

System Voltage and Frequency Regulation

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1. Introduction

One of the objectives of the operation of a shipboard power system is regulating the system voltage and frequency to be near their nominal values and within interface standard requirements. IEEE Std 45.1 for example, recommends a voltage tolerance of +6% and -10% and a frequency tolerance of $\pm 5\%$ for ac power. IEEE Std 45.1 recommends a steady-state voltage range of $\pm 4\%$ and a steady-state voltage tolerance of $\pm 1.5\%$ for dc systems. The voltage range is the range of voltages across which the operator can establish the system voltage setpoint.

As shown in Figure 1, generator sets that are not paralleled with other sources employ a voltage regulator to establish the amount of dc current provided to the generator field windings (via the brushless exciter) on the rotor, based on regulating the output voltage magnitude. The speed governor on the prime mover (gas turbine or diesel engine) controls a fuel throttle valve to regulate the shaft speed, and thus the rotor speed and frequency of the ac power.

If the electrical output of the generator set is immediately rectified with an active rectifier, control algorithms determine the optimal shaft speed (frequency) and voltage to serve as an input to the active rectifier; the active rectifier controls regulate the dc voltage output. Typically, the optimal shaft speed and voltage are chosen based on minimizing fuel consumption for a given electrical power output. The speed governor regulates to the optimal shaft speed and the voltage regulator regulates to the optimal voltage.

For power electronic inverters and converters operating in the grid-forming mode, control algorithms determine the magnitude and frequency of the voltage output; the current is determined by the loads. For power electronic inverters and converters operating in the grid-following mode, control algorithms detect the system voltage and frequency, and create a current waveform to produce the desired amount of output power.

The voltage regulators, speed governors, and control algorithms of paralleled generator sets and power electronic work together to establish the overall system voltage and for ac systems, the system frequency.

Speed governors often incorporate controls to synchronize frequency and phase of a generator set to that of the power system to enable automatic paralleling of the generator set to the power system. Similarly, the voltage regulator may include functionality to match the generator voltage to the power system voltage to facilitate automatic paralleling.



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Additional information on voltage regulation and speed regulation of shipboard generator sets is provided by EDQP SD-311 and Doerry (2020).

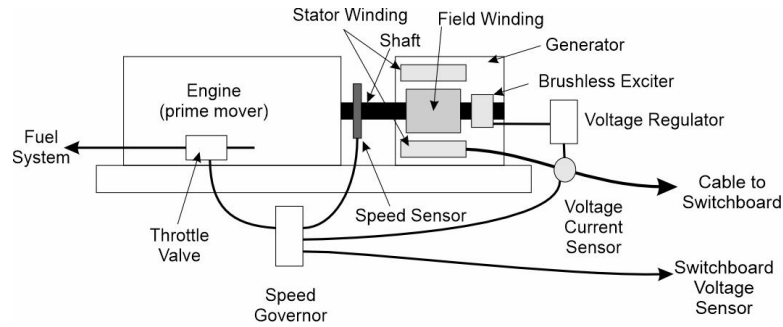


Figure 1: Generator set voltage and frequency regulation

2. PID Controller

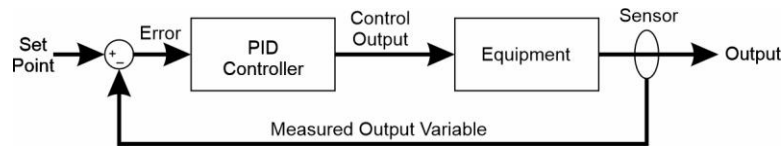


Figure 2: Generic PID closed loop feedback control loop

Many voltage regulators and speed governors employ variations of proportional-integral-derivative (PID) controllers as depicted in Figure 2.

Assigning variables ...

$r(t)$ = set point

$e(t)$ = error

$u(t)$ = control output

$c(t)$ = measured output variable

The PID control loop is described mathematically by:

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

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

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

where

K_p = Proportional Gain

T_i = Integral Time

T_d = Derivative Time

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

The second equation above is the PID controller equation. In some cases, the coefficients for the integral and derivative terms are defined differently:

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

$$K_d = K_p T_d$$

Where:

K_i = Integral Gain

K_d = Derivative Gain

The error variable is the deviation of the system output from the desired setpoint. The goal of a controller is for this deviation to be zero, or as small as possible. The control input due to the proportional gain becomes larger as this error increases. The downside is that the proportional gain provides no control input if the error is zero, hence if the Integral Gain and Derivative Gain are both zero, the equipment transfer function will likely not result in the system output matching the set point. At some value of error, the controller will produce a controller output that when applied to the equipment transfer function will result in the system output and set point combining to the value of error. For the control loop to balance, an error is generally required.

The integral gain can eliminate the error over the long term. The longer that an error exists, the greater the impact of the integral term. At some point, the integral term will equal the value required by the equipment transfer function to produce the value of the setpoint. Once at this point, the proportional and integral terms tend to keep the error near zero.

The derivative gain helps the system respond faster to changes in the measured output variable.

There are a number of techniques for selecting K_p , T_i , K_i , T_d , and K_d to produce satisfactory or ideal responses. These techniques are described in many control system design textbooks such as Ogata (2009). Inappropriate selection of these gains and times may lead to unstable operation.

A number of controllers set the Derivative Gain to zero, largely due to stability concerns. These controllers may be called PI controllers instead of PID controllers.

It is also possible to add additional signals to the summation function depicted in Figure 2. These signals can be used to adjust the output variable to achieve some overall system goal.

3. Droop

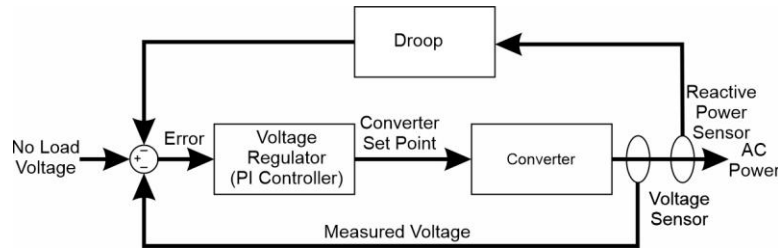


Figure 3: Voltage droop based on reactive power

Droop is a technique for enabling multiple sources to operate in parallel. For ac systems, voltage droop is usually implemented as a reduction in voltage when the reactive power increases. Frequency droop is usually implemented as a reduction in frequency when the real power increases. For dc systems, voltage droop is usually implemented as reduction in voltage when the power increases.

As shown in Figure 3, droop is typically implemented by adding an additional feedback signal from the equipment output to the summation that generates the error signal.

The signal at the output of the droop block (and into the summation) is given by:

$$V_{droop} = n_{vq} \left(\frac{Q}{Q_{rated}} \right) V_{NoLoad}$$

Where:

V_{droop} = reduction in voltage due to reactive power supplied

n_{vq} = droop coefficient (voltage due to reactive power)

Q = reactive power supplied

Q_{rated} = rated reactive power

V_{NoLoad} = no load voltage

The output voltage (V_{out}) is regulated to ...

$$V_{out} = V_{NoLoad} - V_{droop}$$

$$V_{out} = V_{NoLoad} - n_{vq} \left(\frac{Q}{Q_{rated}} \right) V_{NoLoad}$$

A plot of the output voltage as a function of reactive power is shown in Figure 4.

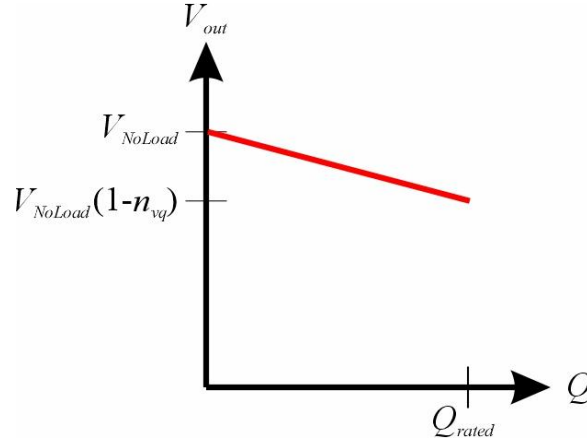


Figure 4: Droop characteristic – Voltage droop as a function of reactive power

Similar droop characteristics may be defined for frequency (f) as a function of real power (P) for ac systems, and voltage (V_{out}) as a function of real power (P) for dc systems.

$$f = f_{NoLoad} - n_{fp} \left(\frac{P}{P_{rated}} \right) f_{NoLoad}$$

$$V_{out} = V_{NoLoad} - n_{vp} \left(\frac{P}{P_{rated}} \right) V_{NoLoad}$$

Where:

n_{fp} = droop coefficient (frequency due to real power)

n_{vp} = droop coefficient (voltage due to power)

P_{rated} = Rated (real) power

f_{NoLoad} = No load frequency

Other droop characteristics based on current or apparent power may also be encountered.

4. Voltage Regulation

4.1. Rotating machines

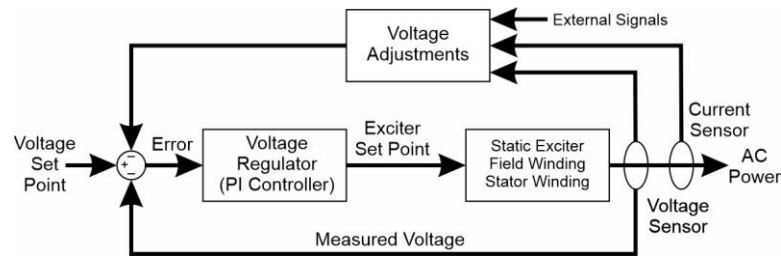


Figure 5: Notional voltage regulation for generator set

Figure 5 depicts a notional voltage regulator for a generator set. The PI controller output is an exciter setpoint for the field winding current. The principal feedback signal is the voltage measured at the output of the generator. A second feedback signal (Voltage Adjustments block) may be present to implement droop or other approaches to safely parallel with other sources.

4.2. Power electronics

Power electronic converters that are not paralleled with other sources are grid forming. Grid forming converters usually generate in digital form, a local waveform of the proper voltage magnitude and frequency. The gating signals for the power electronic switches are created to generate the voltage waveform. Current sensors are used to ensure the converter is not overloaded.

4.3. Parallel Operation

Generator sets are inherently grid forming; when paralleling multiple generator sets and/or grid forming converters, provisions must be made to share both real and reactive power. This can be done through droop or other signals that can be communicated either through digital or analog means. The system voltage and frequency are determined by the method used to implement real and reactive power sharing.

Grid following converters typically sense the voltage and employ a phase lock loop to determine the frequency, voltage phase, and voltage magnitude. The desired real and reactive power is either directly provided, or calculated based on droop using the output of the phase lock loop. From the desired real and reactive power and the voltage characteristics, a desired current waveform is derived. The converter controls then create output currents to match the desired current waveform. Because grid following converters rely upon a voltage waveform existing, grid following inverters must be paralleled with one or more grid forming inverters and/or generator sets. Grid

following converters typically shut down if not connected to a grid forming generator set or converter.

5. Frequency Regulation

5.1. Engines

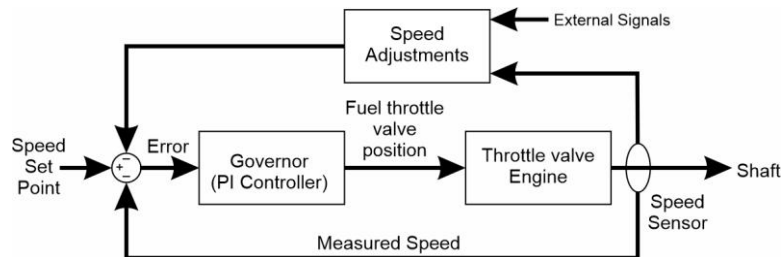


Figure 6: Notional governor for generator set engine.

Figure 6 depicts a notional governor for a generator set engine. The PI controller output is the fuel throttle position. The principal feedback signal is the shaft speed measured on the output shaft. A second feedback signal (Speed Adjustments block) may be present to implement droop or other approaches to safely parallel with other sources.

5.2. Power electronics

Grid forming converters generate a local voltage waveform of the desired frequency. The gating signals for the power electronic switches are created to generate the voltage waveform with the appropriate frequency.

Grid following converters sense the frequency of the bus and create a local current waveform of the desired frequency, phase, and magnitude. The gating signals for the power electronic switches are created to generate the desired current waveform.

6. References

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