1. Introduction

Existing energy systems are characterized by multiple, largely hierarchical systems for transient stability control, load frequency control, etc.

To allow for distributed generation and alternative energy units, these controls need to be replaced by a simpler structure with a local control operating within a global context of situational awareness

Two-tier structure of local and contextual control is proposed:
- Local control: individual components and individual loads operate in a manner to follow some desired trajectory based on local observations
- Contextual control: selects one of a finite number of system-level control goals that best reflects needs based on overall system status at a given moment

Flatness as an extension of controllability is a key to enabling planning and optimization at various levels of the grid in this structure

Frequency and inter area power control is one of the large number of engineering issues that are affected by the introduction of wind units

In this study:
- Flatness-based approach is applied to automatic generation control (AGC) of multi-area systems with wind generation units

2. Flat Systems

When a system is flat it is an indication that the nonlinear structure of the system is well characterized

The nonlinear system
\[ \dot{x} = f(x, u) \]

is said (differentially) flat if and only if there exists \( y = (y_1, ..., y_n) \) such that:
- \( y \) and successive derivatives \( y, \dot{y}, ..., \) are independent
- \( y = h(x, u, \dot{u}, ..., u(T)) \)
- Conversely, \( x \) and \( u \) are given by:
\[
\dot{x} = \psi(y, \dot{y}, ..., y^{(2r-1)}) \quad u = \psi(y, \dot{y}, ..., y^{(a)})
\]

Flat systems structure can be exploited in designing control algorithms for trajectory generation and tracking
- Trajectory generation: Build a smooth curve \( t \rightarrow y(t) \) for \( t \in [t_f, t_f] \) by interpolation, possibly satisfying further constraints
- Trajectory Tracking: Find a feedback law such that the system tracks the reference trajectory following a perturbation

3. Flatness-Based AGC

Flatness-based AGC: deriving equation in flat space

- AGC equations in original space:
\[
\delta_T = \delta_T^{a} - \delta_T^{b} \\
\delta_T^{a} = \frac{1}{2H} [p_{mg} - D(\omega_i - \omega_f) - E_{iL} \Delta x] \sin(\delta_i - \theta_i) \\
\delta_T^{b} = \frac{1}{2H} \left[ p_{ref}^{a} - \omega_i^2 - \omega_f^2 - p_{ref}^{b} \right] \\
\delta_T^{c} = \beta_1 v_{wi} + \beta_2 v_{wind} \delta_T \\
\text{for } i = 1, ..., n
\]

AGC in a n-machine power system is decoupled into n subsystems in canonical form

Two level control structure
- Contextual control
  - Economic dispatch is performed to find the desired operating points
  - To follow load changes and wind variations the operating point is updated every 5 minutes
- Local Control
  - Trajectory generation: The trajectory is calculated for each generator independently through solving equations. The operating points are received from contextual level
  - Trajectory tracking: Appropriate input \( u(T) \) is found using linear or any desired control method such that tracking the generated trajectory is guaranteed. The controller design is also operated at each generator independently

**Contextual Level**

**Local Level**

4. Simulation & Results

- The approach is implemented on WSCC 3 machine, 9-bus system (Ref: P. Sauer and A. Pai, Power System Dynamics and Stability)
- The system is split into area 1 and wind units are applied to area 2
- Two wind power profiles applied to system:

![Flatness-Based Automatic Generation Control with High Penetration of Wind Energy](image)

5. Conclusions

- The two level control consisting of trajectory generation and trajectory tracking replaces the conventional AGC
- The set of nonlinear equations corresponding to an n-area system is decoupled into n linear controllable sub-systems in canonical form and local linear controllers are designed for each subsystem
- The flatness-based control method demonstrates promising performance in mitigating frequency and tie-line flow deviation
- This approach could also replace the conventional area based frequency control and can be applied to other control systems in power system