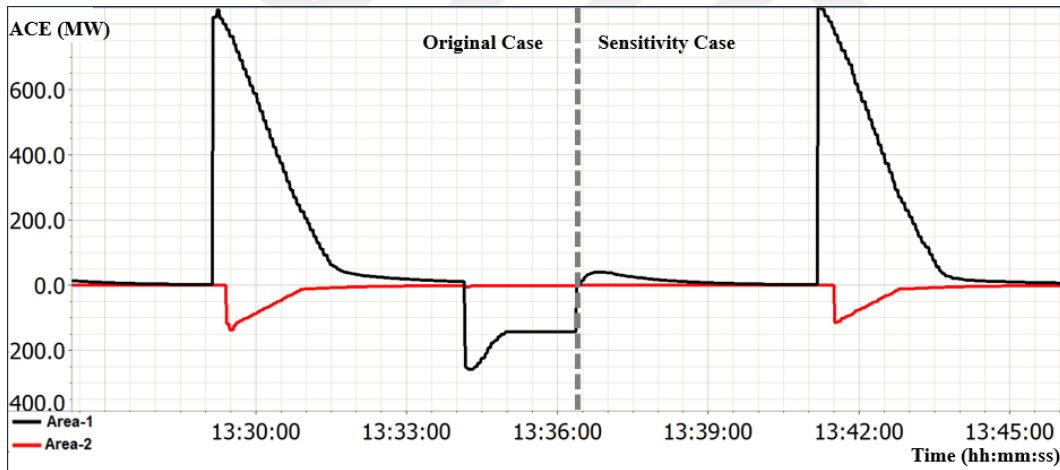


Figure 5.31. Sensitivity Case 1: ACE values (original | sensitivity)

In Sensitivity Case 2, only the total inertia contribution of Area-2 was reduced, while Area-1 remained unchanged. Although load-generation levels were slightly lowered in both areas, no change in I_{GAIN} was observed for Area-1, consistent with the fact that its total inertia contribution and initial ACE remained constant. This result confirms that the adaptive scheme responds primarily to changes in total inertia

contribution, rather than load or generation values alone. In contrast, the I_{GAIN} value for Area-2 increased in response to the local reduction in total inertia contribution, demonstrating the area-specific responsiveness of the adaptive method and its ability to update control parameters independently, without unintended influence across areas. The results are shown in Figure 5.32.

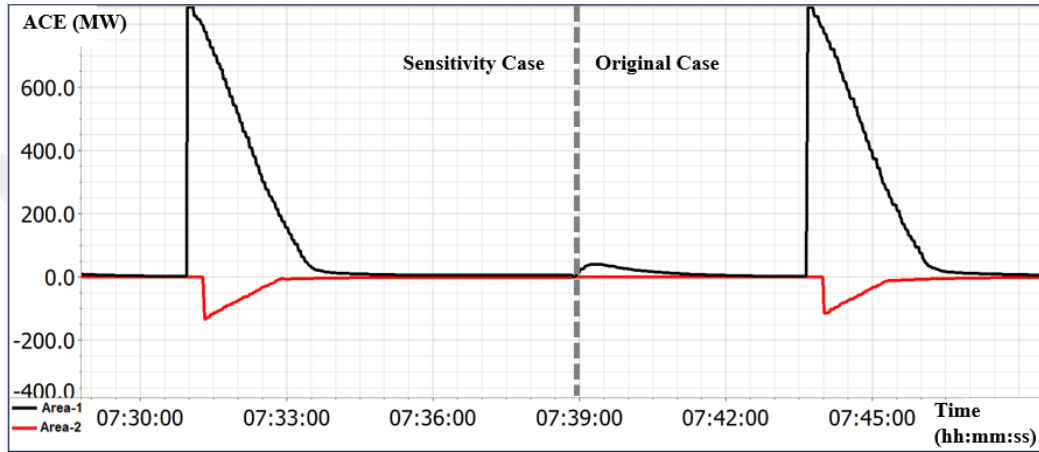


Figure 5.32. Sensitivity Case 2: ACE values (sensitivity | original)

Sensitivity Case 3 (see. Figure 5.33) evaluated the impact of a reduction in FRR in Area-2, from 715.1 MW to 579.4 MW, while keeping total inertia contribution and load-generation levels unchanged in both areas. The proposed AGC scheme maintained stable ACE performance across both areas, indicating that the correlation-based I_{GAIN} formulation, which relies primarily on total inertia contribution, is not significantly affected by moderate changes in FRR. This result reinforces the methodological choice to prioritize total inertia contribution over reserve volume in determining control gain values.

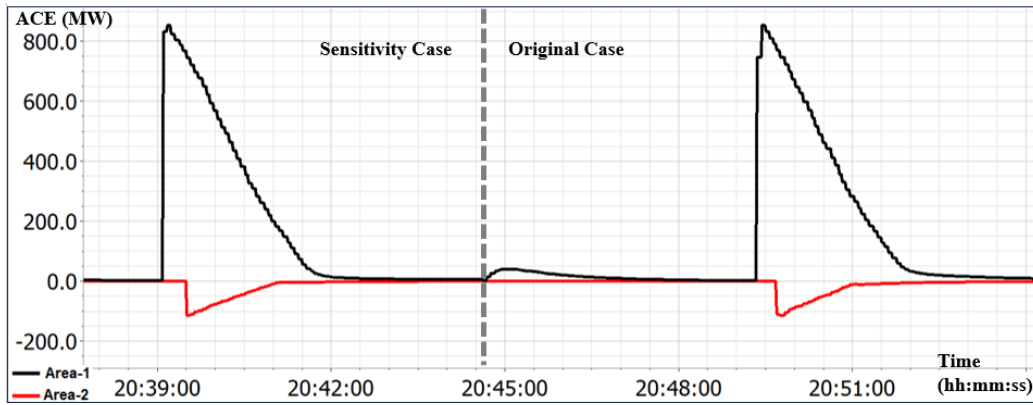


Figure 5.33. Sensitivity Case 3: ACE values (sensitivity | original)

Finally, in Sensitivity Case 4 (Figure 5.34), a 1000 MW generation shift from Area-2 to Area-1 was implemented, creating a dispatch imbalance and inducing positive ACE in both areas. Despite this asymmetric load redistribution, the adaptive AGC correctly recalculated the I_{GAIN} values based on the new ACE profiles, ensuring effective control action under both static and adaptive configurations.

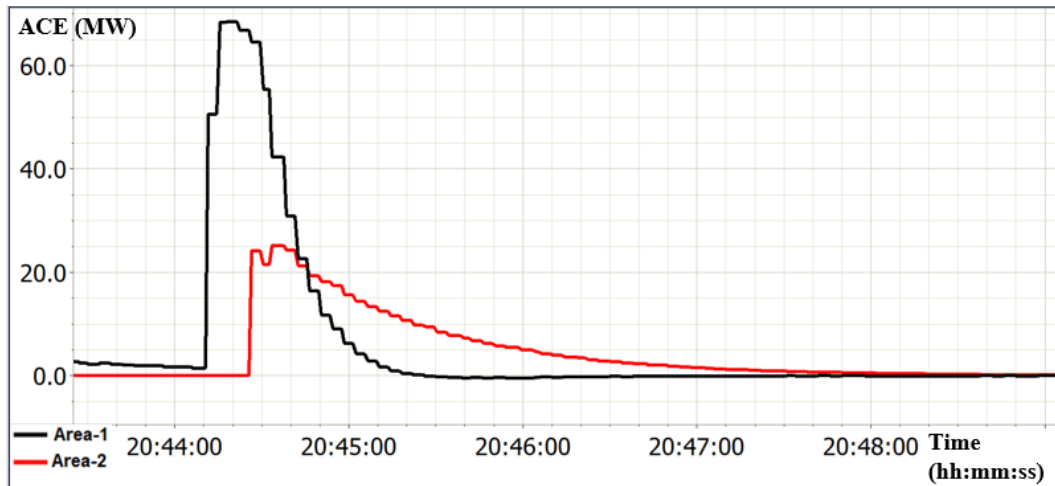


Figure 5.34. Sensitivity Case 4: ACE values

A summary of system parameters and observed control behavior across all sensitivity cases is provided in Table 5.4. These results confirm that the proposed adaptive AGC approach remains stable, modular, and responsive across a wide range of system conditions. Although the computed I_{GAIN} values may not be strictly optimal in every configuration, the overall control strategy demonstrates resilience and alignment with ENTSO-E performance expectations, even under non-nominal operating scenarios.

Table 5.4. Summary of the sensitivity analysis

Metric	Area-1 (Base)	Area-2 (Base)	Area-1 (Sens.)	Area-2 (Sens.)	Sensitivity Case	Observation
$\sum H \cdot P$ (MW·s)	180000	75000	162500	69500	Case-1: Reduced total inertia contribution, reduced load/gen level, Same FRR and dispatch	Slight I_{GAIN} increase in both areas as expected (adaptive method), ACE stable
Load/P Level (MW)	13253	8685	11199	7358		
$\sum H \cdot P$ (MW·s)	180000	75000	180000	69500	Case 2: Reduced total inertia contribution (Area-2 only), reduced load/gen levels, same FRR and dispatch	Area-1 remains same, I_{GAIN} increases in Area-2, performance stable
Load/P Level (MW)	13253	8685	11199	7358		
$\sum \text{FRR}$ (MW)	896,9	715,1	896,9	579,4	Case 3: Reduced FRR (Area-2), same total inertia contribution, load/gen levels, and dispatch	No significant change
Load/P Level (MW)	13253	8685	12253	9685	Case 4: Different dispatch (shifted gen. from Area-2 to Area-1), same total inertia contribution, load/gen levels, and FRR.	Effective adaptive control, both I_{GAIN} values adjusted based on initial ACE handled effectively

5.6 Evaluation on Scalability and Detection Dynamics

This section presents an evaluation of the proposed AGC scheme in terms of its scalability to larger and more complex power systems and its detection dynamics under system splitting conditions. The assessment aims to evaluate the applicability of the coherency-based detection method to complex, interconnected grids and to quantify the responsiveness of the detection mechanism, including considerations for converter-based generations.

The frequency-based coherency detection logic developed in this study has been validated on both the IEEE 9-bus test system and a dynamic model of the Turkish transmission network. The underlying methodology is generalizable to larger and more complex systems, including those operated by TSOs located in the central region of the ENTSO-E synchronous area. In such configurations, however, a splitting event may result in sub-regions that remain electrically connected to strong neighboring systems. These regions often exhibit high inertia and external frequency support, which may cause slower or smaller frequency deviations, making detection more challenging.

To improve robustness in these conditions, the detection method can be refined through several enhancements. The frequency deviation threshold can be adaptively tuned based on local grid strength and measurement resolution. Extending the observation window allows for the identification of slower divergence patterns, particularly in high-inertia environments. Moreover, incorporating additional indicators, such as RoCoF and phase angle differences, can provide complementary information to enhance detection accuracy. In systems with dense measurement infrastructures, advanced clustering techniques such as graph-based or spectral clustering can further improve the identification of coherent generator groups.

In terms of responsiveness, the proposed AGC scheme is able to operate on a 1-second control loop, consistent with ENTSO-E's recommended AGC cycle intervals of 1 to 5 seconds. The splitting detection mechanism is able to be completed within

three AGC cycles, resulting in an average response time of approximately 3 seconds between the onset of the disturbance and the initiation of independent area control. This detection speed has been found sufficient for systems with conventional synchronous generation, where frequency transients develop more slowly due to high inertia.

The integration of converter-based generation does not fundamentally compromise the applicability of the proposed detection method, provided that these units are capable of participating in frequency regulation through suitable control schemes. Although the dynamic response of converter-based resources differs from that of conventional synchronous machines, they can still support AGC operations if appropriately configured. In low-inertia environments where converter-based generation dominates, the frequency response may become more sensitive and faster, which may necessitate adjustments to the splitting detection logic. To ensure continued splitting detection accuracy under such conditions, complementary indicators such as RoCoF and PMU-based phase angle measurements may be incorporated to capture faster and more complex dynamic behaviors. In parallel, faster AGC control loop cycles are required to effectively respond to these rapid changes.

In conclusion, the proposed AGC scheme demonstrates strong potential for scalable application in real-world power systems. Its coherency-based splitting detection integrated with AGC is adaptable to complex grid conditions, and its detection latency is sufficiently low to support timely reconfiguration of control loops.



CHAPTER 6

CONCLUSION

This study introduces a novel adaptive and flexible AGC scheme specifically designed to operate effectively during power system splitting and reconnection events. The proposed scheme ensures continuous frequency regulation and tie-line control by autonomously and simultaneously managing control areas, dynamically adjusting control parameters, and facilitating seamless system re-integration in line with ENTSO-E operational standards.

The proposed methodology consists of two consecutive and interdependent main stages: Area management and flexible AGC operations. The area management stage enables real-time identification and handling of system separation by employing an online frequency-based coherency detection algorithm. By applying network-specific frequency deviation thresholds, the method reliably detects system splitting within the control loop interval, while incorporating safety margins to prevent false triggers due to transient fluctuations. Upon detection, the AGC automatically reorganizes control loops for each coherent area, assigns appropriate operational modes, and initializes area-specific parameters such as bias factors and reserve capacities. This ensures flexible, continuous, and localized load-frequency control with adaptivity and prepares each area for safe and coordinated reconnection.

The proposed methodology also incorporates two complementary control approaches to achieve adaptivity. First, a dynamic PI control strategy adjusts the I_{GAIN} in real time based on ACE and ACS, offering effective regulation during normal operation and in topologically simple networks. However, under complex and wide networks, dynamic gain adjustment alone becomes inadequate due to rapid topology changes and parameter variability. To address this, a correlation-based adaptive I_{GAIN} method is introduced, which maps gain values to system parameters

like total inertia contribution. This approach is implemented through a six-step process: Defining network-specific splitting scenarios, heuristic tuning, correlation analysis, look-up table construction, interpolation or extrapolation, and integration into AGC logic. As a result, the AGC selects context-aware gain values in real time, ensuring robust control performance even during severe separation events.

In addition to the adaptive control design, an improved reserve activation strategy is implemented using the SLSQP optimization method. This mechanism optimizes the deployment of automatic FRR within each control area, while respecting operational constraints such as ramp limits and reserve capacities. The combined use of adaptive I_{GAIN} tuning and SLSQP-based reserve scheduling significantly improves AGC performance in terms of ACE clearance speed, frequency stability, and overall reliability during system separation events.

The proposed AGC scheme is validated in a SIL environment (developed during this study) using both a modified IEEE 9-bus test system and a dynamic model of the Turkish transmission network. A wide range of realistic scenarios, including splitting, reconnection, and load disturbances, are tested alongside sensitivity analyses to evaluate robustness under varying inertia, reserve levels, and dispatch conditions.

Simulation results clearly demonstrate the effectiveness of the proposed AGC scheme under both normal and splitting conditions. Compared to conventional static control, the dynamic and adaptive I_{GAIN} approaches significantly reduce ACE recovery times and mitigate overshoots. For example, in splitting scenarios, the adaptive method achieved up to an 87% reduction ACE clearance while maintaining stability within ENTSO-E-defined limits. The SLSQP-based reserve activation further enhanced performance by ensuring timely and efficient deployment of available FRR, particularly in isolated areas with limited resources. Additionally, sensitivity analyses confirmed that the adaptive gain mechanism responded appropriately to changes in system conditions such as inertia and reserve distribution, preserving robust control performance across a range of operating conditions.

The growing frequency and impact of system separation events across the ENTSO-E region have highlighted the limitations of conventional AGC strategies, especially those that become inactive or ineffective during major disturbances. The proposed adaptive AGC scheme addresses these limitations by enabling real-time control continuity, dynamic gain adaptation based on system-specific parameters, and optimized reserve deployment even in split or islanded regions. These capabilities align with the evolving needs of TSOs and provide a concrete foundation for enhancing ENTSO-E operational policies. In particular, the findings of this study may support future revisions to the Load-Frequency Control and Reserves framework by demonstrating the feasibility and effectiveness of maintaining active AGC functionality during network splitting and reconnection events.

Despite the demonstrated effectiveness of the proposed AGC scheme, certain limitations should be acknowledged. First, as the number of split areas increases, distinguishing coherency groups in real time may become challenging, which can affect scalability and performance. Second, while the correlation-based I_{GAIN} tuning significantly enhances performance, alternative gain values could potentially yield even better results through advanced data-driven or machine learning techniques. Nevertheless, this study prioritizes practical applicability and ease of implementation, ensuring alignment with real-world operational requirements and ENTSO-E standards. Third, the look-up table should be kept dynamic by incorporating newly observed scenarios for better long-term accuracy. Moreover, adapting the methodology to other networks requires careful system-specific scenario definition. Lastly, while this work focuses on I_{GAIN} , future studies may explore joint adaptation of proportional gains to further improve performance. These considerations aim to refine, rather than diminish, the practical value and generalizability of the proposed approach.

Overall, this study contributes a practical and scalable AGC solution for modern power systems facing growing complexity due to renewable integration and dynamic operational conditions. The scheme's real-time adaptability, regulatory compliance, and effectiveness in both interconnected and isolated grids mark a significant

advancement in control system design for TSOs. Future work may extend this framework by incorporating also incorporating proportional gain adaptation, integrating predictive modeling for renewable fluctuations, and applying data-driven approaches to improve gain estimation under evolving grid topologies.



REFERENCES

- [1] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc, 1994.
- [2] J. Machowski, J. W. Bialek, and J. R. Bumby, Power System Dynamics: Stability and Control, Wiley, 2008.
- [3] C. W. Taylor, Power System Voltage Stability, McGraw-Hill, Inc., 1994.
- [4] ENTSO-E, "ENTSO-E Annual Report 2021," 2021. [Online]. Available: <https://annualreport2021.entsoe.eu/>.
- [5] ENTSO-E, "PROJECT INERTIA – PHASE II: Updated Frequency Stability Analysis in Long Term Scenarios, Relevant Solutions and Mitigation Measures," Technical Report, 2021. [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/sdc-documents/231108_Project_Inertia_Phase_II_First_Report_FOR_PUBLICATION_clean.pdf.
- [6] ENTSO-E, "Continental Europe Synchronous Area Separation on 08 January 2021," Executive Summary, Oct. 2021. [Online]. Available: https://www.entsoe.eu/Documents/SOC%20documents/SOC%20Reports/Continental_Europe_Synchronous_Area_Separation_on_08_January_2021_-_Executive_Summary_updated.pdf.
- [7] G. Fotis, V. Vita, and T.I. Maris, "Risks in the European Transmission System and a novel restoration strategy for a power system after a major blackout", Applied Sciences, no. 13(1), pp. 83, Dec. 2022, doi:10.3390/app13010083.

- [8] ENTSO-E, "Continental Europe Synchronous Area Separation on 24 July 2021," Technical Report, Nov. 2021. [Online]. Available: <https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/SOC%20Reports/entso-e CESysSep 210724 211112.pdf>.
- [9] ENTSO-E, "Grid incident in south-eastern part of the Continental Europe power system - Update," ENTSO-E News, Jul. 2024. [Online]. Available: <https://www.entsoe.eu/news/2024/07/15/grid-incident-in-south-eastern-part-of-the-continental-europe-power-system-update/>.
- [10] Project Group Turkey, "Report on Blackout in Turkey on 31st March 2015" ENTSO-E Technical Report, Jun. 2015. [Online]. Available: <https://docs.entsoe.eu/dataset/ops-report-turkey-blackout-march-2015>.
- [11] L. Saribulut, G. Ok, A. Ameen, "A Case Study on National Electricity Blackout of Turkey" Energies, 16, 4419, May 2023, doi:10.3390/en16114419.
- [12] ENTSO-E, "Synchronous 1 Area Operational Agreement for the Synchronous Area CE – Annex 1: Policy on Load-Frequency Control and Reserves," 2024.
- [13] K. Peddakapu, et al. "A state-of-the-art review on modern and future developments of AGC/LFC of conventional and renewable energy-based power systems," Renewable Energy Focus, vol. 43, pp. 146–171, Sep. 2022, doi:10.1016/j.ref.2022.09.006.
- [14] R. Verma et al. "A state of art review on the opportunities in automatic generation control of hybrid power system", Electric Power Systems

Research, vol. 226, pp. 109945, Oct. 2023
doi:10.1016/j.epsr.2023.109945.

- [15] M. Ranjan and R. Shankar, "A literature survey on load frequency control considering renewable energy integration in power system: Recent trends and future prospects", *Journal of Energy Storage*, 45, p. 103717. doi:10.1016/j.est.2021.103717.
- [16] Y. Güler, M. Nalbantoğlu, and İ. Kaya, "Cascade controller design via controller synthesis for load frequency control of electrical power systems," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 32: No. 2, Article 5 (2024) <https://doi.org/10.55730/1300-0632.4069>
- [17] N. Kumar, V. Kumar, and B. Tyagi, "Optimization of PID parameters using BBBC for a multiarea AGC scheme in a deregulated power system," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 24: No. 5, Article 58, (2016). <https://doi.org/10.3906/elk-1408-36>
- [18] H. Bevrani, F. Daneshfar and T. Hiyama, "A New Intelligent Agent-Based AGC Design With Real-Time Application," in *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 42, no. 6, pp. 994-1002, Nov. 2012, doi: 10.1109/TSMCC.2011.2175916.
- [19] C. Tan et al., "Multi-Area Automatic Generation Control Scheme Considering Frequency Quality in Southwest China Grid: Challenges and Solutions," in *IEEE Access*, vol. 8, pp. 199813-199828, 2020, doi: 10.1109/ACCESS.2020.3035067.
- [20] N. C. Patel, B. K. Sahu, and M. K. Debnath, "Automatic generation control analysis of power system with nonlinearities and electric vehicle

aggregators with time varying delay implementing a novel control strategy," Turkish Journal of Electrical Engineering and Computer Sciences: Vol. 27: No. 4, Article 47. <https://doi.org/10.3906/elk-1809-131>

- [21] N. NGuyen, Q. Huang, and T. Dao, "An investigation of intelligent controllers based on fuzzy logic and artificial neural network for power system frequency maintenance," in Turkish Journal of Electrical Engineering and Computer Sciences, vol. 24, no. 4, article 61, Apr. 2016 doi: 10.3906/elk-1404-165
- [22] S. Jasmine G, M. Mary D, and Thenmalar K, "Fuzzy logic based load frequency control of power system", Materials Today: Proceedings, vol. 45, p. 9, pp. 8170-8175, 2021, doi:10.1016/j.matpr.2021.02.536.
- [23] B. Li and J. Chen, "Automatic Generation Control Strategy Based on Deep Forest," in IEEE Access, vol. 11, pp. 23495-23504, 2023, doi: 10.1109/ACCESS.2023.3254501.
- [24] L. Yin, L. Zhao, T. Yu, and X. Zhang, "Deep Forest Reinforcement Learning for Preventive Strategy Considering Automatic Generation Control in Large-Scale Interconnected Power Systems," Applied Sciences, 8(11):2185, 2018, doi:10.3390/app8112185.
- [25] G.-Q. Zeng, X.-Q. Xie, and M.-R. Chen, "An Adaptive Model Predictive Load Frequency Control Method for Multi-Area Interconnected Power Systems with Photovoltaic Generations", Energies, 10, 1840, Nov. 2017, doi:10.3390/en10111840.
- [26] K. Chen, J. Lin, Y. Qiu, F. Liu and Y. Song, "Model Predictive Control for Wind Farm Power Tracking With Deep Learning-Based Reduced Order

- Modeling," in IEEE Transactions on Industrial Informatics, vol. 18, no. 11, pp. 7484-7493, Nov. 2022, doi: 10.1109/TII.2022.3157302.
- [27] J. He, C. Shi, T. Wei and D. Jia, "Stochastic Model Predictive Control of Hybrid Energy Storage for Improving AGC Performance of Thermal Generators," in IEEE Transactions on Smart Grid, vol. 13, no. 1, pp. 393-405, Jan. 2022, doi: 10.1109/TSG.2021.3111610.
- [28] A. Oshnoei, M. Kheradmandi, R. Khezri and A. Mahmoudi, "Robust Model Predictive Control of Gate-Controlled Series Capacitor for LFC of Power Systems," in IEEE Transactions on Industrial Informatics, vol. 17, no. 7, pp. 4766-4776, July 2021, doi: 10.1109/TII.2020.3016992.
- [29] N.Z. Saharuddin, Zainal Abidin, H. Mokhlis, K. Naidu, "Intentional Islanding Methods as Post Fault Remedial Action: A Review" in Indonesian Journal of Electrical Engineering and Computer Science, vol. 12, no. 1, pp. 182-192, October 2018
- [30] Z. Lin, F. Wen, J. Zhao, Y. Xue, "Controlled Islanding Schemes for Interconnected Power Systems Based on Coherent Generator Group Identification and Wide-Area Measurements," in J. Mod. Power Syst. Clean Energy, vol. 4, no. 3, pp. 440-453, June 2016
- [31] Z. Lin et al., "WAMS-Based Coherency Detection for Situational Awareness in Power Systems With Renewables," in IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 5410-5426, Sept. 2018.
- [32] M. Naglic, M. Popov, M. A. M. M. van der Meijden and V. Terzija, "Synchronized Measurement Technology Supported Online Generator Slow Coherency Identification and Adaptive Tracking," in IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 3405-3417, July 2020.

- [33] T. Jiang, H. Jia, H. Yuan, N. Zhou and F. Li, "Projection Pursuit: A General Methodology of Wide-Area Coherency Detection in Bulk Power Grid," in *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 2776-2786, July 2016.
- [34] A. M. Khalil and R. Iravani, "A Dynamic Coherency Identification Method Based on Frequency Deviation Signals," in *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 1779-1787, May 2016.
- [35] Z. Lin et al., "Application of Wide Area Measurement Systems to Islanding Detection of Bulk Power Systems," in *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 2006-2015, May 2013.
- [36] B. G. Wang, B. H. Zhang, Z. G. Hao, J. Shu, P. Li and Z. Q. Bo, "A Novel Real-Time Searching Method for Power System Splitting Boundary," in *IEEE Transactions on Power Systems*, vol. 25, no. 4, pp. 1902-1909, Nov. 2010.
- [37] P. Pinceti and M. Vanti, "An Algorithm for the Automatic Detection of Islanded Areas Inside an Active Network," in *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 3020-3028, Nov. 2015.
- [38] W. Liu, Y. Liu, and Y. Wang, "Modeling and simulation of AGC systems with frequency control under islanding conditions," *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4728–4737, 2017.
- [39] H. Bevrani, A. Ghosh, and G. Ledwich, "A review of intelligent control techniques applied to load frequency control," in *Proc. IEEE Int. Conf. Industrial Technology (ICIT)*, 2010, pp. 1404–1409.

- [40] A. Molina-García, F. Bouffard, and D. S. Kirschen, "Decentralized demand-side contribution to primary frequency control," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 411–419, Feb. 2011.
- [41] Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., ... and SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, 17(3), 261-272.
- [42] Zhang et al., *Power System Coherency Recognition and Islanding: Practical Limits and New Indicators*, 2023.
- [43] Schäfer & Yalcin, "Dynamical Modelling of Cascading Failures in the Turkish Power Grid", 2019.
- [44] Kock et al., "Analysis and Simulations of the Primary Frequency Control During a System Split", 2021
- [45] S. W. Sung, J. Lee, In-B. Lee, "Proportional–Integral–Derivative Controller Tuning," in *Process Identification and PID Control*, John Wiley & Sons (Asia) Pte Ltd, 2009, ch. 5, sec. 2, pp. 151–199.
- [46] R. Chattamvelli, "Pearson's Correlation," in *Correlation in Engineering and the Applied Sciences - Synthesis Lectures on Mathematics & Statistics*, Cham, Springer, 2024, doi:10.1007/978-3-031-51015-1_2.
- [47] P. McNamara and F. Milano, "Efficient implementation of MPC-based AGC for real-world systems with low inertia," *Electric Power Systems Research*, vol. 158, pp. 315–323, 2018, doi:10.1016/j.epsr.2018.01.017.

- [48] K. T. Gribbon and D. G. Bailey, "A novel approach to real-time bilinear interpolation," Proceedings. DELTA 2004. Second IEEE International Workshop on Electronic Design, Test and Applications, Perth, WA, Australia, 2004, pp. 126-131, doi: 10.1109/DELTA.2004.10055.

- [49] G. Torrisi, S. Grammatico, R. S. Smith and M. Morari, "A variant to Sequential Quadratic Programming for nonlinear Model Predictive Control," 2016 IEEE 55th Conference on Decision and Control (CDC), Las Vegas, NV, USA, 2016, pp. 2814-2819, doi: 10.1109/CDC.2016.7798688.



APPENDICES

A. DETAILS ON THE CORRELATION ANALYSIS

Appendix A provides a detailed account of the statistical analysis conducted to assess the correlation between I_{GAIN} and key power system parameters under varying ACE levels. The analysis employs Pearson's correlation coefficient (ρ), which quantifies the strength and direction of a linear relationship between two variables. The coefficient ranges from -1 (a perfect negative linear correlation) to $+1$ (a perfect positive linear correlation), with values near ± 1 reflecting strong linear association.

Each computed correlation value is accompanied by a *p-value*, which indicates the statistical significance of the observed relationship. A *p-value* below 0.05 is typically considered statistically significant, implying that the correlation is unlikely to be due to random chance. However, due to the limited number of observations ($n = 3$ scenarios per ACE level), some correlations lack statistical significance despite showing strong trends. These trends, while not conclusive in a strict statistical sense, still provide meaningful insights and are valuable for engineering interpretation and control strategy development.

To assess the statistical significance of each observed correlation, a *p-value* is calculated under the null hypothesis that no true linear relationship exists in the underlying population. The test statistic (t_{stat}) is computed as in (A.1):

$$t_{\text{stat}} = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}} \quad (\text{A.1})$$

This statistic follows a Student's *t*-distribution with $n-2$ degrees of freedom, assuming the null hypothesis is true. The Student's *t*-distribution is a probability distribution commonly used in hypothesis testing when the sample size is small and the population variance is unknown. In this study, it provides the reference

distribution for evaluating the significance of the computed Pearson correlation coefficients. Specifically, the t-statistic derived from the correlation coefficient follows a t-distribution with $n - 2$ degrees of freedom, enabling the calculation of p-values that account for small-sample uncertainty. The p-value is obtained by evaluating the tail probability of the corresponding distribution as in (A.2):

$$p - value = 2 \cdot (1 - F_t(|t_{stat}|)) \quad (A.2)$$

Where F_t is the Cumulative Distribution Function (CDF) of the t-distribution with $n - 2$ degrees of freedom. The resulting *p-value* quantifies the probability of observing a correlation coefficient as extreme as ρ , assuming no actual correlation exists. In most statistical analyses, a threshold of $p < 0.05$ was used to determine significance. However, due to the limited number of observations per ACE level in this study ($n=3$), p-values should be interpreted with caution. Even if not statistically significant, strong correlations may still offer valuable engineering insights. The following tables (Table A.1 to Table A.8) present the results for the correlation analysis in this study.

Table A.1. The correlation table (Area 1, ACE=600)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.95	0.204	Strong negative correlation, but not statistically significant ($p > 0.05$) due to low sample size
FRR	-0.86	0.34	Strong negative correlation, but again, not statistically significant
T.Load	-0.87	0.33	Similar to FRR — strong trend but inconclusive
H	+0.86	0.35	Unexpected positive correlation with I_{GAIN} (opposite of expected), and not significant

Table A.2. The correlation table (Area 1, ACE=480)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.96	0.17	Very strong negative correlation, but not statistically significant due to limited sample size
FRR	-0.89	0.30	Strong negative trend, not significant
T.Load	-0.89	0.30	Almost identical to FRR
H	+0.88	0.31	Positive correlation (unexpected) and not significant

Table A.3. The correlation table (Area 1, ACE=280)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.997	0.0499	Very strong negative correlation, and statistically significant ($p < 0.05$)
FRR	-0.962	0.177	Strong correlation, not significant
T.Load	-0.959	0.184	Strong correlation, not significant
H	+0.955	0.192	Strong positive correlation (unexpected), not significant

Table A.4. The correlation table (Area 1, ACE=140)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.999	0.023	Extremely strong negative correlation, statistically significant
FRR	-0.987	0.103	Very strong trend, but not significant
T.Load	-0.985	0.111	Very strong trend, but not significant
H	+0.983	0.119	Strong positive correlation

The correlation analysis conducted across ACE values ranging from 140 to 600 consistently revealed a strong negative relationship between I_{GAIN} and $\sum H \cdot P$. Notably, the correlation reached statistical significance ($p < 0.05$) for ACE = 140 and 280, with ρ as -0.999 and -0.997 , respectively. These results confirm $\sum H \cdot P$ as the dominant variable for adaptive gain tuning, offering a physically meaningful and statistically validated input to the I_{GAIN} look-up mechanism.

Table A.5. The correlation table (Area 2, ACE=130)

Param.	Corr. (ρ)	p-value	Comment
$\sum H \cdot P$	-0.89	0.306	Strong trend, but not significant
FRR	-0.77	0.438	Moderate correlation, weaker than others
T.Load	-0.87	0.323	Strong trend, but not significant
H	-0.96	0.172	Very strong negative correlation, not statistically significant

Table A.6. The correlation table (Area 2, ACE=100)

Param.	Corr. (ρ)	p-value	Comment
$\sum H \cdot P$	-0.966	0.166	Very strong correlation, not significant
FRR	-0.892	0.298	Moderate correlation, weaker than others
T.Load	-0.959	0.183	Strong trend, not significant
H	-0.999	0.032	Very strong negative correlation, statistically significant

Table A.7. The correlation table (Area 2, ACE=80)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.933	0.234	Strong trend, not significant
FRR	-0.840	0.365	Moderate trend, weakest correlation again
T.Load	-0.924	0.251	Strong trend, not significant
H	-0.988	0.099	Very strong negative correlation, approaching statistical significance

Table A.8. The correlation table (Area 2, ACE=60)

Param.	Corr. (ρ)	p-value	Comment
$\Sigma H \cdot P$	-0.933	0.234	Strong trend, not significant
FRR	-0.840	0.365	Moderate trend, weakest correlation again
T.Load	-0.924	0.251	Strong trend, not significant
H	-0.98	0.099	Very strong negative correlation, approaching statistical significance

The consolidated correlation analysis across ACE levels for Area-2 confirms that H value exhibits the most consistent and statistically significant relationship with I_{GAIN} . Although the correlation analysis for Area-2 indicates that average H exhibits the strongest statistical relationship with I_{GAIN} , $\Sigma H \cdot P$ was selected as the primary tuning parameter to ensure methodological consistency with Area-1. This choice allows for a unified look-up based adaptive control framework across interconnected and isolated areas. Furthermore, sensitivity analyses confirmed that the use of $\Sigma H \cdot P$ in Area-2 still yields stable and responsive AGC performance, even under varying ACE levels and operating conditions.

To assess the influence of broader interconnections, an additional correlation analysis was performed by including the ENTSO-E side in the calculation of system-wide parameters. While the primary design of the lookup mechanism focuses on local Area-1 variables, the dynamic behavior of the interconnected ENTSO-E grid can indirectly affect local frequency response and ACE dynamics. However, from an operational standpoint, TSOs are typically responsible only for their own control areas and do not have access to control over external grid parameters. Therefore, although $\sum H \cdot P$ values computed with ENTSO-E inclusion continued to show strong correlations with I_{GAIN} (e.g., $\rho = -0.999$ for ACE = 280 and -0.998 for ACE = 140), the tuning method was deliberately based on TSO-observable data only. H , even when including ENTSO-E, showed a positive correlation not aligned with expected control dynamics. These findings further reinforce the selection of $\sum H \cdot P$, calculated strictly within the TSO's area, as a physically meaningful, statistically valid, and operationally feasible parameter for adaptive I_{GAIN} tuning in interconnected systems.

Table A.9. The correlation table with and without ENTSO-E (Area-1)

ACE Levels (MW)	600	480	280	140
$\sum H \cdot P$	-0,989	-0,964	-0,997	-0,999
$\sum H \cdot P$ (ENTSO-E included)	-0,958	-0,972	-0,999	-0,998
H	0,856	0,882	0,956	0,982
H (ENTSO-E included)	0,778	0,810	0,906	0,948

This study also highlights a clear pathway for strengthening the proposed methodology: Increasing the number of scenarios and data samples would enhance the statistical validity and robustness of the correlation analysis. While the current sample size limits some statistical significance, the observed trends are consistent and physically meaningful. Overall, the methodology has demonstrated solid performance and reliability, even under limited data conditions, confirming its practical applicability and foundational strength.

B. STATIC DATA STRUCTURES

Generator Definition File

This CSV file includes all information and parameters about the defined and used generators in the Turkish System. It has two columns and 12720 rows in total. The representative data set is presented in the following:

DATA, VALUE

PF.G1__agc_status_info, 1
PF.G1__base_pow, 306
PF.G1__droop, 0.04
PF.G1__max_lfc, 306
PF.G1__maxcpr, 306
PF.G1__interface_mincpr,30.6
PF.G1__interface_p_set,0
PF.G1__remote_pfc_active, 0
PF.G1__remote_sfc_active, 0
PF.G1__remote_auto, 1
PF.G1__remote_local, 0
PF.G1__scada_def_rez_rat_po, "[1.0, 0.0, 0.0, 0.0, 0.0]"
PF.G1__scada_no, 1
PF.G1__scada_pmax, 306
PF.G1__scada_pmin, 30.6
PF.G1__scada_ramp_up_rate1, 9.18
PF.G1__scada_ramp_up_rate2, 13.77
PF.G1__scada_ramp_down_rate2, 9.18
PF.G1__scada_type, 'G'
PF.G1__scada_gen_name, 'BAND1 DGKC'

..., ...

Line Definition File

This CSV file includes all information about the transmission lines defined and used in the Turkish System. It has 6 columns and 281 rows in total. The representative data set is presented in the following:

NBR	NAME	P_TAG	FLOW_CONVENTION	BREAKER_TAG	FLOW_CONV_TAG
1	Line1	"['PF.scada_p_line1_1','PF.scada_p_line1_2']"	"[1,-1]"		
		"['PF.SITE6_CB_400KV_SW_1823_BK_RES','PF.SITE7_CB_400KV_SW_1650_BK_RES']"			
		PF.scada_flow_conv_line1_1			
...	...	...	...	...	...

Busbar Definition File

This CSV file includes all information about the busbars defined and used in the Turkish System. It has 3 columns and 154 rows in total. The representative data set is presented in the following:

NAME	NUMBER	TAG
ALAG2	1	PF.NODE_f_BUS_1
BLIKSR2	10	PF.NODE_f_BUS_10
...	...	...

Daily Schedule Definition File

This CSV file includes all information about the daily schedule of base power, FCR, and FRR in 15-minutes schedules defined for the Turkish System. It has 96 rows and 313 columns (1 for time interval, 3 for each AGC participated units) and 154 rows in total. The representative data set is presented in the following:

DT	1_P	1_FCR	1_FRR	10_P	10_FCR	10_FRR	...
15	229	22.9	22.9	100	10	10	...
15	229	22.9	22.9	100	10	10	...
...	...	...	...	...	...	...	...

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Temiz, Armağan

Nationality: Turkish (TC)

Date and Place of Birth: 28 July 1989, Antakya

Marital Status: Married

Research Interests: Energy management systems, power system stability, SCADA, renewables in power systems

EDUCATION

Degree	Institution	Year of Graduation
Ph.D.	METU Electrical and Electronics Engineering	2025
MS	METU Electrical and Electronics Engineering	2015
BS	TOBB ETU Electrical and Electronics Engineering	2012
High School	Selim Nevzat Şahin Anadolu High School	2007

Master Thesis Title: Assessment of impacts of electric vehicles on low voltage distribution networks in Turkey

Content: The increasing number of Electric Vehicles (EVs) worldwide has raised concerns regarding their impact on distribution networks due to economic and environmental factors. The scope of the thesis is to analyze the effects of EV penetration on low voltage distribution networks in Turkey and identify necessary investment requirements. The thesis includes preliminary studies on customer behavior modeling, network configurations, and regional load scenarios; probabilistic EV modeling based on Gaussian and Weibull distributions; Monte Carlo-based load flow simulations under varying tariff structures; and network

performance evaluations. The results focus on transformer and cable overloads, voltage deviations, and grid losses to support planning processes of distribution companies.

Advisor: Prof. Dr. Ali Nezih Güven

FOREIGN LANGUAGES

Turkish (Native)

English (Advanced)

Spanish (Elementary)

PROFESSIONAL EXPERINECES

Senior Team Leader / Systems Engineer

ASELSAN Inc., Ankara, Türkiye.

2019 – Present

- Technical leader of SCADA system development for wind and solar power plants, responsible for full lifecycle from requirements to commissioning
- Technical leader for the development of Power Plant Controllers ensuring grid code compliance (active/reactive power control, frequency response)
- Led the design and verification of an AGC system for TSOs within the ENTSO-E region, including algorithm development and SIL testing setup
- Conducted distribution network modeling and analysis using PowerFactory, including site visits, scenario studies, and operational planning assessments
- Applied systems engineering principles across the full project lifecycle, collaborating with multidisciplinary teams to integrate control,

communication, and grid compliance requirements into robust SCADA and power plant controller solutions.

Senior Researcher

TÜBİTAK MAM – Energy Institute, Ankara, Türkiye.

2012 – 2019

- Coordinated H2020 project proposals and managed consortiums for hydropower flexibility and smart grid initiatives
- Contributed to EU-funded ELECTRA IRP project by developing concepts for voltage stability and adaptive protection strategies in Web-of-Cells architecture
- Designed and deployed smart grid monitoring and control systems for PV networks in LV grids, including site installation in Saudi Arabia
- Performed MV and LV distribution network simulations using PowerFactory

PUBLICATIONS

- A. Temiz and A. N. Güven, "Dynamic PI Control Approach for AGC Under Power System Splitting," 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Antalya, Türkiye, 2025, pp. 1-6, doi: 10.1109/CPE-POWERENG63314.2025.11027234.
- A. Temiz and A. N. Güven, "An AGC Algorithm for Multi-Area Power Systems in Network Splitting Conditions," 2023 IEEE PES GTD International Conference and Exposition (GTD), Istanbul, Türkiye, 2023, pp. 77-81, doi: 10.1109/GTD49768.2023.00041.
- Armağan Temiz, Abdulmajeed M Almalki, Özgür Kahraman, Saad S Alshahrani, Eda B Sönmez, Shafi S Almutairi, Abdullah Nadar, Mohammed S

- Smiai, Ayman A Alabduljabbar. "Investigation of MV Distribution Networks with High-Penetration Distributed PVs: Study for an Urban Area", *Energy Procedia*, 141, p. 517-524. DOI: <https://doi.org/10.1016/j.egypro.2017.11.069>
- Julia Merino, J. E. Rodriguez-Seco, Íñigo García-Villalba, Armağan Temiz, Chris Caerts, Roman Schwalbe, Thomas I. Strasser. "Electra IRP voltage control strategy for enhancing power system stability in future grid architectures", *CIREN - Open Access Proceedings Journal*, 2017(1), p. 1068 – 1072. DOI: 10.1049/oap-cired.2017.0749
 - S.M. Blair, G.M. Burt, A. Lof, S. Hänninen, B. Kedra, M. Kosmecki, J. Merino, F.R. Belloni, D. Pala, M. Valov, B. Lüers, A. Temiz. "Minimising the impact of disturbances in future highly-distributed power systems", In: 2017 CIGRE B5 Colloquium, 2017.
 - A. Temiz and A. N. Guven, "Assessment of impacts of Electric Vehicles on LV distribution networks in Turkey," Leuven, 2016 IEEE International Energy Conference (ENERGYCON), 2016
 - A. Frascella, J. Swiderski, G. Proserpio, E. Rikos, A. Temiz, A. Babs, M. Usler, S. Branchetti, G. Graditi. "Looking for the unified classification and evaluation approach of SG interface standards for the purposes of ELECTRA IRP", Vienna – EDST 2015
 - R. D'hulst, C. Cearts, J. Merino Fernandez, E. Rikos, D. Kolodziej, K. Heussen, D. Gabriel, and A. Temiz. "Voltage and Frequency Control for Future Power Systems: the ELECTRA IRP Proposal", Vienna – EDST 2015
 - Julia Merino, J. E. Rodriguez-Seco, Chris Caerts, Reinhilde D'hulst, Klaas Visscher, Evangelos Rikos, and Armağan Temiz. "Scenarios and Requirements for the Operation of the 2030+ Electricity Network", Lyon – CIREN 2015

- Armağan Temiz, Özgür Kahraman, Abdullah Nadar, Mohamed S. Smiai, S. S. Almutairi, S. Alshahrani. “A smart Grid Controller for Low Voltage PV Network”, Riga – POWERENG 2015
- A. Temiz, “Assessment of Impacts of Electric Vehicles on Low Voltage Distribution Networks in Turkey”, Master Thesis, 28.08.2015

TECHNICAL & PERSONAL SKILLS

- **Software & Programming:** PowerFactory, Python, MATLAB, TwinCAT, IEC 61131-3 PLC programming
- **System Modeling & Analysis:** Power system modelling, Static/dynamic simulations, grid/plant control algorithms, SIL setups, grid code compliance analysis
- **Control Systems & SCADA:** SCADA/EMS architecture, HMI design, field integration, communication protocols, AGC systems, PPC for renewables
- **Tools & Reporting:** MS Office, SAP, documentation, and reporting practices
- **Leadership & Management:** Technical project coordination, cross-functional team leadership, work package ownership
- **Personal Attributes:** Quick learner, highly motivated, results-oriented, strong analytical and systems thinking approach
- **Hobbies & Interests:** Tennis, volleyball, football, Formula 1, playing guitar/piano/bağlama (Turkish saz), reading about blockchain technologies