Power Systems Operation and Control
Lecture 11
Load Frequency Control (LFC)
Lecturer: Teshome Goa (Assist. Prof.)

Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Understand the Tie-line power control

ii. Knows the importance of Tie-line control

iii. Differentiate the Tie-line control mechanisms

iv. Develop the model for Area control Error (ACE)

Content

1. Introduction

- The regulating of electrical power flow between interconnected power systems or grids is known as tie-line power control.
- By making sure that the electricity transferred between various regions or utilities stays balanced based on demand and generation capacity, this control mechanism is essential for preserving the stability and dependability of the entire power system.
- By facilitating the transfer of electricity between linked grids, tie-lines enable regions with excess power to supply regions with high demand..
- By assisting in the regional balance of supply and demand, load balancing makes sure that energy out-put can keep up with demand even during outages or peak periods

Introduction Cont.…

Tie-line control includes[1]:

- Monitoring Power Flows: Keeping track of how much energy is transmitted via tie-lines, which are the c onnections between different grid systems.
- Modifying Generation: The outputs of either or both interconnected systems' generating units can be al tered in order to regulate the power flow and maintain system frequency.
- Supply and demand must be balanced such that the total power generated in one place meets the tota l demand in another in order to prevent overloads and maintain system stability.

2. Importance of the Interconnected Power system Control

Power control in interconnected systems is vital for several reasons[2]:

- Maintaining system stability and reliability, ensures that electrical systems remain stable while preventing the frequency fluctuations and voltage instability, which can lead to blackouts or system failures.
- Ensures the supply and demand balancing: Interconnected systems can share resources to balance load effectively, which is especially important during peak demand periods, specifically during the outage of generations
- Enhances efficiency, optimizing power flows between interconnected grids the operators can reduce transmission losses and improve overall system efficiency.

Importance of Power Control Cont.…

- Efficient Integration of RE, since RE are variable, efficient power control helps to moderate these variations, enabling a greater penetration of renewables without affecting the system stability.
- Enabling the trading of electricity, interconnected systems enable areas with surplus generation to sell power to those in need ,which leads for economic benefits.
- Rapid responses to emergency : Interconnected systems can swiftly shift electricity from other sections of the grid in the case of an outage or breakdown in one location, increasing resilience.
- Positive environmental Impact: Efficient power regulation can help lower greenhouse gas emissions and lessen the environmental impact by facilitating the more effective use of a variety of energy resources.

3. Types of Tie-Lines

Tie-lines can be classified as[3]:

- Alternating Current (AC) Tie-Lines, which is the most common type that uses AC transmission to connect the grids.
- It facilitate synchronous operation between the interconnected systems and are suitable for short to medium distances.
- Direct Current (DC) Tie-Lines, uses high-voltage direct current (HVDC) technology to connect two power systems.
- It’s particularly beneficial for long-distance transmission, reducing losses and allowing for the interconnection of asynchronous grids.
- The AC and DC-Tie lines is given in Fig. 1.

Types of Tie-Lines Cont.….

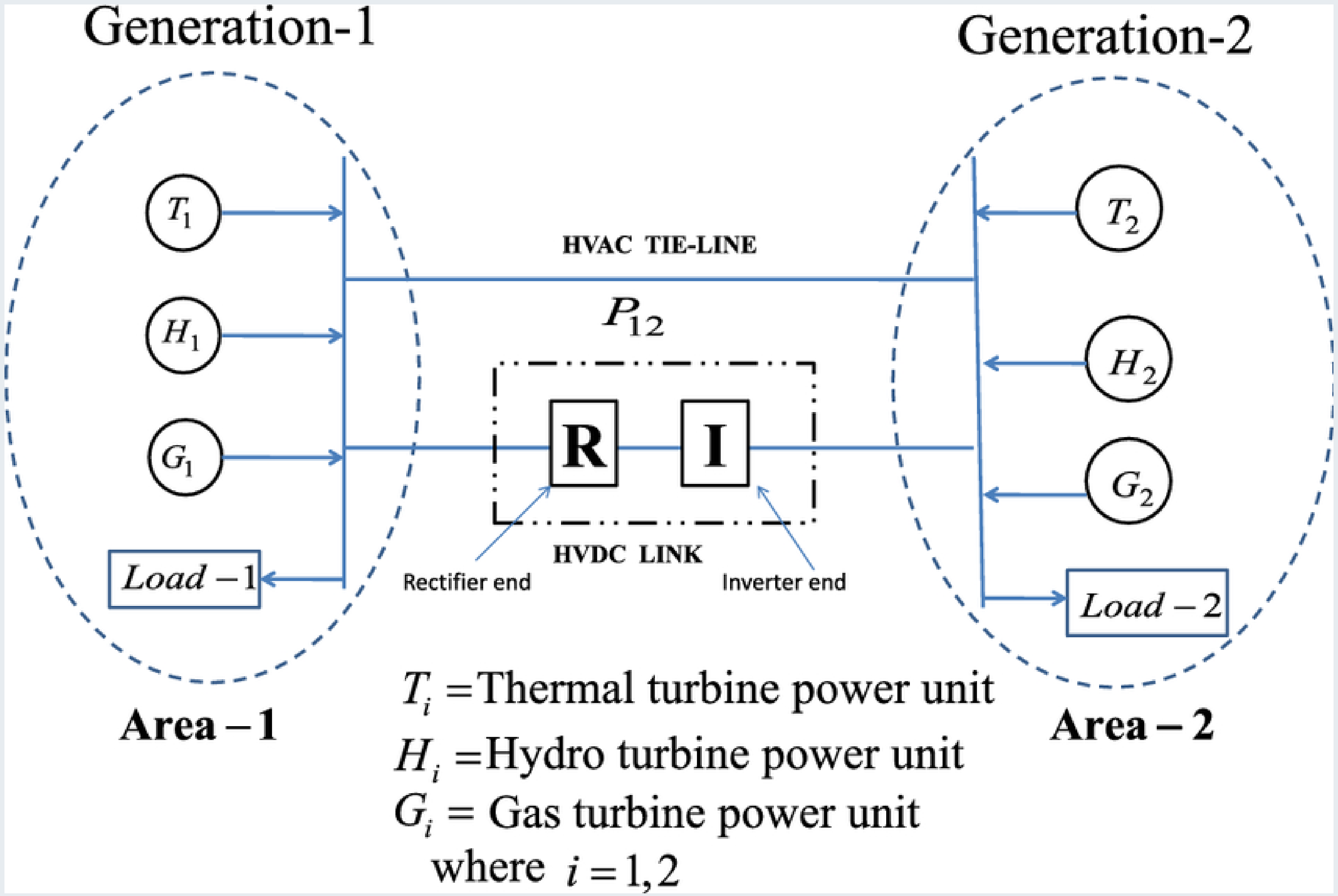

Figure 1. The Two-area power system with AC-DC Tie-lines.

URL: https://www.researchgate.net/publication/358365482/figure/fig2/AS:1133722929770497@1647312018938/Schematic-diagram-of-a-two-area-power-system-with-AC-DC-parallel-tie-lines.png

Types of Tie-Lines Cont.….

- Inter-tie lines: are made expressly to facilitate power exchange between two or more regional power s ystems.
- Its relationships is frequently function under various market systems and legal frameworks.
- Bilateral Tie-Lines: Usually regulated by contracts, these link two particular areas or utilities and permit a certain quantity of power transfer between them.
- Multi-Party Tie-Lines: These enable for larger-scale power transfers and facilitate complex power tradin g agreements by connecting several regions or utilities as presented in Fig.2.
- Scheduled Tie-Lines: Frequently utilized in energy trading markets, these entail planned power transfer s based on operating timetables and market agreements.

Types of Tie-Lines Cont.….

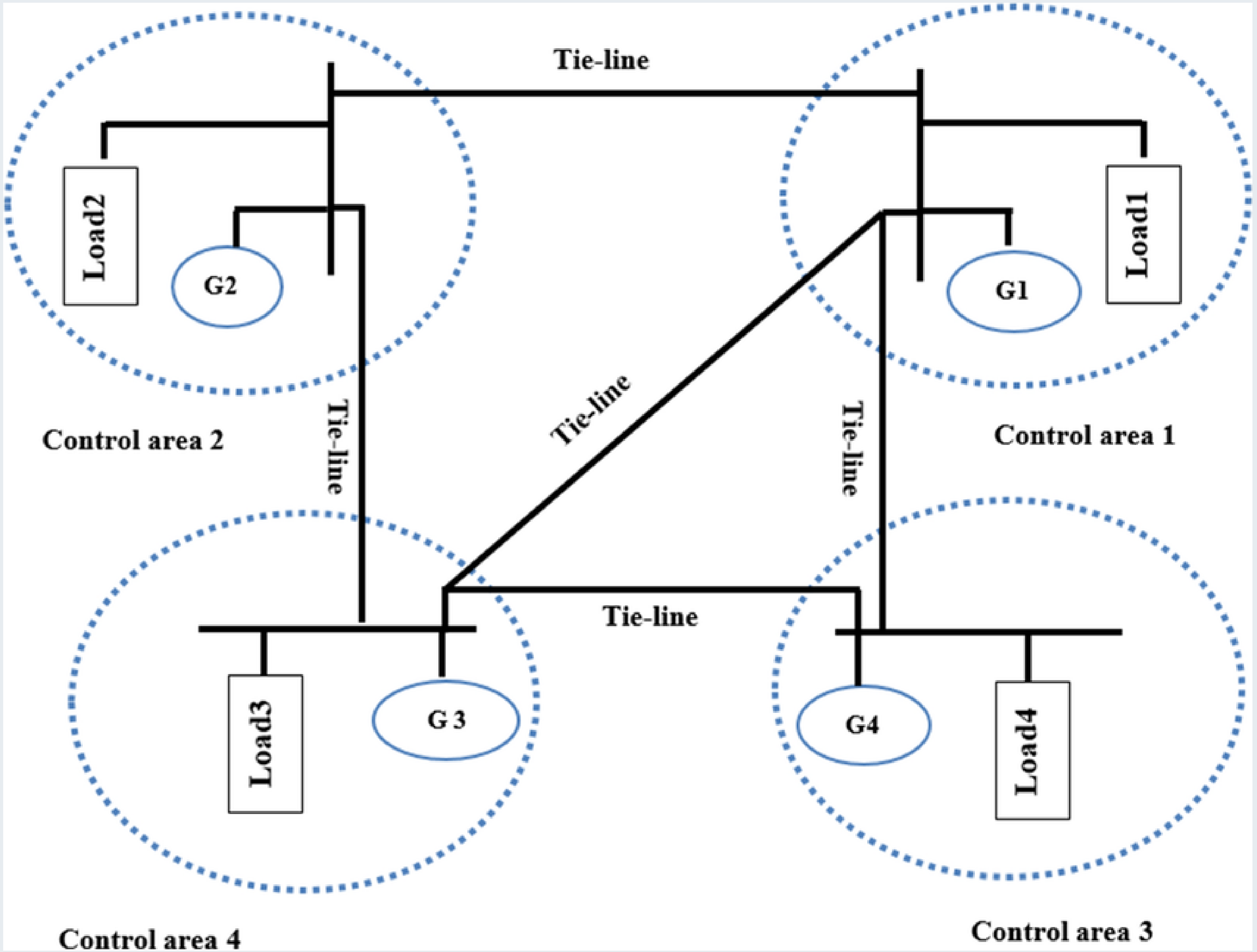

Figure 2. IMulti-Party (Four-area)-interconnected-power-system-with-tie-lines.

URL: https://www.researchgate.net/publication/368574154/figure/fig3/AS:11431281120697491@1676607078021/Proposed-four-area-interconnected-power-system-with-tie-lines.png

Types of Tie-Lines Cont.….

- Emergency Tie-Lines: These are activated during crises to provide backup power or support syste m stability, connecting systems in times of high demand or outages.
- Regional Tie-Lines: These connect power systems within a specific geographic area, often used to enhance local grid reliability and support regional power sharing.
- Each type of tie-line serves specific functions and advantages, allowing power systems to operate more efficiently and reliably while supporting a diverse energy mix.

4. Role of The Interconnecting Power Systems

- In order to connect various power systems and enable a number of advantages and functions, tie-lines o perators are essential for[4]:
- **Power Exchange: R**esource sharing while ensuring that regions with excess generation can supply thos e with shortages, this exchange improves overall dependability.
- Load balancing: This is especially crucial when demand is at its highest or when a generator fails, enabli ng other regions to make up for it and keep things stable.
- Increased Reliability: By connecting electricity systems with tie-lines, the electrical grid's overall dependa bility is increased. Power can be diverted from other connected regions in the event of an outage in one area, reducing the impact on customers.

Operators Role Cont…..

- Economic Efficiency: By facilitating the trading of electricity across interconnected systems, tie-lines en able areas to purchase and sell power according to cost-effectiveness.
- Integration of Renewable Energy: By enabling excess renewable power from one location to be shared with others, tie-lines help manage variability as more renewable energy sources are included into the g rid.
- Regulation of Frequency and Voltage: Tie-lines help keep interconnected systems' frequency and volta ge levels constant.
- This is essential for preventing disruptions and guaranteeing the dependable operation of electrical eq uipment.

Operators Role Cont.….

- Emergency Support: Tie-lines offer a way to get emergency power from nearby sources in the case of a crisis or major disruption in one area of the grid.
- Facilitating Regional and National Markets: Tie-lines allow for the development of larger electrical markets by tying together disparate power networks, which encourages competition, innovation, and infrastructure investment.
- Environmental Benefits: By facilitating the sharing of cleaner energy, interconnected systems can maximize the usage of a variety of energy sources, reducing dependency on fossil fuels and greenhouse gas emissions.

5. Tie-line Power Flow Control Mechanisms

- The management of electrical power transmission between interconnected systems requires tie-line power flow control techniques [5]. The following are some essential tie-line power flow regulation mechanisms:
- **AGC, or automatic generation control**: AGC systems respond to variations in frequency or load by automatically modifying the output of generating units.
- Through the *coordination of generation modifications* in linked grids, they aid in preserving the power balance across tie-lines..
- **Power System Stabilizers (PSS)**:it enhance the damping of oscillations in power systems.
- PSS typically work by ***adjusting the excitation system of synchronous*** generators.
- By modifying the generator's excitation voltage, the PSS can influence the generator’s active power output in response to oscillations, thus providing the necessary damping.

Tie-line Power Flow Control Mechanisms Cont.…

- Load Frequency Control (LFC):In order to ensure that electricity flowing over tie-lines is adjusted in real-time based on demand and generating conditions
- Technology known as High-Voltage Direct Current (HVDC): HVDC systems enable accurate regulation of power flows between grids.
- They are very efficient for long-distance transmission because they can link asynchronous systems and control power transfers with little losses.
- Flexible AC Transmission Systems (FACTS): FACTS devices improve the controllability of AC transmission systems. Examples of these devices include Unified Power Flow Controllers (UPFCs) and Static VAR Compensators (SVCs). They have real-time stability improvement, power flow management, and voltage regulation capabilities.

Tie-line Power Flow Control Mechanisms Cont.…

- Frequency Control Systems: These systems modify power flows in response to frequency readings, making sure that any departures from the normal frequency result in remedial measures like reducing or increasing generation.
- Economic Dispatch Algorithms: These algorithms make sure that tie-lines are used effectively for power transfers based on economic considerations by optimizing the operation of generating units to minimize costs while fulfilling demand.
- Manual Control Operations: In certain situations, especially in emergency situations or when automated systems might not react fast enough.

Tie-line Power Flow Control Mechanisms Cont.…

- Operators may manually modify power flows in response to observed conditions
- Real-time Monitoring and SCADA Systems: It provides the real-time data like power flows, frequency, and other critical parameters. Accordingly, the informed decision will be carried out,
- Interconnection or power pool agreements: established operational protocols and responsibilities for managing power flows, which can include specific control strategies for tie-lines.

Tie-line Power Flow Control Cont.…

- **The objective of any extended power system control mechanism are:**

a. Getting the commercial benefit from neighboring systems

b. To meet the sudden requirement of energy demand and improve the reliability

c. Share the installed capacity based on the energy mix.

d. Enhance the political and economic share

- However, controlling and managing these complex system is very difficult, which needs effective system modeling, analysis and suggesting the remedial solutions as given by:

Tie-line Power Flow Control Cont.…

- The control objective now is to regulate the frequency of each area and to simultaneously regulate the t ie line power as per inter-area power contracts.
- As in the case of single area frequency control, the PI controller will be installed to get zero steady stat e error in tie line power flow based on the contracted power.
- The AI based tuning of PID or other modern control system is another aspect.
- **Therefore, developing the mathematical** model is the first task in two area control.
- Consider Fig.3 and the power transferred from area 1 to area 2 is using the power transfer equation is derived as:

Tie-line Power Flow Control Cont.…

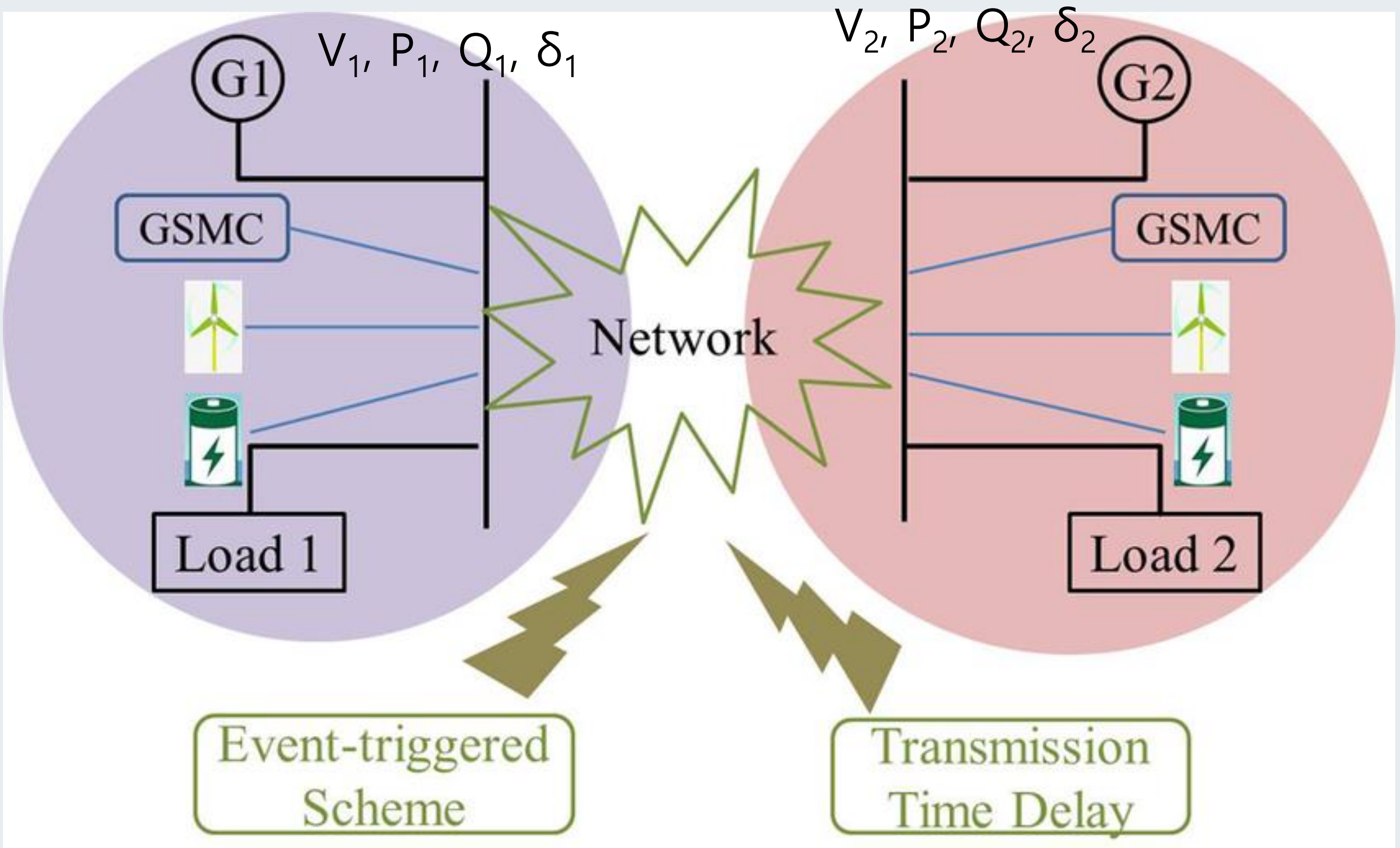

Figure 3. Interconnected Two-area system.

Url: https://www.researchgate.net/publication/346887120/figure/fig3/AS:11431281179055197@1691150005511/Block-diagram-of-two-area-power-system.png

Tie-line Power Flow Control Cont.…

- **The power transferred from Area 1 to Area 2 is given by:**
- Based on the concepts of real, reactive and apparent power, when two area is connected trough trans mission line, Z=R+jX , current 'I' is defined as:

$$I = \frac{V}{Z} = \frac{V < \delta}{Z < \theta} \Rightarrow \frac{V}{Z} < (\delta - \theta) \qquad \text{eqn.(1)}$$

- Then, based on Fig.3, the current flow through line is:

$$I = \frac{V_1 < \delta_1 - V_2 < \delta_2}{Z < \theta} \qquad \text{eqn.(2)}$$

- Then, the power between two area, S12 is given by:

$$S_{12} = V_1 I^*$$
$$= V_1 < \delta_1 \left(\frac{V_1 < \delta_1 - V_2 < \delta_2}{Z < \theta}\right)^* \qquad \text{eqn.(3)}$$

Tie-line Power Flow Control Cont.…

- Which implies

$$S_{12} = (\frac{V_1^2 < (\theta) - V_2 V_1 \angle(\delta_1 - \delta_2 + \theta)}{Z}) \qquad \text{eqn.(4)}$$

- Using the same approach, the power transfer from Area 2 to Area 1 is derived and given as :

$$S_{21} = (\frac{V_2 V_1 \angle(\delta_2 - \delta_1 + \theta) - V_2^2 < (\theta)}{Z}) \qquad \text{eqn.(5)}$$

- Then, the active and reactive power at the sending and receiving ends are :

$$P_{12} = (\frac{V_1^2 \cos(\theta) - V_2 V_1 \cos(\delta_1 - \delta_2 + \theta)}{Z})$$

$$Q_{12} = (\frac{V_1^2 Sin(\theta) - V_2 V_1 Sin(\delta_1 - \delta_2 + \theta)}{Z}) \qquad \text{eqn.(6)}$$

$$P_{21} = (\frac{V_2 V_1 \cos(\delta_2 - \delta_1 + \theta) - V_{21}^2 \cos(\theta)}{Z})$$

$$Q_{21} = (\frac{V_2 V_1 Sin(\delta_2 - \delta_1 + \theta) - V_{21}^2 Sin(\theta)}{Z})$$

Tie-line Power Flow Control Cont.…

- For a HV transmission line, reactance is normally very high compared to resistance and therefore th e effect of resistance is minimal and can be assumed to be zero.
- Therefore, θ=j=90 degree and the above equations become

$$P_{12} = (\frac{V_1^2 \cos(\pi/2) - V_2 V_1 \cos(\delta_1 - \delta_2 + \pi/2)}{X}) = \frac{V_1 V_2 Sin(\delta_2 - \delta_1)}{X}$$

$$Q_{12} = (\frac{V_1^2 Sin(\pi/2) - V_2 V_1 Sin(\delta_1 - \delta_2 + \pi/2)}{X}) = (\frac{V_1^2 - V_2 V_1 Cos(\delta_2 - \delta_1)}{X})$$

$$P_{21} = (\frac{V_2 V_1 \cos(\delta_2 - \delta_1 + \pi/2) - V_{21}^2 \cos(\pi/2)}{X}) = \frac{-V_1 V_2 Sin(-\delta_2 + \delta_1)}{X}$$

$$Q_{21} = (\frac{V_2 V_1 Sin(\delta_2 - \delta_1 + \pi/2) - V_{21}^2 Sin(\pi/2)}{X}) = (\frac{V_2 V_1 Cos(-\delta_2 + \delta_1) - V_2^2}{X})$$

eqn.(7)

Tie-line Power Flow Control Cont.…

- Therefore, the power transported from Area 1 to Area 2 is given by

$$P_{tie,1} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1^o - \delta_2^o) \qquad \text{eqn.(8)}$$

where δ_1^o, δ_2^o are power angles of equivalent machines of the two areas.

- Assume, there is change in load that results in incremental changes in δ_1 and δ_2 , then the incremen tal tie line power can be expressed as

$$\Delta P_{tie,1} = \left[\frac{|V_1||V_2|}{X_{12}} \cos\left(\delta_1^o - \delta_2^o\right) \right] (\Delta\delta_1 - \Delta\delta_2) \qquad \text{eqn.(9)}$$

$$\Delta P_{tie,1} = T_{12} (\Delta\delta_1 - \Delta\delta_2) \qquad \text{eqn.(10)}$$

Where T_{12} is synchronizing coefficient.

Tie-line Power Flow Control Cont….

- Since incremental power angles are integrals of incremental frequencies (Δf1 and Δf2), the above equation can be written as :

$$\Delta P_{tie,1} = 2\pi T_{12}(\int \Delta f_1 dt - \int \Delta f_2 dt) \quad \text{eqn.(12)}$$

$$\Leftrightarrow \Delta P_{tie,1} = \frac{2\pi T_{12}}{s}(\Delta F_1 - \Delta F_2) = \Delta P_{12}$$

- Similarly the incremental tie line power out of Area 2 is given by:

$$\Delta P_{tie,2} = 2\pi T_{21}(\int \Delta f_2 dt - \int \Delta f_1 dt)$$

$$\Leftrightarrow \Delta P_{tie,2} = \frac{2\pi T_{21}}{s}(\Delta F_2 - \Delta F_1) = -\Delta P_{12} \quad \text{eqn.(13)}$$

- The block diagram representation is presented in Fig.4

Tie-line Power Flow Control Cont.…

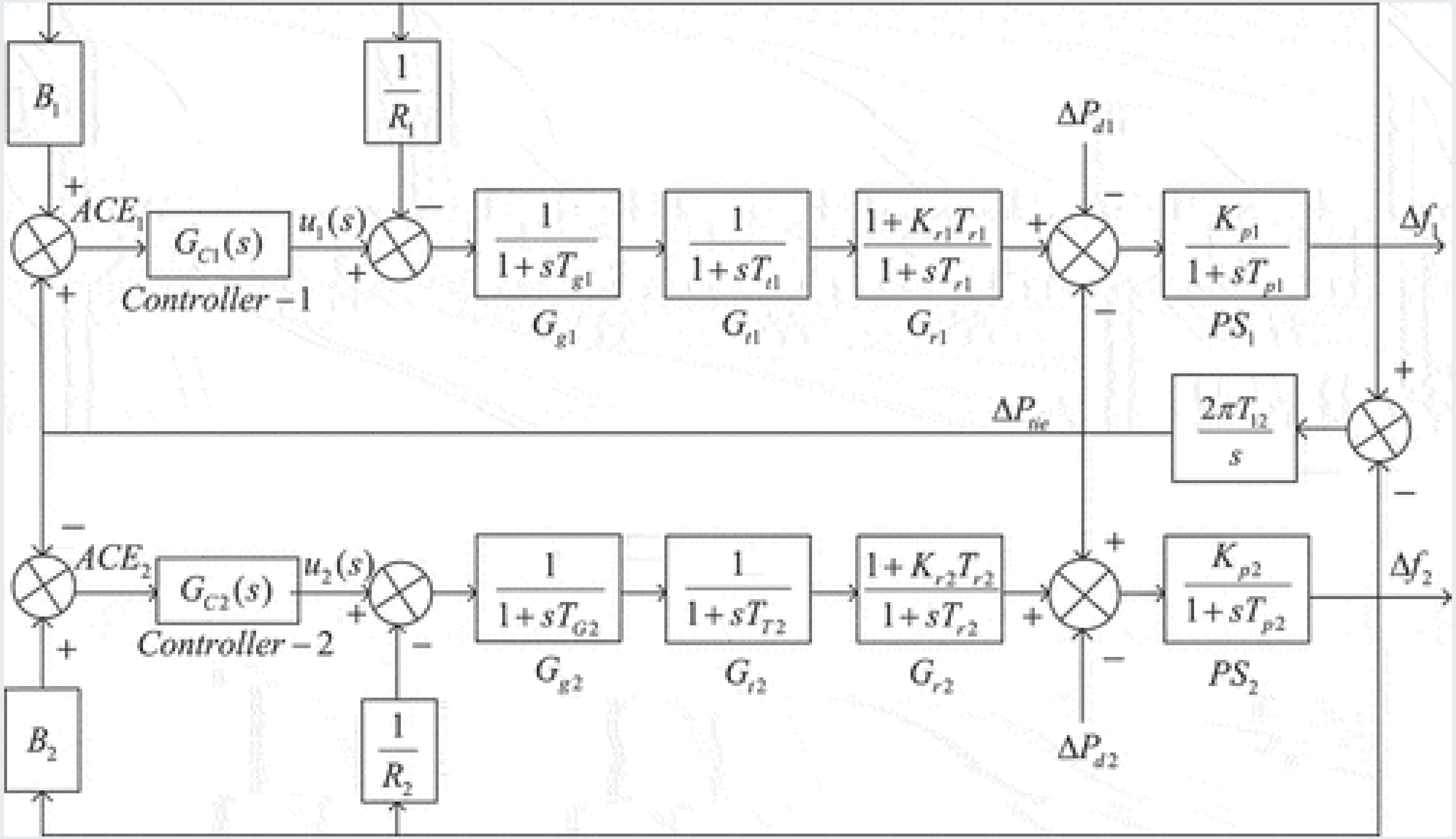

Figure 4. Two area control system diagram.

url: https://www.tandfonline.com/cms/asset/88de35c7-e0e0-4a73-9660-98457c20f7cf/tjms_a_2112009_f0003_b.gif

Tie-line Power Flow Control Cont….

- The steady state response of this two area system can be determined as follows.
- Consider the speed changer position is fixed (ΔP_{ref1} and ΔP_{ref2}) and there are step load changes in both areas (ΔPL1 and ΔPL2).
- The turbine input change ($\Delta P_{m1\ ss}$ & $\Delta P_{m2\ ss}$) due to the valve opening by the regulation characteristics in the two areas in steady state condition becomes ,

$$P_{m1ss} = -(1/R_1)\,\Delta F_{ss} \qquad \text{eqn.(14)}$$

$$P_{m2ss} = -(1/R_2)\,\Delta F_{ss}$$

Tie-line Power Flow Control Cont.…

- Under this condition,

$$\left[-\left(\frac{1}{R_1}\right)\Delta F_{ss} - \Delta P_{12} - \Delta P_{L1}\right]D_1 = \Delta F_{ss}$$

eqn.(15)

And

$$\left[-\left(\frac{1}{R_2}\right)\Delta F_{ss} + \Delta P_{12} - \Delta P_{L2}\right]D_2 = \Delta F_{ss}$$

eqn.(16)

- Solving for steady state frequency and tie line power, we get

$$\Delta F_{ss} = -\frac{[\Delta P_{L1} + \Delta P_{L2}]}{[\beta_1 + \beta_2]}$$

eqn.(17)

And

$$\Delta P_{12} = \frac{[\beta_1 \Delta P_{L2} - \beta_2 \Delta P_{L1}]}{[\beta_1 + \beta_2]}$$

eqn.(18)

Where, $\beta_1 = D_1 + 1/R1$ and $\beta_2 = D_2 + 1/R_2$

Tie-line Power Flow Control Cont.…

- It is concluded that , just as in the case of a single area system in the uncontrolled mode, has a steady state error
- But, to a lesser extent and the tie line power deviation and frequency deviation exhibit oscillations that are damped out latter.
- Hence, in interconnected operation to avoid these deviations and also to enable each area control the c hanges in such a fashion that it absorbs its own load change in steady state, area control error signals s hould be sent to reference (speed changer) in the two areas respectively as follows

$$ACE_1 = \Delta P_{12} + \beta_1 \Delta f_1$$

$$ACE_2 = \Delta P_{21} + \beta_2 \Delta f_2$$

eqn.(19)

Tie-line Power Flow Control Cont.…

- Using Laplace transform:

$$\Delta P_{ref\,1} = -K_1 \int \left(\Delta P_{12} + \beta_1 \Delta f_1\right) dt$$

$$\Delta P_{ref\,2} = -K_2 \int \left(\Delta P_{21} + \beta_2 \Delta f_2\right) dt$$

eqn.(20)

$$\Delta P_{ref\,1} = -\frac{K_1}{s}\left(\Delta P_{12} + \beta_1 \Delta f_1\right)$$

$$\Delta P_{ref\,2} = -\frac{K_2}{s}\left(\Delta P_{21} + \beta_2 \Delta f_2\right)$$

eqn.(21)

Tie-line Power Flow Control Cont.…

- The two area system with controller is presented in Fig.5

ACE 1

ACE 2

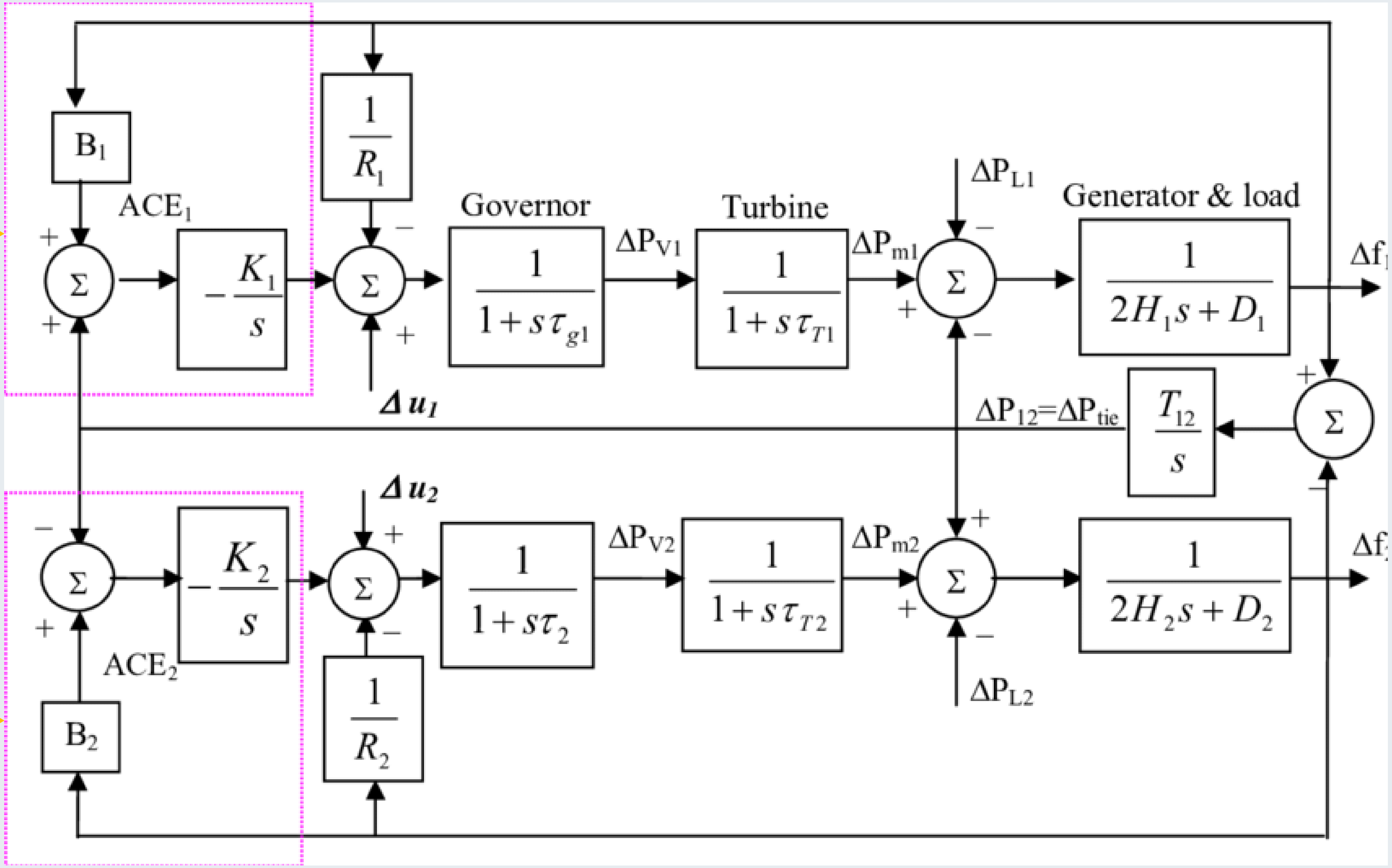

Figure 5. Two-area control , ACE representation.

URL: https://www.researchgate.net/publication/266459484/figure/fig1/AS:650039277936701@1531992849893/Block-diagram-of-Load-frequency-control-LFC-of-two-area.png

6. Advantages of Area Control Error (ACE)

- Enhances the Continuous monitoring of System Stability and Reliability: ACE is an effective measure to ensure that the grid is balanced in real time.
- Allows the operators to detect and respond to mismatches between generation and load, helping to avoid frequency deviations that could lead to system instability.
- Prevents power Blackouts: By constantly controlling ACE and minimizing frequency deviation, power systems can prevent major outages and cascading failures that occur when the grid is out of balance.
- Efficient Load Frequency Control by Optimal Generation Dispatch: by keeping ACE close to zero, the AGC system can adjust generation in real time to match fluctuations in demand
- Provides Improved Frequency Regulation: ACE is crucial for maintaining the desired frequency in the system.
- It helps to balance generation and load in a way that minimizes frequency fluctuations.

Advantages of Area Control Error Cont.….

- Flexible Integration of Renewable Energy while handling Intermittency: With the increasing integration of renewable energy sources like wind and solar, which are intermittent by nature, ACE plays a signific ant role in accommodating fluctuations in generation.
- By controlling ACE, power systems can better handle the variability in renewable generation, ensurin g that the grid remains stable despite changes in renewable output.
- Facilitates Smoothing Generation Changes: ACE helps manage the rapid changes in generation caus ed by wind and solar fluctuations, ensuring that these fluctuations do not cause significant frequency d eviations that could affect grid
- Coordination of Multiple Control Areas, Inter-Area Coordination: In interconnected power grids, differe nt control areas need to share generation resources and balance loads efficiently.

Advantages of Area Control Error Cont.….

- Minimized Frequency Deviations Across Areas: ACE allows for the correction of discrepancies betwee n interconnected areas, reducing the potential for regional instability that could propagate across the network.
- Performance and Compliance Monitoring System Performance Evaluation: ACE provides a performa nce measure for power system operations, allowing grid operators to evaluate how well a particular c ontrol area is performing with respect to maintaining frequency and power balance.
- High ACE values may indicate that control strategies need to be adjusted or that there is an issue wit h the generation fleet.
- Regulatory Compliance: ACE is also important for ensuring compliance with regulatory requirements r elated to frequency and generation performance standards set by grid operators or regulatory bodies.

Summary

- In summary, power control in interconnected systems is essential for maintaining operational efficiency, reliability, and economic stability while supporting the transition to more sustainable energy sources.
- The tie-lines are crucial to building a strong and adaptable electrical grid that maximizes sustainability, efficiency, and dependability while enabling various power systems to work together.
- Tie-line control work in tandem to ensure that power flows over tie-lines are effectively managed, contributing to the stability, reliability, and efficiency of interconnected power systems.
- ACE is a critical tool in maintaining the stability, reliability, and efficiency of power systems. Its main advantages lie in its ability to monitor and correct system imbalances in real time, ensuring optimal operation across interconnected areas, supporting the integration of renewables, and preventing system-wide failures.

References

[1]. A., Tayyab; A., Muhammad; T., Ezzeddine and etl. ‘’Terminal Voltage and Load Frequency Control in a Real Four-Area Multi-Source Interconnected Power System With Nonlinearities via OOBO Algorithm’’. IEEE Access. V.12(2024). DOI:10.1109/ACCESS.2024.3453755.

[2].D., Doan; K., Nguyen and Q., Thai. ‘’Load-Frequency Control of Three-Area Interconnected Power Systems with Renewable Energy Sources Using Novel PSO~PID-Like Fuzzy Logic Controllers’’. Engineering, Technology & Applied Science Research. V.12(3), 2022.PP: 8597–8604. DOI:https://doi.org/10.48084/etasr.4924.

[3]. M., Nico. ‘’Distributed Optimal Power Flow in Hybrid AC–DC Grids’’. IEEE TRANSACTIONS ON POWER SYSTEMS. V.34(4), 2019. DOI: 10.1109/TPWRS.2019.2892240.

[4]. J., Arévalo-Soler; D., Groß; E., Prieto-Araujo and etl. "Scheduling Role Assignment and System Reconfiguration in AC/DC Segmented Systems Interconnected by Power Converters." IEEE Transactions on Power Delivery. V.39(3), pp: 1524-1537, 2024, doi: 10.1109/TPWRD.2024.3368636.

[5]. S., Said; A., Ali and B., Hartmann. "Tie-line Power Flow Control Method for Grid-connected Micro-grids with SMES Based on Optimization and Fuzzy Logic“. Journal of Modern Power Systems and Clean Energy. V.8(5), pp: 941-950, 2020. doi: 10.35833/MPCE.2019.000282.

Thank you !