

Torques

1.0 Two torques

We have written the swing equation where speed is in rad/sec as:

$$\frac{2H}{\omega_{Re}} \dot{\omega}(t) = T_{au} = T_{mu} - T_{eu} \quad (1)$$

and when speed is in per-unit as

$$2H\dot{\omega}_u(t) = T_{au} = T_{mu} - T_{eu} \quad (2)$$

We note that in both cases the right-hand-side of the swing equation is comprised of a mechanical torque and an electrical torque. We will consider these two components in this set of notes.

2.0 Mechanical torque – regulated machines

Almost all hydro and steam turbines have speed governors (although sometimes the governors will be blocked or inactivated for some types of machines, e.g., nuclear units are sometimes operated on blocked governors).

The basic idea of a speed governor is to

- Regulate the
 - Steam valve
 - Penstock gate } And thus mechanical torque
- In response to deviations in turbine shaft speed.

A high-level block diagram appears in Fig. 1 to illustrate this.

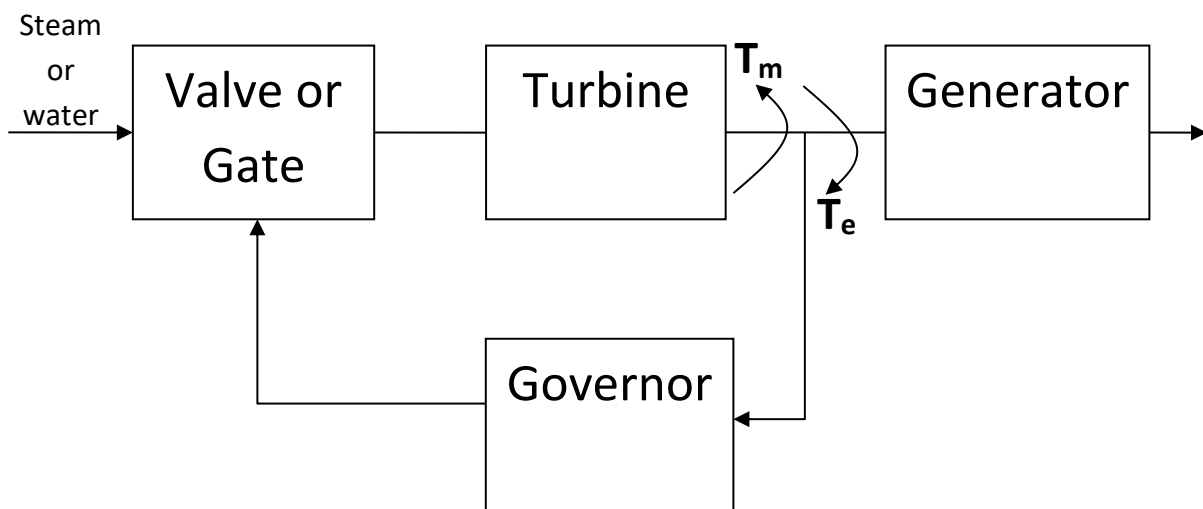


Fig. 1

When the governor is active, we say that the machine is regulating. Therefore, your text calls this case the “regulated machine” and addresses it in Section 2.3.2.

Please note that the control system of Fig. 1 has dynamics, but the discussion below is confined to the **steady-state response** to speed change. This response is governed by eq. 2.28 in your text, which is

$$\Delta T_{mu} = \Delta P_{mu} = -\frac{1}{R_u} \Delta \omega_u \quad (3)$$

where the “u” indicates, as before, that all values are in pu, and R_u is the regulation (or droop) constant in per-unit. The regulation constant can be understood, from (3), as

$$R_u = -\frac{\Delta \omega_u}{\Delta P_{mu}} \quad (4)$$

Assuming the per-unit power is given on the machine base, we see from (4) that R_u is the per-unit *steady-state* frequency drop necessary to increase the *steady-state* mechanical power output of the machine by 1 pu.

We can say this a little differently, but perhaps more intuitively for some of you, by saying that R_u is the percentage steady-state frequency drop necessary to increase the steady-state mechanical power output of the machine by 100 percent of the unit rating.

All regulating machines in an interconnection should have the same per-unit regulation constant in order to ensure that generators of different size respond to frequency variations in the same proportion to their size.

In the North American grid, the per-unit regulation constant is supposed to be 5%, meaning that each unit with an active speed governor is supposed to respond so that a 5% frequency decline (3 Hz) causes a 1 pu change in mechanical torque on the machine base.

This relationship is illustrated by Fig. 2 below.

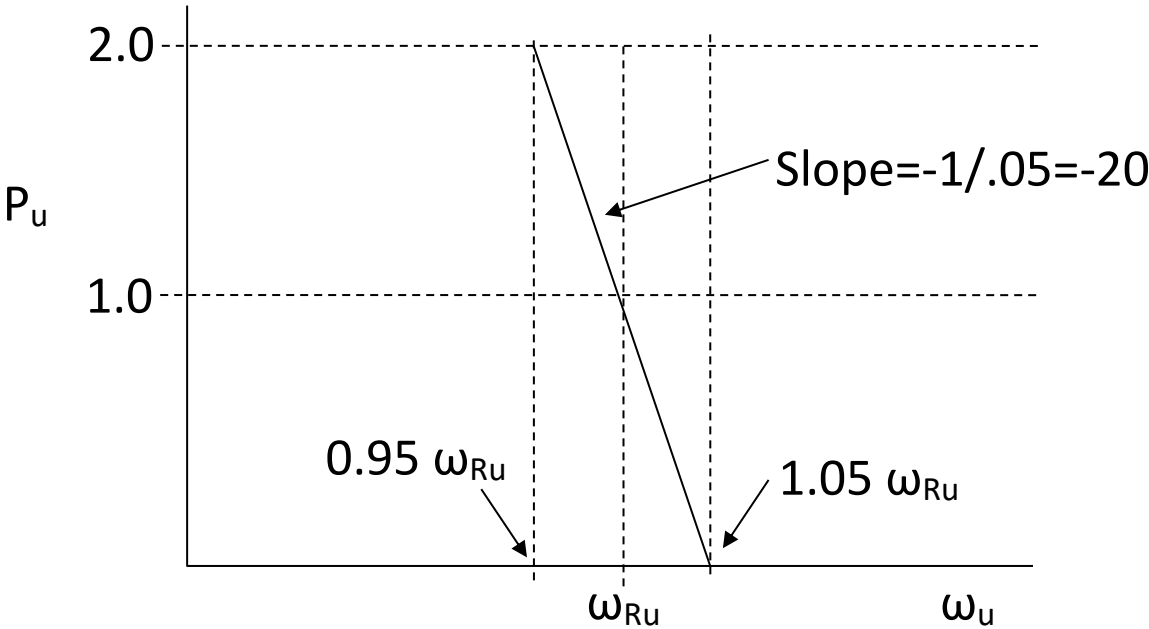


Fig. 2

Note that the amount of frequency drop and the amount of mechanical power increase are the values observed at the end of the control action. This point is clarified by Fig. 3 where we observe the response in bus voltage frequency deviation for several buses in the western US grid for loss of a large amount of power supply. We observe the existence of a transient response up to about 8 seconds after the disturbance, after which the frequency deviation reaches a steady-state. However, there is still a steady-state deviation in frequency that will not be zeroed until the secondary control system (automatic generation control, or AGC) takes effect. We typically do not model AGC for 10-second transient simulations because it does not have any influence in this time frame. (It is the steady-state frequency deviation that corresponds to the horizontal axis of Fig. 2.)

The time to average in which governor action is needed - when real power demand of the system is changed - either by loss of gen or addition of loads.

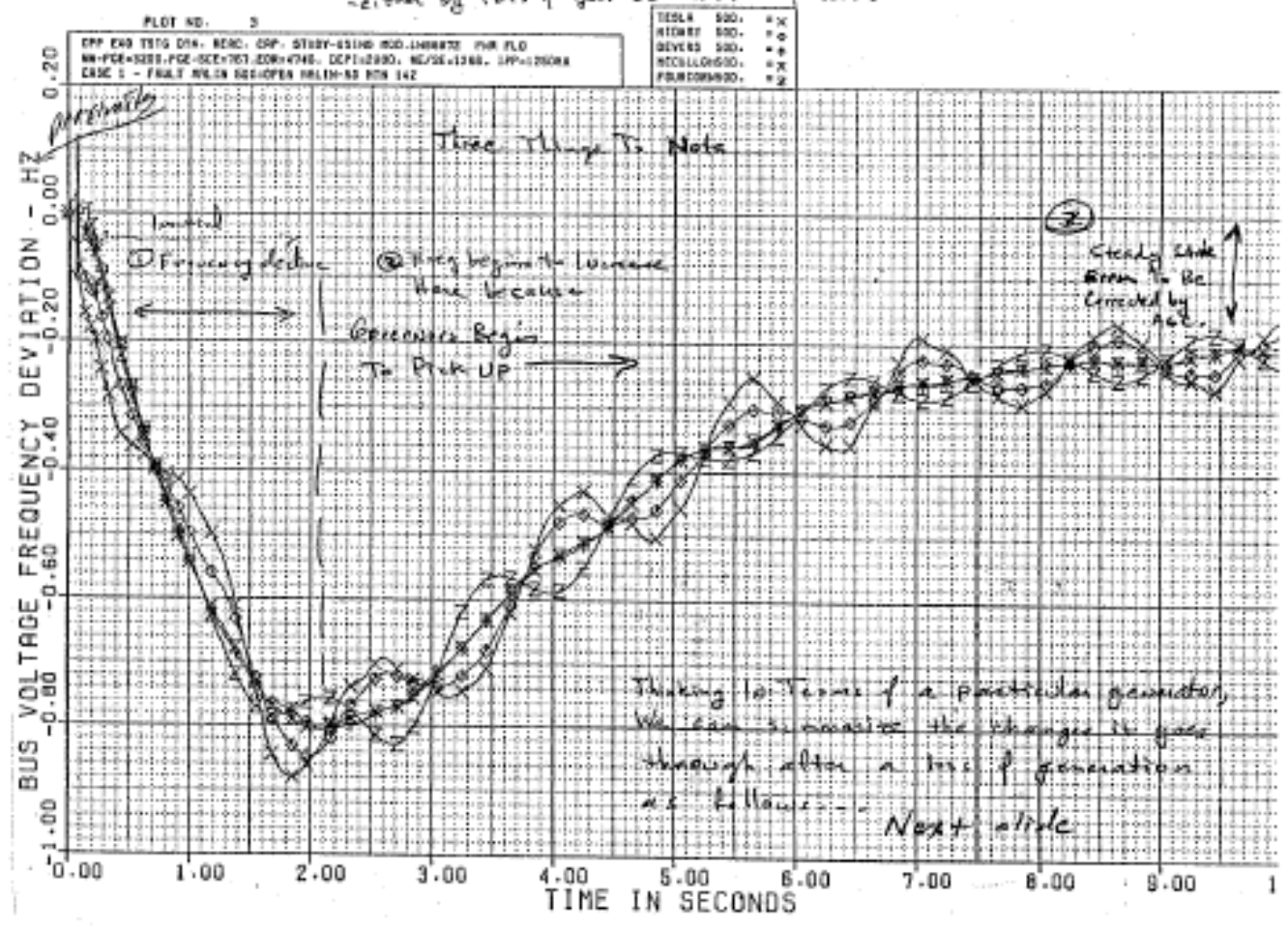


Fig. 3

3.0 Mechanical torque – unregulated machines

The unregulated machine corresponds to the situation when the governor is inactive (blocked) or not present. In this case, your text derives that (eq 2.24 in your text):

$$\Delta T_{mu} = \Delta P_{mu} = -\Delta \omega_u \quad (5)$$

This “natural” response of the machine is a drooping one as well. However, whereas the regulation constant in the regulated case is, per eq. (3), R_u ,

$$\Delta T_{mu} = \Delta P_{mu} = -\frac{1}{R_u} \Delta \omega_u \quad (3)$$

here, in the unregulated case, per eq. (5), it is 1. So, in the unregulated case, we do not get nearly the sensitivity in power output to frequency deviation that we do in the regulated case.

- When $R_u=0.05$, we need only a 5% change in frequency for a 100% change in power output.
- When $R_u=1.0$, we need a 100% change in frequency for a 100% change in power output.

Comparison of these two cases is illustrated in Fig. 4, which reflects the same information as do Figs. 2.3 (a) and (b) in VMAF.

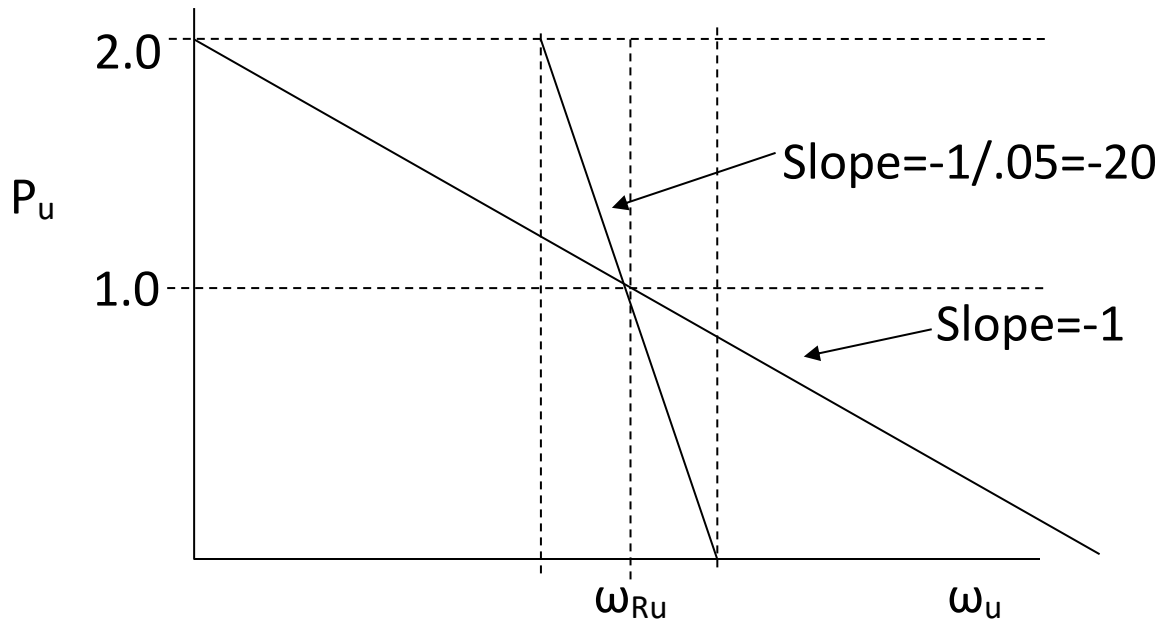


Fig. 4

I address three additional issues:

1. Why does the unregulated case have a drooping torque-speed characteristic?
2. Why is a drooping torque-speed characteristic a good thing to have in a power system?
3. What kind of droop characteristic do wind turbines have?

Answers:

1. Why does the unregulated case have a drooping torque-speed characteristic?

⇒ Consider a motor-driven room fan, which most of us have at home. Imagine when the fan is at steady-state, with electric torque driving a mechanical load (the windage load) that you increase the frictional forces on the shaft by pushing a heavy brush against it. What happens? It naturally slows down. To understand the unregulated response of the synchronous generator, you need only consider that the mechanical torque is driving and the electric torque is loading. When we increase the electrical torque, it naturally slows down.

2. Why is a drooping torque-speed characteristic a good thing to have in a power system?

⇒ Consider if slope was positive.

- Then, when the load decreased causing a frequency increase, the generator speed would increase, causing further frequency increase, and

this would continue until something failed. Such a system is unstable.

- Likewise, when the load increased causing a frequency decrease, the generator speed would decrease, causing further frequency decrease, and this would continue until something failed. Such a system is unstable.

3. What kind of droop characteristic do wind turbines have?

- ⇒ Interestingly, most existing wind turbines in the US have almost 0 regulation constant. This means that they are insensitive to frequency changes, i.e., they continue producing the same amount of power independent of the frequency. It is possible to make them otherwise with additional control loops, but as of now, very few, if any, developers have done so. As wind penetration levels increases, this could pose a significant problem for power systems.

4.0 Electrical torque

We may divide electrical torque into two components.

$$\Delta T_e = \underbrace{T_S \Delta \delta}_{\text{synchronizing torque}} + \underbrace{T_D \Delta \omega}_{\text{Damping Torque}} \quad (6a)$$

4.1 Synchronous torque

This is the component of the electrical torque that results from the two interacting magnetic fields.

- The magnetic field from the rotor winding: this magnetic field is fixed with respect to the rotor and therefore moves at the rotor speed.
- The resultant field produced by the stator currents in the a, b, and c windings. This field moves at a speed dictated by the frequency of the currents.

When the speeds of these two fields are the same, the electromagnetic synchronous torque is maximized, expressed as

$$T_e = F_s F_r \sin \delta \quad (6b)$$

where F_s and F_r are the peak values of the stator and rotor MMF waves, respectively, and δ is the angle between the two magnetic field axes.

When the speeds of the two magnetic fields are not the same, then there will be variation in the electrical torque and there will be variation in the electrical angle.

The component of variation in synchronous torque, ΔT_e , that is in phase with the variation in torque angle, $\Delta\delta$, is called the synchronizing torque.

4.2 Asynchronous (damping) torque

The asynchronous torques are developed as a result of asynchronous operation, i.e., when the rotor speed deviates from synchronous speed.

Thus, these torques are in phase with speed deviation $\Delta\omega$.

Because $\Delta\omega = \frac{d\Delta\delta}{dt}$, speed deviation is 90 degrees out of phase with angle deviation and therefore asynchronous torques are 90 degrees out of phase with synchronous torques.

The most important asynchronous torque is positive sequence damping.

Kimbark, Vol 3, dedicates an entire chapter (Chapter XIV) to the topic of damping; it is an excellent treatment.