System Voltage and Frequency Regulation

Shipboard Power System Fundamentals

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Essential Questions

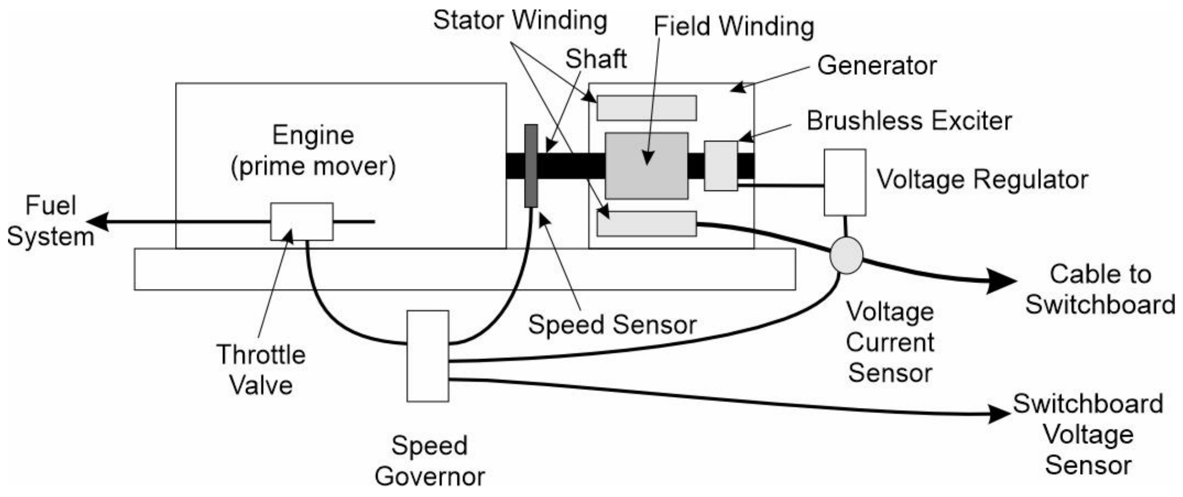
What hardware and software implement voltage and frequency regulation?	Understand
How does a PID controller work and how is it applied to voltage and frequency regulation?	Understand
What is droop and why is it used?	Understand
What are the differences between rotating machines and power electronic converters with respect to system voltage and frequency regulation?	Understand

Introduction

- One of the goals of power system design is ensuring the voltage and frequency remain within interface standard limits
  - IEEE Std. 45.1 ac voltage tolerance: +6% and -10%
  - IEEE Std. 45.1 ac frequency tolerance: ±5%
  - IEEE Std. 45.1 dc voltage range: ±4% (setpoint adjustable)
  - IEEE Std. 45.1 dc voltage tolerance: ±1.5%
- Regulating voltage and frequency depends on …
  - Whether the interface to the power system is the output of a synchronous generator or a power electronic converter.
  - Whether there is only one source of power on the system, or multiple sources of power on the system.
  - The method for sharing real and reactive (for ac systems) power if there are multiple sources of power on the system.

Generator sets with synchronous generators

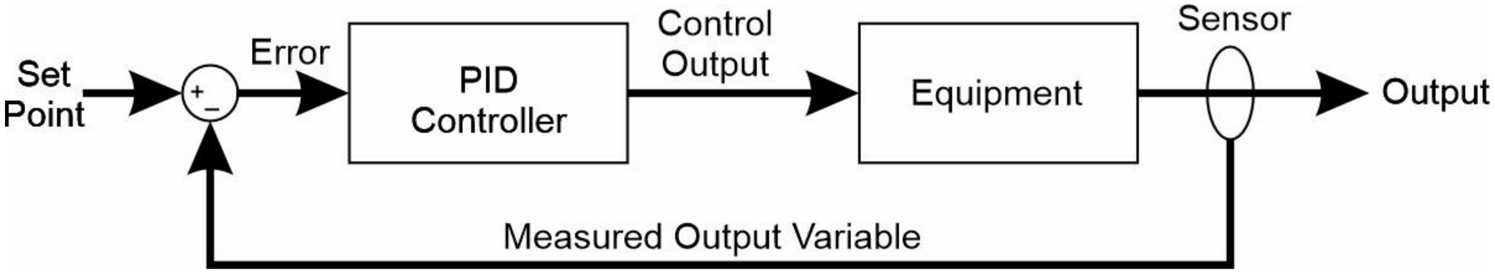
- Voltage regulator controls the field winding current.
  - Usually via a brushless exciter (instead of field brushes).
  - May include functionality to assist in paralleling generators.
- Speed governor regulates shaft speed (frequency) by controlling the fuel throttle valve.
  - May include functionality to match frequency and phase for paralleling generators.
- If output of generator set immediately rectified for dc operation …
  - Control algorithms determine the voltage and speed (frequency) set points for regulation.
- If paralleled to other ac sources …
  - Voltage reference modified to enable sharing of reactive power.
  - Shaft speed reference modified to enable sharing of real power.



Power electronic converters

- Grid-forming
  - Control algorithms determine the magnitude and frequency (for ac) of the voltage output.
  - May include functionality to enable parallel operation with multiple grid-forming power electronic converters and synchronous generators.
- Grid-following
  - Control algorithms determine the magnitude, frequency (if ac) and phase (if ac) of the voltage at the interface and create a current waveform to produce the desired amount of power.
  - May include functionality for sharing real and reactive (for ac) power with other sources.
  - Requires at least one grid-forming converter or synchronous generator to be paralleled to it; a converter detects loss of voltage reference:
    - It may shut down, or
    - It may switch to a grid-forming control algorithm.

PID Controller



- PID controllers often used to implement voltage regulators and speed governors.

$$e(t) = r(t) - c(t)$$

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(\tau)d\tau + K_p T_d \frac{de(t)}{dt}$$

$r(t)$ = set point
$e(t)$ = error
$u(t)$ = control output
$c(t)$ =measured output variable

$$c(t) = C_{equipment}(u(t), t)$$

K_p = Proportional Gain
T_i = Integral Time
T_d = Derivative Time

$C_{equipment}(u(t), t)$ = Equipment transfer function

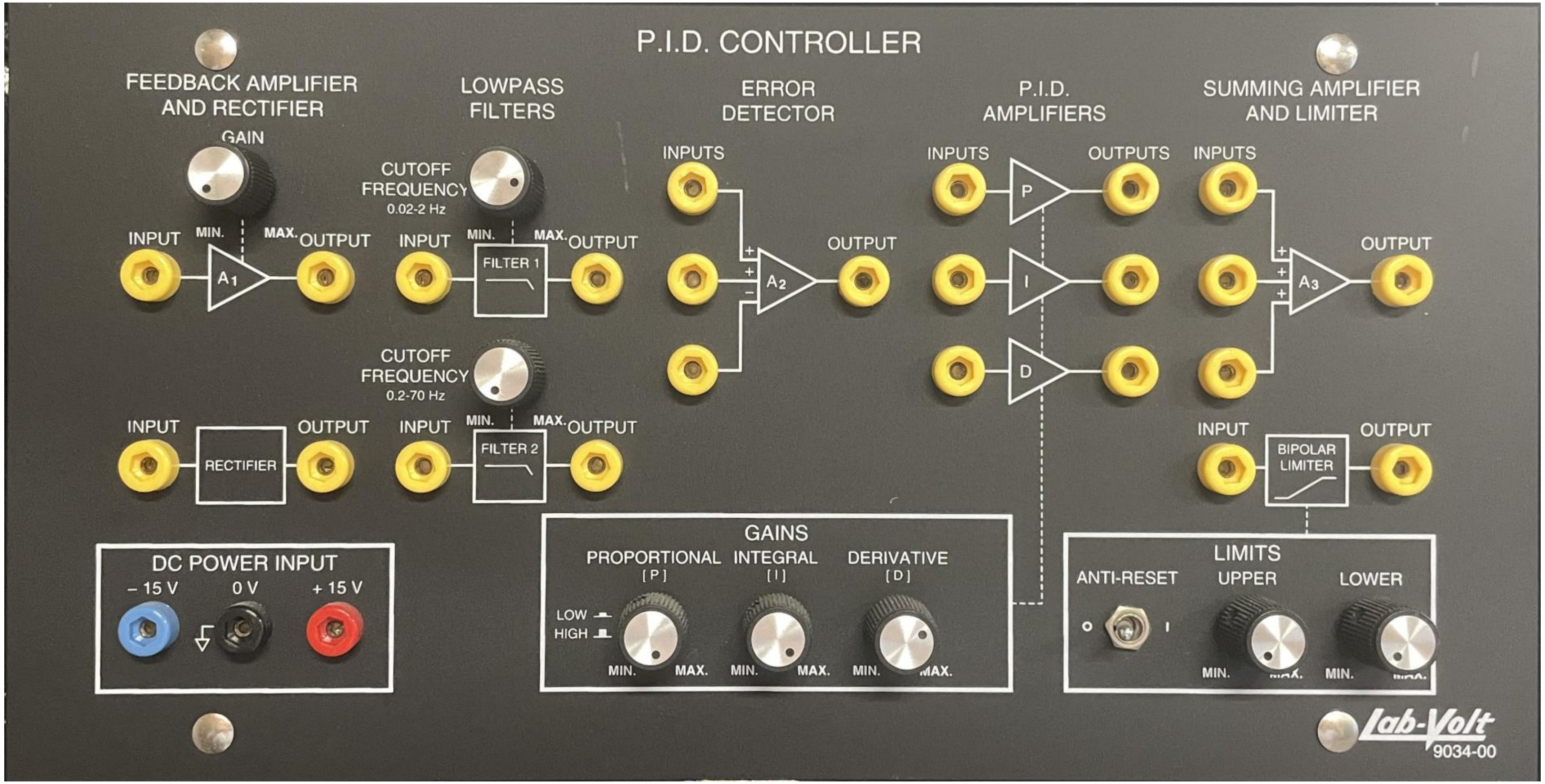
Alternate Definition

K_i = Integral Gain
K_d = Derivative Gain

$$K_i = \frac{K_p}{T_i}$$

$$K_d = K_p T_d$$

Lab-Volt PID Controller

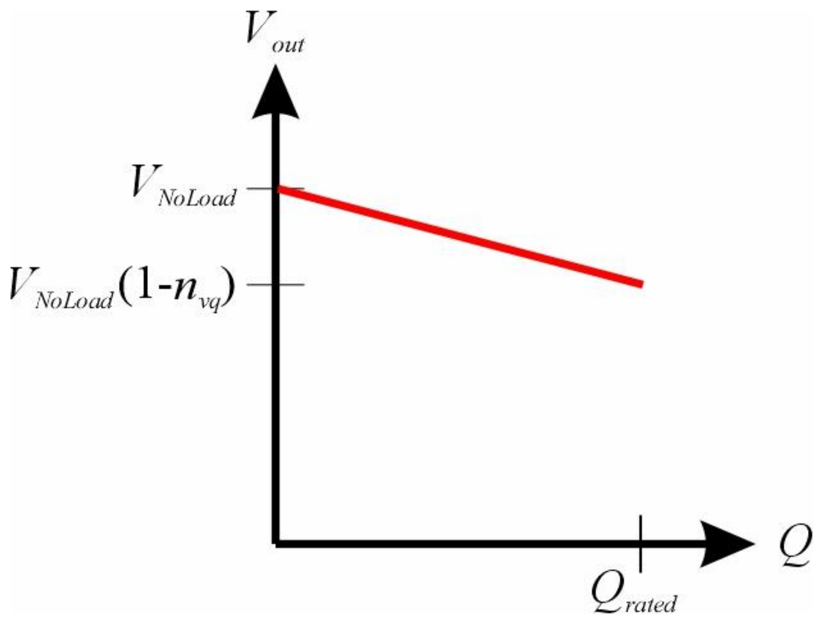


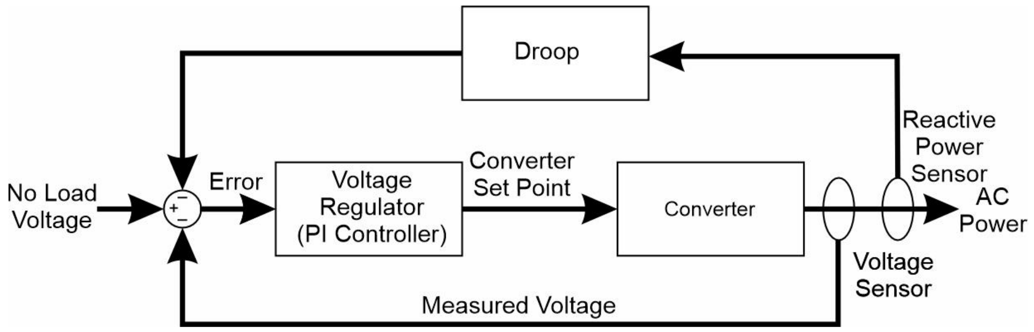
PID Controller Tuning

- Many techniques for choosing PID parameters K_p, T_i, K_i, T_d, and K_d
  - Often empirical methods are used.
- For many controllers, T_d and K_d are set to 0, largely due to stability concerns.
- Can add additional signals to error summation.
- Ziegler-Nichols method for PID tuning (empirical method)
  - K_i and K_d gains initially set to zero
  - K_p is increased until the ultimate gain K_u at which the output of the loop starts to oscillate constantly
    - T_u is the oscillation period (s).
  - For P controller: $K_p = 0.5\ K_u$
  - For PI controller: $K_p = 0.45\ K_u$ $K_i = 0.54\ K_u / T_u$
  - For PID controller: $K_p = 0.6\ K_u$ $K_i = 1.2\ K_u / T_u$ $K_d = 0.075\ K_u T_u$

Droop

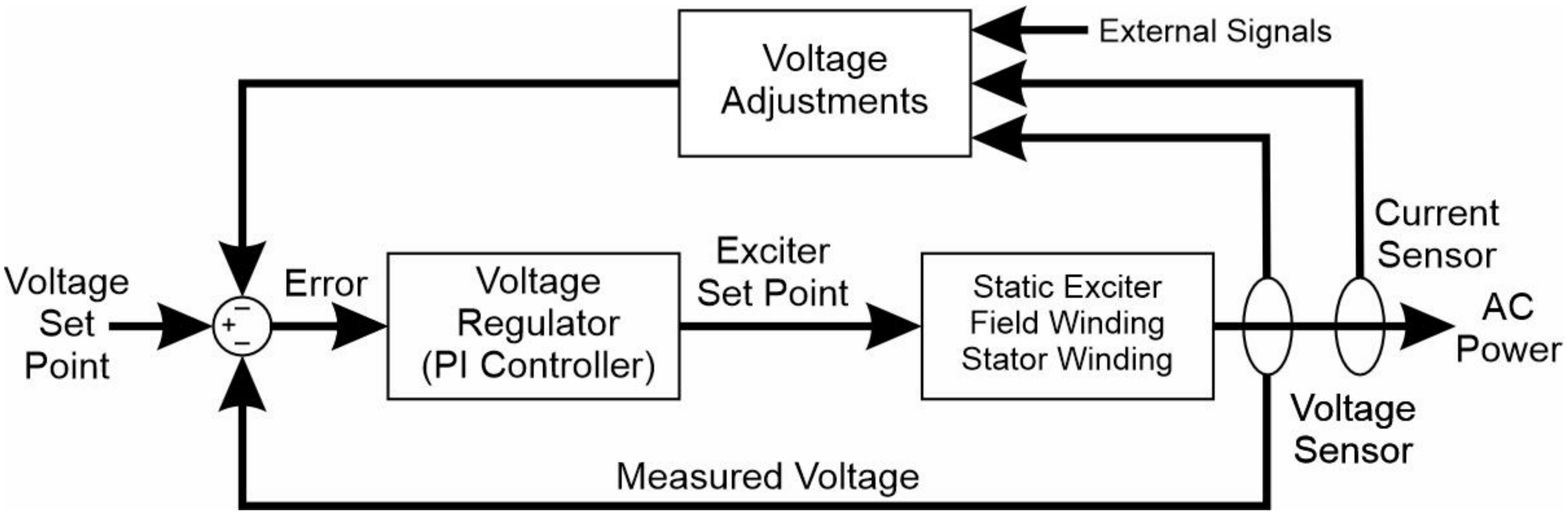
- Droop is one way for multiple sources to operate in parallel.
- AC systems:
  - Voltage setpoint decreases as the reactive power increases
  - Frequency setpoint decreases as the real power increases
- DC systems:
  - Voltage setpoint decreases as the real power increases
- Droop often implemented by adding an additional feedback signal to the error signal of a PI controller.





Voltage Droop for ac system

Voltage Regulation Implementation: Synchronous Generator



Frequency Regulation Implementation: Generator set prime mover