Introduction to Electric Power Systems
Lecture 13
Automatic Generation Control

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1 Frequency Control In Practice

In order for electric power systems to maintain a relatively constant frequency it is necessary that power generation and load are met

- almost exactly at every moment in time, and
- exactly, averaged over a long time period.

Q. *Why is it hard to plan generation ahead of time so that it exactly matches demand?*

Droop control ensures that supply and demand are met almost exactly at every moment in time, but still allows for steady state error. Furthermore, the droop control adjustments change the power flows on the network, which could violate network constraints.

Modern grids implement tiered generation control on top of droop control, including Automatic Generation Control (AGC) and Economic Dispatch. The high-level control paradigm for most modern grids is:

0. Create a schedule for the generators on the network a day in advance based on long-term contracts and/or a market (Economic Dispatch, round 1), including a protocol and rules for responding to unexpected events.
1. Respond to load/generation imbalances immediately, in a decentralized manner, while allowing for deviations from the nominal operating state (Droop control).
2. Gradually adjust the droop curves to restore the frequency to the nominal value (AGC control).
3. Adjust generation using a shorter horizon, e.g. five minute, "real time" market/optimization (Economic Dispatch, round 2) to increase operating efficiency.

This traditional operation paradigm has been semantically split up into "primary," "secondary," and "tertiary" control. Primary control includes the local droop control response. Secondary control typically consists of automated AGC control. Tertiary control typically consists of an optimization-based dispatch that optimizes economic efficiency. Note, these separations are design decisions for network control. Inertia, on the other hand, is a physical property of the system. The table below describes the approximate time scales of primary, secondary, and tertiary control, and how they are implemented.

Type of response	**Time scale**	**How is it implemented?**
Primary Control (Droop)	1 to 30 seconds	Locally using governor response. Governor can be implemented using analog or digital design.
Secondary Control (AGC)	30 seconds to a few minutes	For each region, a central control center sends signals to individual generators, adjusting their droop curves.
Tertiary Control (Economic Dispatch)	5 minutes to a day	For each region, a centralized optimization dispatches generators taking operating cost into account.

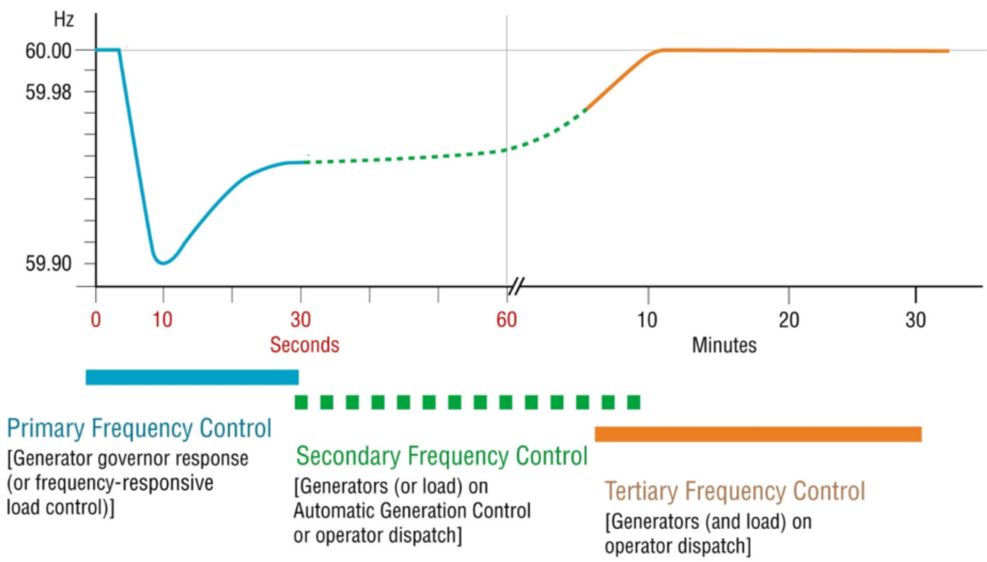

Figure 1: Timescales for primary, secondary, and tertiary response

2 Automatic Generation Control

As described in the previous lecture, droop control is a purely local response that allows each generator to adjust the real power that it is generating in order to balance the supply and demand on the network. The droop control equation is:

$$\Delta f_i = -R_i \Delta p_{m,i}$$
$$f - f_{\text{ref},i} = -R_i (p_{m,i} - p_{\text{ref},i,\text{init}}).$$

Droop control includes steady state error, which allows all of the generators (or loads) to participate in sharing the burden of the deviations from the forecasted load and generation. This steady state error is undesirable in the long run, though, as the system frequency must be kept within bounds. The frequency error can be eliminated by adjusting the droop curves for the participating generators. Typically this is done by adjusting the reference power for generator i, $p_{\text{ref},i}$. Defining $\Delta p_{\text{ref},i}$ as the change from an initial $p_{\text{ref},i,\text{init}}$

to a new $p_{\text{ref},i,\text{new}}$, $\Delta p_{\text{ref},i} = p_{\text{ref},i,\text{new}} - p_{\text{ref},i,\text{init}}$, we get

$$\begin{aligned} \Delta f_i &= -R_i(\Delta p_{m,i} - \Delta p_{\text{ref},i}), \\ f - f_{\text{ref},i} &= -R_i(p_{m,i} - p_{\text{ref},i,\text{new}}). \end{aligned} \tag{1}$$

To restore system frequency, AGC adjusts the setpoints of the droop curves on the network. This can be done with integral control starting at some arbitrary time $t = 0$ up to the current moment $t = T$:

$$\Delta p_{\text{ref},i} = -\int_0^T B_{f,i}\big(f(\tau) - f_{\text{ref},i}\big)d\tau, \tag{2}$$

where $f(t)$ is the frequency at time t and $B_{f,i}$ is the controller gain constant. Implementing this negative-feedback integral AGC frequency control will restore the system frequency.[1]

Q. *How does (2) adjust the mechanical power of generator i $p_{m,i}$ if the frequency f is too high?*

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3 Area Control Error-based Automatic Generation Control

Because droop control is purely local feedback, there are no guarantees that the aggregate generation response will not violate network constraints such as line flow limits. The same applies to the power adjustments produced by (2)—while the frequency is restored to the nominal operating point, the resultant power flows could violate network constraints. This is where Area Control Error (ACE)-based AGC comes in. ACE-based AGC control serves two distinct purposes:

1. It restores system frequency to the nominal operating frequency.
2. It restores the net outflow of power for each predefined area to the outflow that was scheduled ahead of time by the Economic Dispatch optimization.

Q. *ACE-based AGC maintains the net power outflow for a given region so that the line flows into/out of the region match their scheduled values. Why doesn't ACE-based AGC instead just directly maintain the line flows on each line into/out of the region?*

ACE-based AGC is defined for an *area*, rather than individual generators. That is, ACE-based AGC adjusts $\Delta p_{\text{ref},k}$, the aggregate droop characteristic for a given area k. Within area k, an area authority divides $\Delta p_{\text{ref},k}$ up amongst the participating generators.

The ACE equation consists of two terms: the net outflow error term and the integral control term from (2). For area k at time t, the equation is

$$\begin{aligned} \text{ACE}_k(t) &= \Delta p_{\text{tie},k}(t) + B_{f,k}\Delta f(t), \\ &= (p_{\text{tie},k}(t) - p_{\text{tie,sched},k}(t)) + B_{f,k}(f(t) - f_{\text{ref},k}), \end{aligned} \tag{3}$$

[1] It is important to note that (2) introduces dynamics into the system, which can destabilize the system if $B_{f,i}$ is too large. Therefore, $B_{f,i}$ is typically small, making AGC relatively slow.

where $p_{\text{tie},k}(t)$ is the net power flow out of area k at time t and $p_{\text{tie,sched},k}(t)$ is the scheduled net power flow out of area k at time t. The $\Delta p_{\text{tie},k}(t)$ and $B_{f,k}\Delta f(t)$ terms are *not* intended to cancel one another out. Instead, both the $\Delta p_{\text{tie},i}$ in the first term and the $\Delta f(t)$ in the second term are driven to zero (somewhat) independently.

Similar to (2), ACE-based AGC adjusts the droop setpoints of the participating generators $\Delta p_{\text{ref},k}$ using integral control:

$$\Delta p_{\text{ref},k} = -K_k \int_0^T \text{ACE}_k(\tau) d\tau, \tag{4}$$

where K_k is also a controller gain constant.

Q. *How does (4) adjust $\Delta p_{\text{ref},k}$, the droop characteristic for area k, if $f = f_{\text{ref},k}$, but the net outflow $p_{\text{tie},k}(t)$ is less than the scheduled outflow $p_{\text{tie,sched},k}$?*

Considering the effects of both the $\Delta p_{\text{tie},k}(t)$ and $B_{f,k}\Delta f(t)$ terms for all of the regions in the network can be challenging. One helpful way to think about how ACE-based AGC control controls both of these terms is to consider what needs to happen in order for the system to be in steady state. For the system to be in system to be in steady state, $\Delta p_{\text{ref},k}$, $\Delta p_{\text{tie},k}$ and Δf have to reach (or asymptotically approach) a constant value.

Q. *What has to happen for $\Delta p_{\text{ref},k}$ to reach a constant value?*

Q. *Is it possible for the ACE$_k$ for a given area k to be = 0, with $\Delta p_{\text{tie},k} \neq 0$ and $B_{f,k}\Delta f \neq 0$?*

Q. *Is it possible for the ACE-based AGC for ALL areas to be = 0, with $\Delta p_{\text{tie},k} \neq 0$ and $B_{f,k}\Delta f \neq 0$?*

Thus, it starts to become apparent why the ACE-based AGC control equations were designed the way they were: implementing the ACE-based AGC equations creates a stable dynamic feedback system. The stable equilibrium point for the system is the operating state at which the (aggregate) droop curves for each area have been adjusted such that frequency has been returned to the stable operating point, *and* the tie line outflows for each area exactly match the scheduled flows.

Now that we understand the basic steady state behavior of the ACE-based AGC control scheme, let's consider the ACE-based AGC design parameters, K_k and $B_{f,k}$.

Q. *Why are there two terms in the ACE? ($B_{f,k}\Delta f$ and $\Delta p_{\text{tie},i}$)*

Q. *If you would like the ACE-based AGC to respond aggressively to net outflow deviations, but less aggressively to frequency deviations, what K_k and $B_{f,k}$ should you choose (small/large)?*

Q. *If you would like the ACE-based AGC to respond less aggressively to net outflow deviations, but aggressively to frequency deviations, what K_k and $B_{f,k}$ should you choose (small/large)?*
