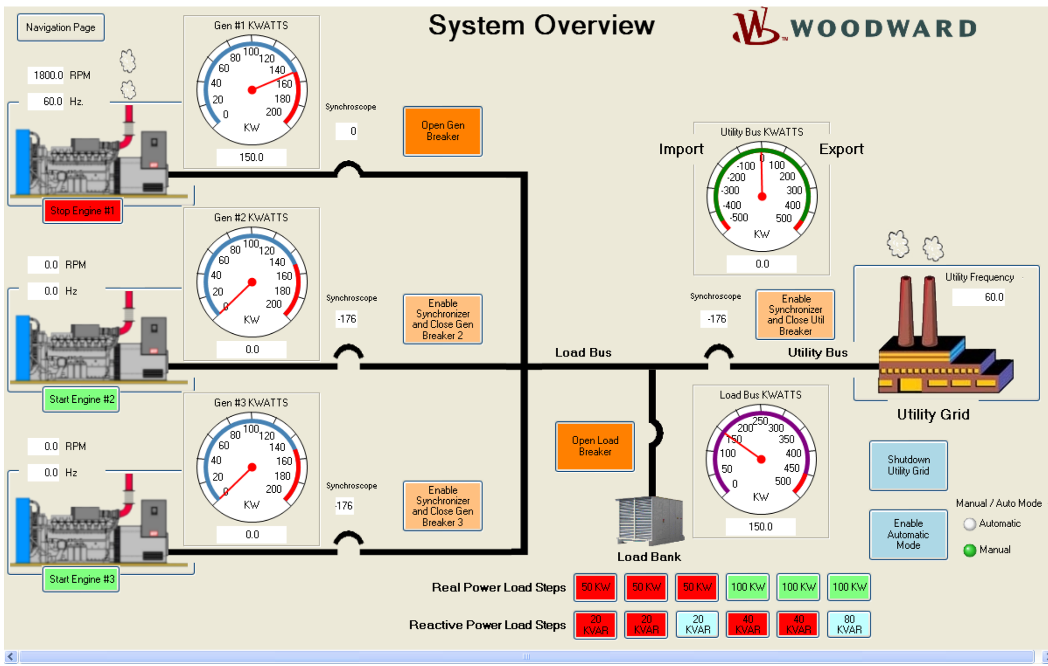
Product Manual 26736
(Revision NEW, 5/2014)
Original Instructions



Power Generation Learning Module Guide

Installation and Operation Manual

⚠ **General Precautions**	**Read this entire manual and all other publications pertaining to the work to be performed before installing, operating, or servicing this equipment.** **Practice all plant and safety instructions and precautions.** **Failure to follow instructions can cause personal injury and/or property damage.**

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Revisions—Changes in this publication since the last revision are indicated by a black line alongside the text.

Contents

Chapter 1.
Overview

This Power Generation Training Module was created to help students learn the basics of the following items:

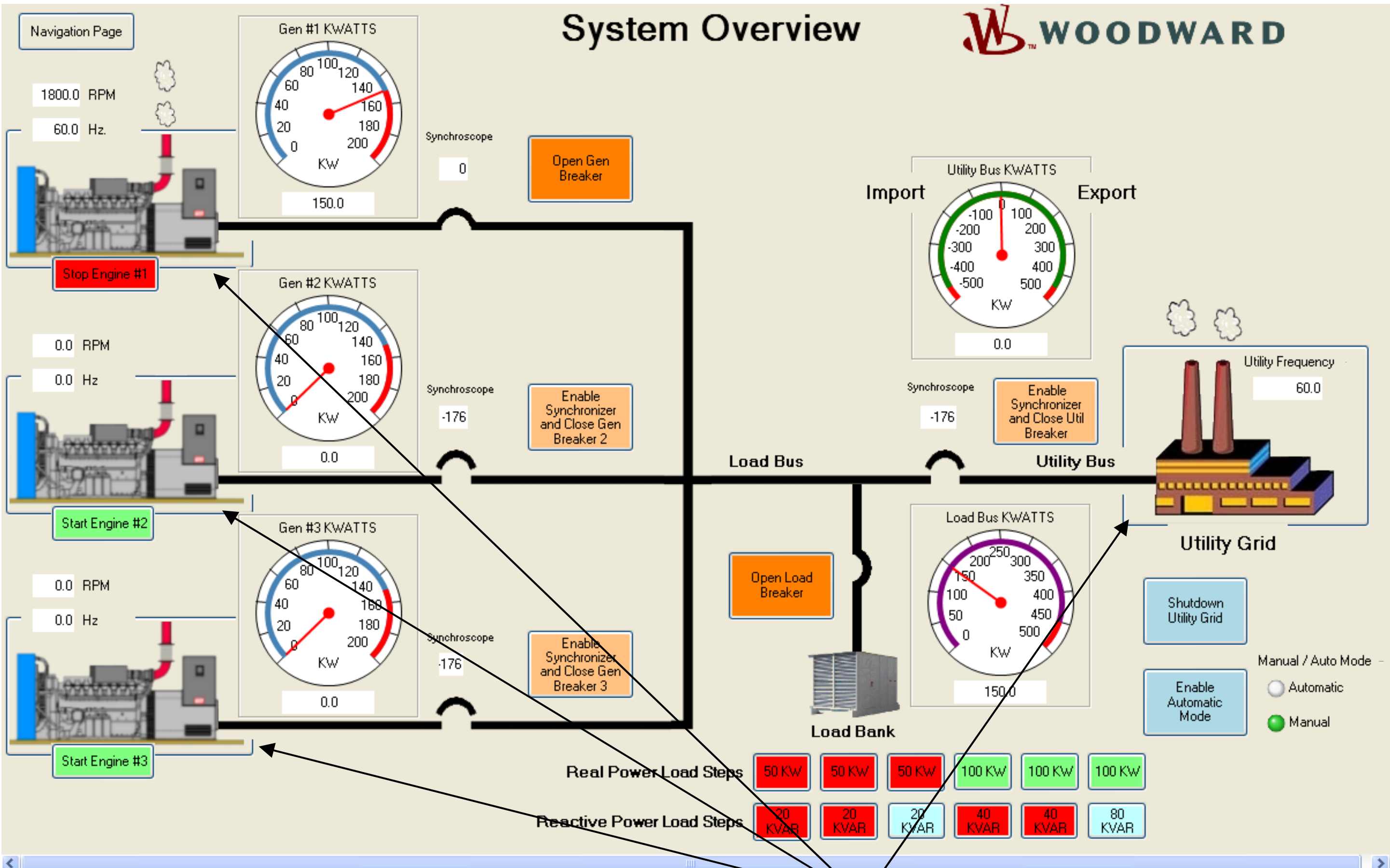
- Engine Speed Control Fundamentals
- Speed Control Dynamic Tuning - PID (Proportional, Integral, and Derivative)
- Generator Automatic Voltage Regulation Fundamentals
- Electrical Power Generation and the basics of Voltage, Current, Watts, Volt-Amps, Volt-Amps-Reactive (VARs, Circulating Currents)
- Power Factor and VAR Control
- Synchronizing Fundamentals
- Various Load Control Schemes, consisting of:
  - Isochronous
  - Droop
  - Droop – Droop Load Control
  - Isochronous Load Sharing
  - Droop Baseload
  - Isochronous Baseload
  - Import / Export Control
  - Fully Automatic Control for Emergency Backup Generators

The dynamic model consists of three engine-generators, rated at 150 kW, with resistive and reactive load banks, associated generator breakers, and a utility grid. The engines have start – stop capability with overspeed protection. The engines run at a synchronous speed of 1800 rpm. The generators are capable of automatically synchronizing to each other and to the Utility Grid (Mains) and are protected for reverse power, over-current, and overload.

The user has the capability to start / stop engines, synchronize generators and close breakers, and tune Engine #1 active speed dynamics on the Speed Control. This will help in understanding the closed loop speed control of the PID (proportional gain, integral gain, and derivative) algorithm. Trending is available to see the effects of the PID during transient load conditions.

The model was created using several software tools, including MATLAB / Simulink, Woodward GAP (Graphical Application Program) software, Woodward NetSim Control Executive software and Woodward ToolKit software.

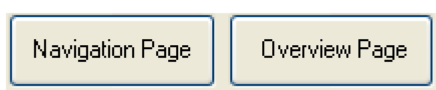
Below is a picture of the System Overview:



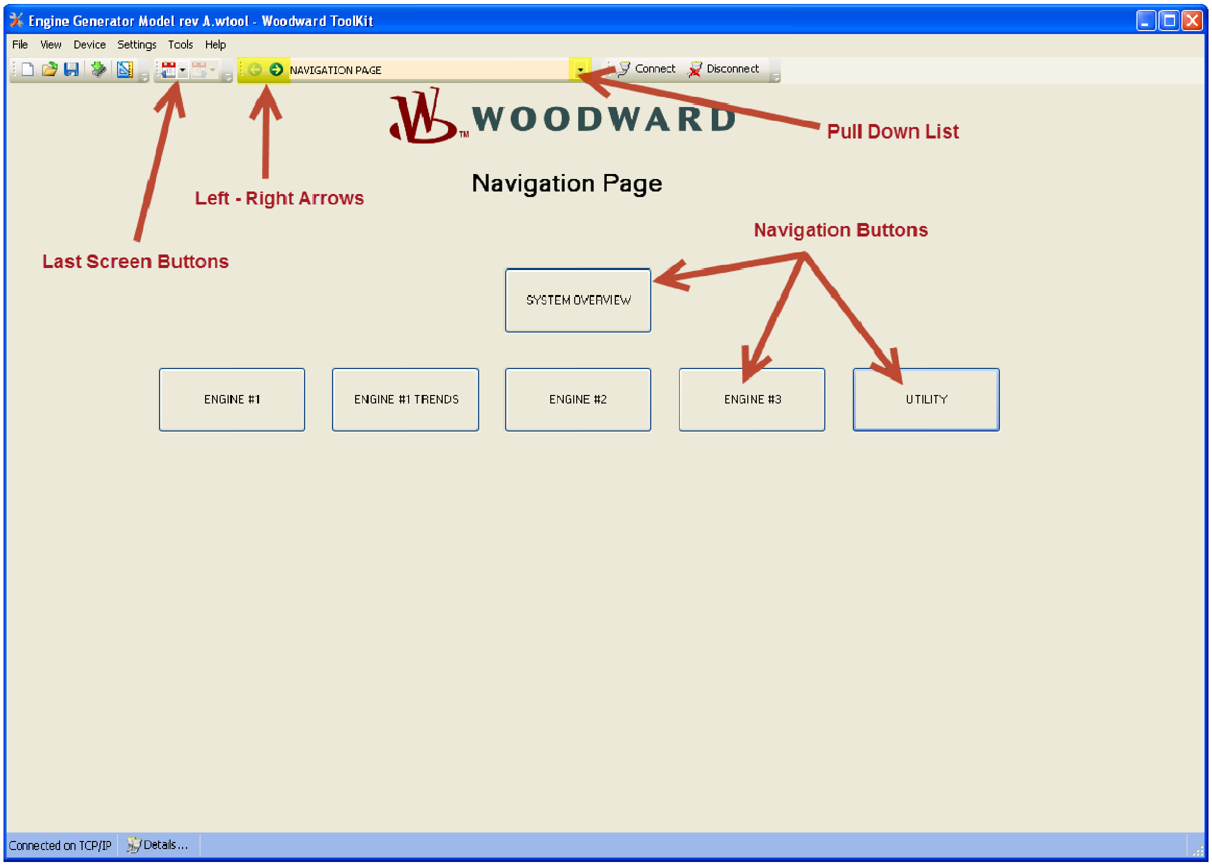
Each engine and the Utility Grid (Mains) is a **HOT BUTTON**. Clicking on each of the engine icons or the Utility Grid (Mains) icon will allow you to navigate to these pages.

There are other Navigation Buttons that allow the user to navigate to the "Navigation Page" and the "System Overview" page.

Example:



Navigation through the pages can be done through multiple methods. The shown icon buttons, Left – Right arrows, the pull down list, or the computer up – down buttons:



Chapter 2.
Getting Started

The student must have the following items:

The “Power Generation Learning Module” USB memory flash drive, part number 8447-1012.

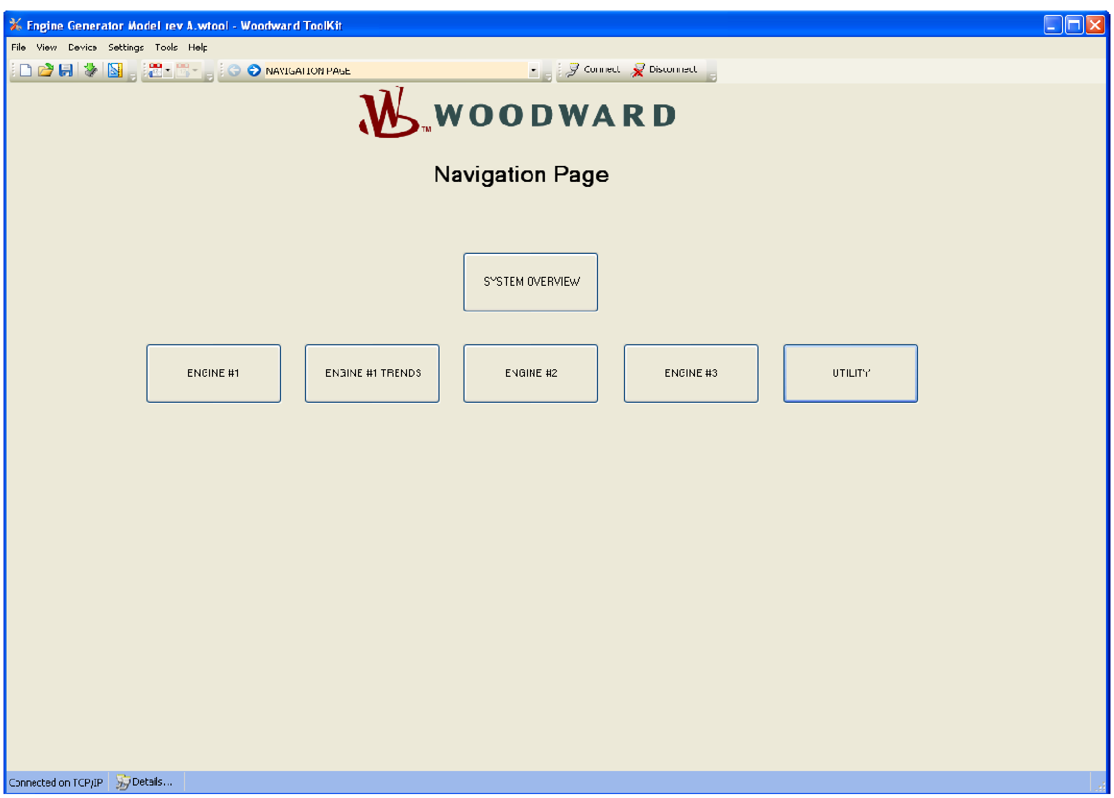
A computer with Windows XP, Windows Vista, or Windows 7 or 8

The USB memory flash drive contains the following files:
1. An install executable file, part number 9927-2187.
2. A Woodward folder. This folder contains the license for the NetSim software.
3. Woodward manual 26736, *Power Generation Learning Module Guide*, in PDF format. Adobe Acrobat is required to open this file format.
4. Woodward product specification 03412, *Power Generation Learning Module*, in PDF format.
5. With the USB flash drive installed on your computer, double click on the 9927-2187.exe file to install the Toolkit and NetSim software.

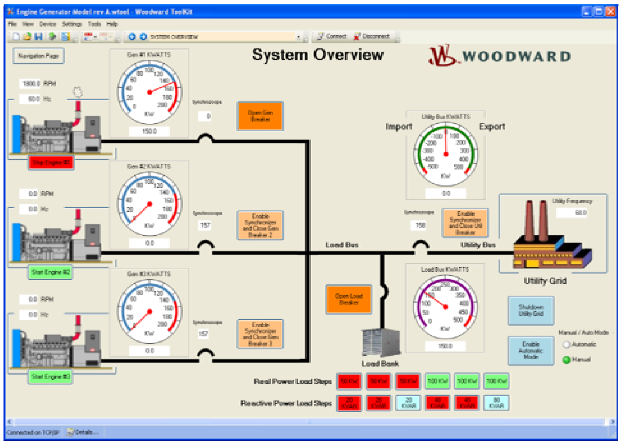
IMPORTANT	**The NetSim Control Executive software is licensed to the USB flash memory drive and cannot be moved or transferred to another computer.**

To start and run the model, open and follow these steps in the Power Generation Learning Module Quick Start Guide (manual 51474).

Once running and connected, the model should look like this:

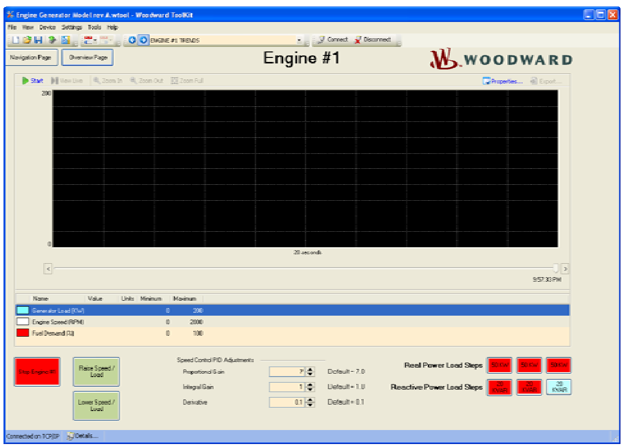


Shown here are the screens available from the "Navigation Page", by selecting the right arrow:

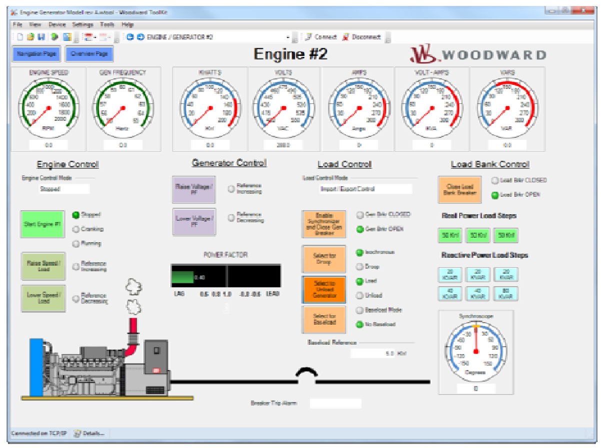


System Overview Screen

Engine #1 Monitor and Control Screen

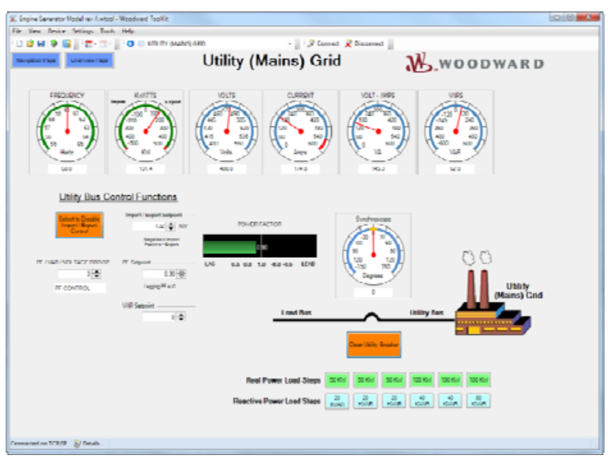


Engine #1 Trending Screen



Engine #2 Monitor and Control Screen

Engine #3 Monitor and Control Screen



Utility Grid (Mains) Monitor and Control Screen

Chapter 3.
Engine Speed Control Fundamentals

Speed Control

The need for precise speed control in connection with the generation of electrical power is probably the largest incentive for precise governor control. The need to hold the generator precisely at 60 Hz (or 50 Hz in other parts of the world) has increased due to frequency sensitive devices. Although mechanical governors are still in use, electronic controllers can provide better control and can also control electrical loads, control exhaust emissions, utilize variable dynamics, and start and stop an engine with less visible smoke and help meet specific environmental requirements.

A speed control must include the following items:

- A way to set the desired speed or speed reference
- A way to sense the actual speed
- A way to compare the actual speed to the desired speed
- A way of stabilizing the engine after a fuel change
- A way to change the fuel demand to the engine

Speed Reference

The speed reference is the rpm of the engine, typically the synchronous speed of the generator, described by the following equation:

$$\text{Engine RPM} = \text{Generator Frequency } \times 120 \ \div \text{Number of Generator Poles}$$
$$\text{Example: } 1800 \text{ RPM} = 60 \text{ Hertz } \times 120 \ \div 4 \text{ poles}$$
$$\text{Example: } 1500 \text{ RPM} = 50 \text{ Hertz } \times 120 \ \div 4 \text{ poles}$$

Actual Speed

The most common method of sensing engine speed is the use of a variable reluctance magnetic pickup (MPU) mounted close to a ferrous metal gear that is either on or driven directly by the engine. It is basically a single pole alternating current electric generator, consisting of a single magnet with a multiple layer coil of copper wire wrapped around an iron core pole piece. The magnetic field of the magnet is continuously interrupted by the ferrous gear teeth passing by to create an AC waveform that is proportional to the speed of the engine. The number of teeth on the gear determines the number of pulses per revolution of the gear. Thus an 80 tooth gear turning at 3600 rpm would produce a frequency of 4800 Hz, as calculated by the following equation:

$$\text{Frequency (Hz)} = \text{Number of Teeth } \times \text{Engine Speed (RPM) } \div 60$$
$$\text{Example: } 4800 \text{ (Hz)} = 80 \text{ teeth } \times 3600 \text{(RPM) } \div 60$$

Picture of a Magnetic Pickup measuring the teeth of a gear and a Magnetic Pickup:

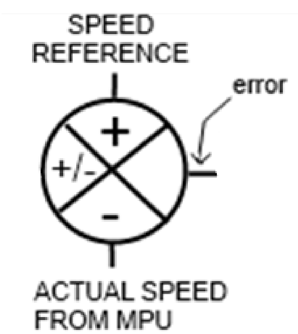
A second method of sensing speed is to use a proximity probe or proximity switch. This device is a powered electronic device, which uses “Hall Effect” or some other means of detecting gear teeth.

The third method for sensing speed is to measure the frequency of a generator being driven by the prime mover. This generator may be the primary generator, an auxiliary PMA (permanent magnet alternator), or a PMG (permanent magnet generator).

The fourth method for sensing speed is to sense the spark plug firing on a spark ignited gas engine.

Summing Point

The key to understanding electronic speed controls is the concept of a summing point. A typical summing point is shown in the Figure below.

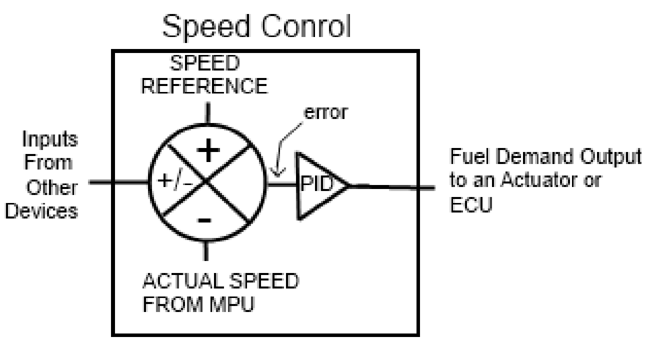


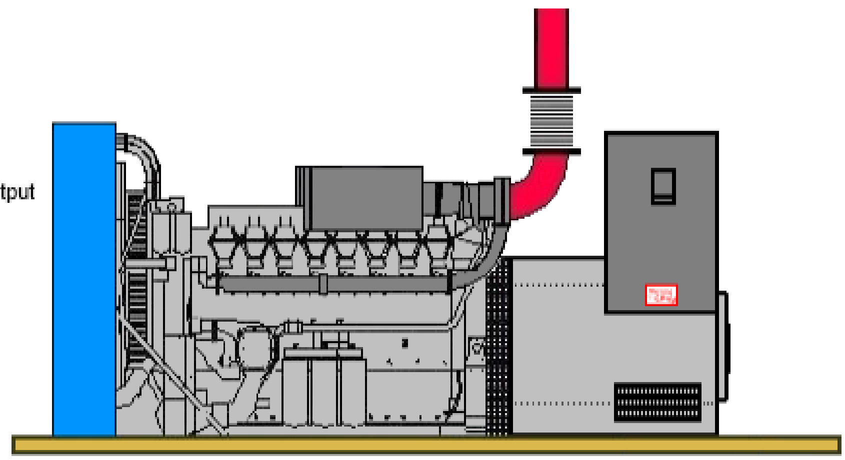
The summing point is where all signals in a control loop add up and must equal zero to allow the electronic control to be controlling the engine at a steady state condition. The advantage of a summing point is that many parameters, in addition to speed, can be sensed and sent to a summing point and controlled at a desired set point. A few examples are speed, pressure, temperature, kW power, and fuel demand limiting.

The desired speed reference and the actual speed reference are added algebraically at the summing point producing an error if the speed reference and the actual speed are different. When these inputs are equal, the engine is running at a constant and steady state speed.

If the error at the summing point is positive, the engine is not running as fast as the desired speed reference. A signal is sent from the output to increase the fuel in order to speed up the engine and increase the engine speed. When the speed increases sufficiently to balance out the summing point to zero difference, the engine is again running at constant and steady state speed.

If the result from the summing point is a negative error, the engine is running faster than the desired speed reference. A signal is sent from the output to reduce fuel in order to slow down the engine and decrease the engine speed. This process is a continuous action and is constantly trying to maintain constant speed.





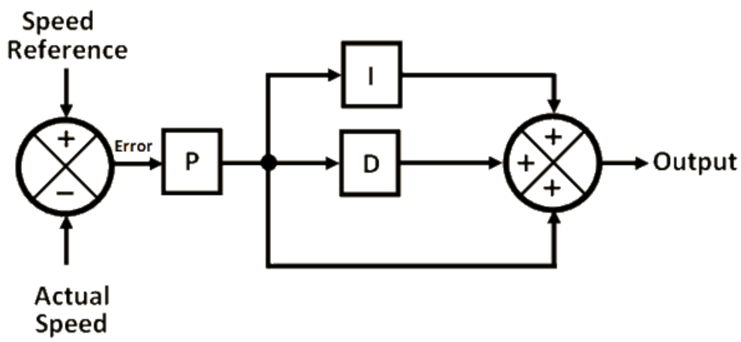
PID

After the summing point in the controller, the error difference between the speed reference and the actual speed is sent to a mathematical type of controller called a PID Controller. PID stands for Proportional, Integral, and Derivative. This type of controller is designed to eliminate the need for continuous operator attention. The ideal notation for the PID algorithm is as follows:

$$\text{Output} = \text{Kp}\left[e(t) + \frac{1}{\text{Ti}}\int e(t)dt + \text{Td}\,\frac{de(t)}{dt}\right]$$

where: e(t) = error between the speed reference and actual speed with respect to time
Kp = proportional term
Ti = integral time
Td = derivative time

The block diagram for this equation would look like this:



An explanation of each of the components follows:

Proportional Response (Kp)

The proportional component depends only on the difference between the speed reference and the actual speed. This difference is referred to as the Error term. The proportional gain (Kp) determines the ratio of output response to the error signal. For instance, if the error term has a magnitude of 10, a proportional gain of 5 would produce a proportional response of 50. In general, increasing the proportional gain will increase the speed of the control system response. However, if the proportional gain is too large, the actual speed will begin to oscillate. If Kp is increased further, the oscillations will become larger and the system will become unstable and may even oscillate out of control.

Integral Response (Ti)

The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the Steady-State error to zero. Steady-State error is the final difference between the actual speed and the speed reference. A phenomenon called integral windup results when integral action saturates a controller without the controller driving the error signal toward zero.

Derivative Response (Td)

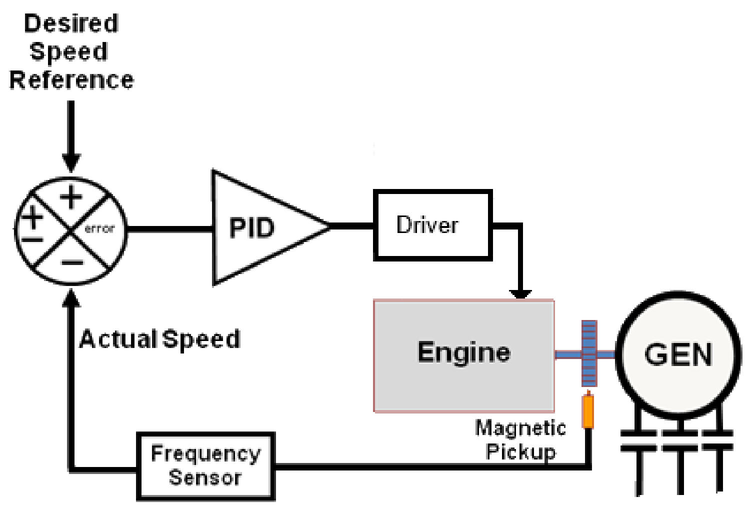
The derivative component causes the output to decrease if the speed signal is increasing rapidly. The derivative response is proportional to the rate of change of the actual speed. Increasing the derivative time (Td) parameter will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response. Most practical control systems use very small derivative time (Td), because the Derivative Response is highly sensitive to noise in the process variable signal.

Fuel Demand

The fuel demand output is used to regulate the energy into the engine. It could be an electrical / hydraulic actuator, an all electric type of actuator, or an ECU (Engine Control Unit) that is controlling the timing and duration of the fuel injectors. The fuel demand is specific to each engine type and whether the engine is a mechanical fuel injected engine, electronic fuel injected engine, natural gas engine, propane engine, ...

Closed Loop Speed Control

This diagram illustrates closed loop speed control. The summing point takes the difference between the Speed Reference and the Actual Speed and sends the error to a PID algorithm then onto to the engine, through a driver, to control the fuel demand. When the engine is running, this closed loop action is continuous . The speed control is always trying to get the engine to control at the desired speed reference.



Exercise

Navigate to the Engine / Generator #1 page. Select the Start Engine #1 button. The sequence of starting is to crank the engine. Once the speed controller sees engine speed, the fuel demand will increase allowing the engine to come up to the speed reference of 1800 rpm / 60 Hz on the generator. Select the Stop Engine #1 button to shutdown the engine.

Navigate to the Engine #1 Trends page. This page allows you to trend and watch the engine speed as it increases up to rated speed. Start the trend by pushing the Start icon in the upper left hand corner. Push the Start Engine #1 button to start the engine. The engine will crank up to about 250 rpm, the fuel demand will go to full fuel and the engine will increase in speed to 1800 rpm.

Let's view how the speed control is set up for transient load response by putting load on and off the generator. In order to do this a couple of breakers have to be closed. Navigate back to the System Overview page and push the "Enable Synchronizer and Close Gen Breaker #1 " button. The animation will show that generator breaker #1 closed. Push the "Close Load Breaker" button on the Load Bank and the animation will show that the load breaker closed. Navigate back to the Engine #1 Trends page and close the 50 kW button on the Load Bank labeled Real Power Load Steps. Notice that the engine speed dropped a small amount and recovered back to 1800 rpm. Also notice that the Fuel Demand increased to carry the 50 kW.

Let's zoom in a little and watch the speed change a little closer. Select the Properties... icon in the upper right hand corner. Select the Engine Speed (rpm) under Plot Properties and change the High and Low settings to 2000 and 1600. Select Close. Remove the 50 kW load button and watch the speed increase as the load is removed and decrease as the load is increased.

Tuning the Control

On the Engine #1 Trends page, the PID (Proportional Gain, Integral Gain and Derivative) adjustments were brought out to watch the effects of these adjustments. The Proportional Gain variable is the "How Much" fuel to give the engine, during a load transient. With the current settings, the speed offset increases to about 1822 rpm when load is removed and 1778 rpm when load is applied.

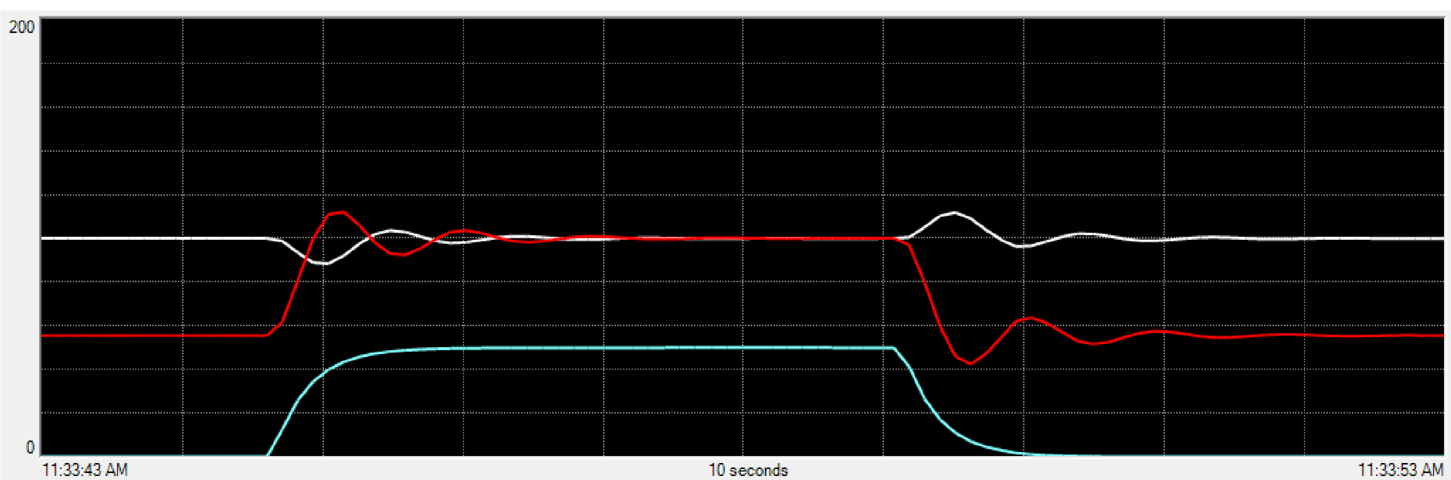
Increase the Proportional Gain to 12, by using the UP Arrows next to the adjustment. By applying the 50 kW load on and off, the speed offset decreases to about ±13 rpm. Even thought the speed offset is decreased, the time to recover back to 1800 rpm is still the same.

Increase the Proportional Gain to 20. By applying the 50 kW load on and off, the speed offset decreases to about ±8 rpm. You can now see the effects of increasing the Proportional Gain variable.

Increase the Proportional Gain to 35. Apply the 50 kW load. The Fuel Demand and Engine Speed will become violently unstable. This is a real life situation, and is called "Hunting" or "Surging". Slowly decrease the Proportional Gain variable until the engine is stable (usually about 25). Return the Proportional Gain to 7.0.

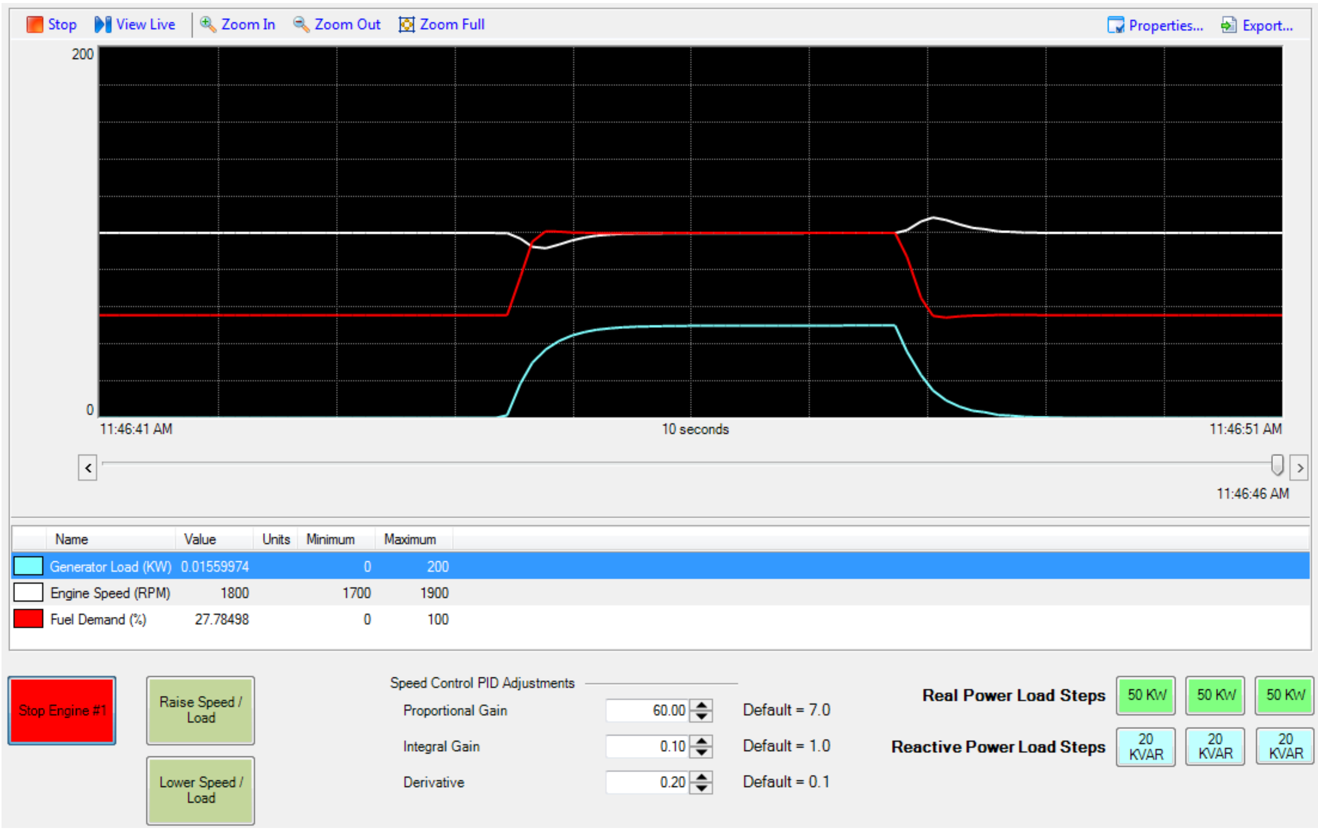
The Integral Gain is the "How Fast" variable. It determines how quickly the speed returns to 1800 rpm. With the Integral Gain set at 1.0, the return time is about 4.5 seconds. Increase the Integral Gain to 3. The return time is now at about 6 seconds. Decrease the Integral Gain to 0.5. Notice now, by applying the load, the return time is about 2 seconds, but there is a little overshoot. Decrease the Integral Gain to 0.25 and perform a load step. The return time is faster but the overshoot is larger yet.

A combination of increasing the Proportional Gain and decreasing the Integral Gain will result in a faster transient response. Put the Proportional Gain to 60.0 and the Integral Gain to 0.1. The response should look fairly good. See diagram below:



The Derivative variable helps with overshoots and undershoots. Derivative means “Rate of Change” or the “Slope of the Line”. The “Rate of Change” that we are discussing is the rate at which the speed returns to 1800 rpm. As the speed is returning to 1800 rpm, a derivative variable will tend to “Put the Brakes on” and allow the speed to smoothly match the speed reference. Increase the Derivative variable to 0.2. By applying a 50 kW step load, notice how smoothly the load transient looks. Feel free to adjust the numbers of all three variables and get a feel for tuning the engine.

This diagram shows good transient load response.

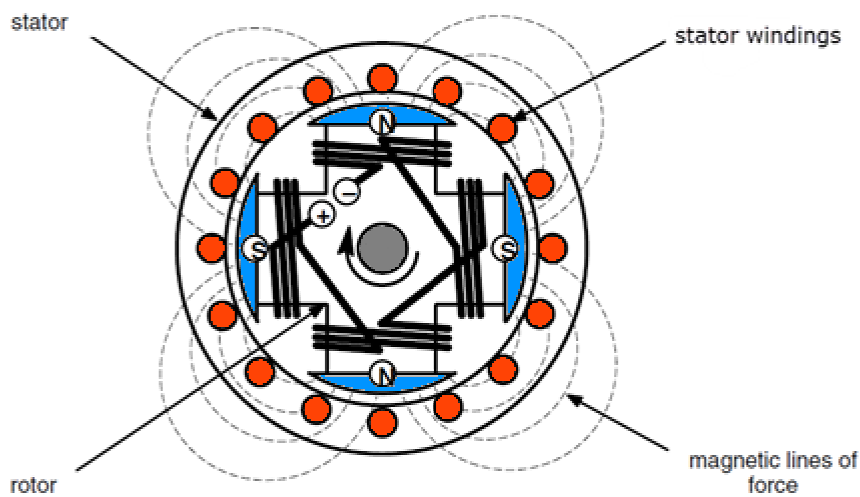


Put the Speed Control PID Adjustments back to the default values when done. Proportional Gain = 7.0, Integral Gain = 1.0, and Derivative = 0.1. Stop all of the engines and open all of the breakers.

Chapter 4.
Generator Automatic Voltage Regulation Fundamentals

A synchronous generator is an electromagnetic device that uses Faraday's law. Michael Faraday discovered that a voltage potential could be induced into a conductor by passing a conductive material through a magnetic flux field. This principle is called "Electromagnetic Induction" and is the basis for power generation.

A synchronous generator is designed so that the three requirements of electromagnetic induction are satisfied. These are; a conductor, a magnetic flux field, and relative motion between the two. The synchronous generator is comprised of an armature and a rotating field. The armature is the stationary part of the generator is known as the "Stator". The stator is made up of conductive windings and from the above analogy, is the conductor. The rotating field, on the rotor of the generator, is the medium by which the magnetic flux is produced. The automatic voltage regulator provides a DC (direct current) voltage to create an electromagnet field in the coil windings. The rotor, through its rotating action, causes the relative motion of the electromagnetic field to the stationary stator windings and, through this action, an output voltage is induced from the generator. Shown below is a cross section of a generator:

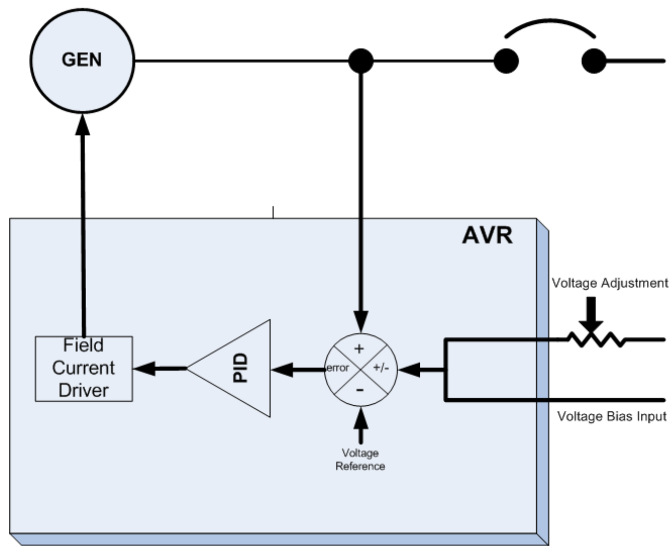


Control or regulation of the generator voltage is similar to that of the engine speed control.

Voltage control must consist of the following items:

- A way to set the desired voltage or voltage reference
- A way to sense the actual voltage
- A way to compare the actual voltage to the desired voltage
- A way of stabilizing the generator voltage after a load change
- A way to change the excitation to the generator

The diagram below shows a simple block diagram of the automatic voltage regulator:



Voltage Reference

The Voltage Reference is typically the nameplate voltage of the generator. The model introduced in Chapter 2 uses 480 Vac as the voltage reference.

Voltage Adjustment

There is usually a method of changing the nominal voltage, typically giving the operator ±10% voltage change. The diagram above shows a potentiometer for adjustment.

Voltage Sensing, Error Detection, PID and Field Current Driver

The Voltage is sensed from the output of the generator and compared with the voltage reference. The error or difference between the actual voltage and the voltage reference is sent to PID controller then onto the field current output driver. The field current output is called the “excitation” of the generator.

Voltage Droop

Voltage droop is defined as a decrease in voltage for an increase in Reactive Load on the generator. This is required when paralleling two or more engines together or a generator to the Utility Grid.

When two generators are tied together or a generator to the utility grid, the voltages of the generators are electrically locked together once the breaker is closed. This is an important concept to remember. This means that they have to be running at exactly the same excitation voltage. If they aren’t excited at exactly the same voltage, then when the breaker is closed one of them will drop in voltage and the other will increase. This can cause an increase in Reactive Power unless there is droop in the AVR.

Exercise

Navigate to the Engine / Generator #1 page and press the Start Engine # 1 to start the engine. Once the engine is at 1800 rpm, close the generator breaker by selecting the "Enable Synchronizer and Close Gen Breaker #1" button. The generator breaker should close. Select the "Close Load Breaker" button on the Load Bank to close the Load Bus to the Load Bank. The generator voltage should be at 480 Vac. The voltage is adjustable from the Raise Voltage and Lower Voltage buttons under the Generator Control column. Raise and Lower the voltage to verify the voltage control. Return the voltage to 480.0 Vac.

Add 60 kVAR of reactive load from the Reactive Power Load Steps. Notice how the voltage decreases down to about 476 Vac. This is the effect of Voltage Droop. Voltage Droop is a decrease in generator voltage for an increase in reactive load.

Remove the Reactive Load, open the Load Bank Breaker and the Generator Breaker, and Stop the engine.

Chapter 5.
Power Generation Fundamentals

Real Power

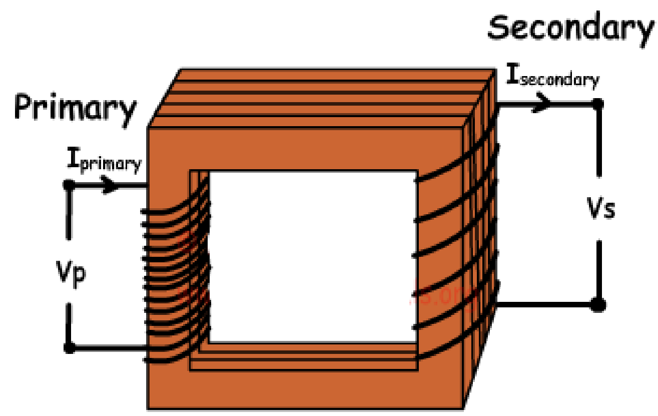
Real power is defined by the following equation:

$$\textbf{Real Power} = \sqrt{3} * \textbf{Voltage} * \textbf{Current} * \textbf{Power Factor}$$

The square root of three equals 1.7321, the voltage is the output of the generator (480 Vac in the model), the current is the current developed by the generator from the load and the power factor is a ratio of real power to apparent power.

$$\textbf{Real Power} = \sqrt{3} * \textbf{Voltage} * \textbf{Current} * \textbf{Power Factor}$$
$$\textbf{Example: 50.3 kW} = \sqrt{3} * \textbf{477.6 Vac} * \textbf{78 A} * \textbf{0.78}$$

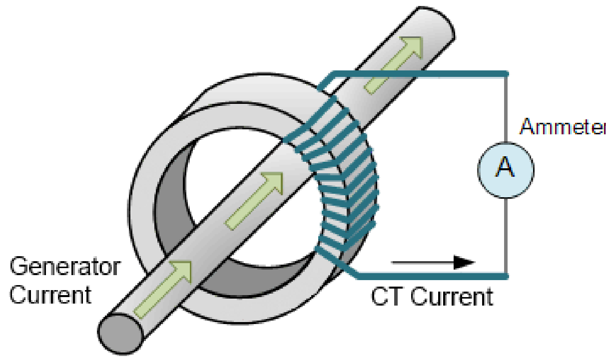
To calculate the real power of the generator, two electrical components must be used. The generator voltage is measured utilizing a Potential Transformer (PT). The generator voltage is applied to the Primary of a transformer and due to the turns ratio of the transformer, the voltage is stepped down to a useable voltage. Example of a 480 Vac generator, the turns ratio of the transformer would be 4:1. Which means with 480 Vac on the primary, the secondary would read 120 Vac.



The generator can output many different voltages depending on what a user wants. AC voltages of 480, 4160, 11 000, 12 480, and 13 800 are common generator voltages in the world.

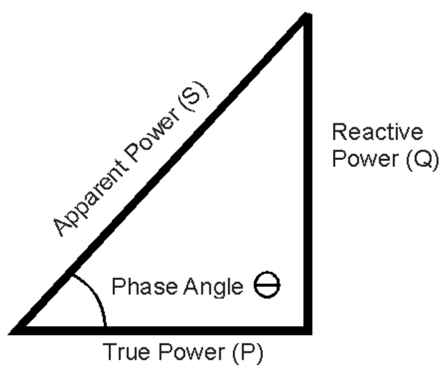
The current of a generator is measured utilizing Current Transformers (CTs). The Current Transformers are installed around the primary leads of the generator. The winding turns ratio of the CT is sized so that the CT current is typically 5 A at full load or full current of the generator. Example if the generator output current was sized at 1000 A, the turns ratio of the CT would be 1000:5. Meaning 1000 A is reduced to 5 A and is proportional from no load to full load.

A current transformer is shown below:



The measurement of the voltage and current, when multiplied together along with the $\sqrt{3}$ provides the Volt-Amp calculation of the generator. The Power Factor piece of the equation is explained below.

The "Power Triangle" relates **apparent power** to **true power**, **reactive power** and **power factor**. Using the laws of trigonometry, you can solve for the length of any side, given the lengths of the other two sides, or the length of one side of and an angle.



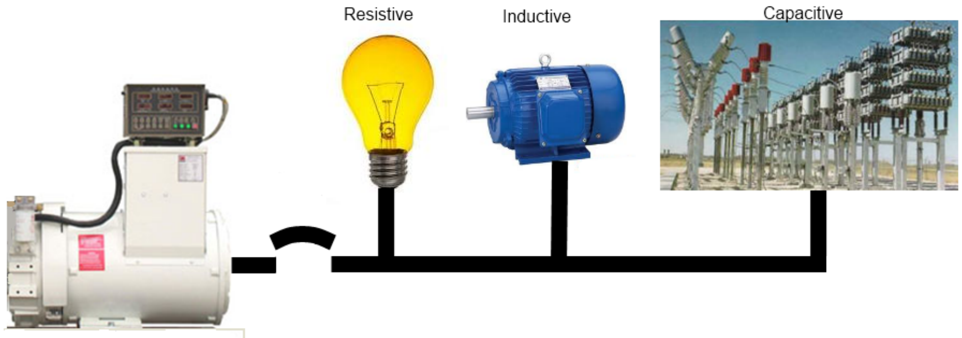
Power Factor and Reactive Power

Power factor is defined as the ratio of **real power** flowing to the load to **apparent power** created by the load. It is a dimensionless number between 0 and 1. Unity Power Factor is the term used for a power factor of 1.0. The power factor of a system is determined by the amount of reactive load in the system. Power factor (PF) can be determined by the equation PF = cos θ, where cos θ is the phase difference between the voltage and the current.

What do the loads on your generator consist of? There are three types of load that your generator will react to: 1-Resistive Loads, 2-Inductive Loads and 3-Capacitive Loads.

1. Resistive loads are physical devices such as the line resistance of the wires, base board heaters, and incandescent light bulbs. These are devices that are purely resistive in nature, with no inductive or capacitive reactance.
2. Inductive loads are inductors or coils and usually consist of induction motors, fluorescent light ballasts, and anything with a coil of wire inside it.
3. Capacitive loads are not very common as there are not many physical devices that are capacitive, except a capacitor. Synchronous motors can act a little capacitive.

Example of typical loads:



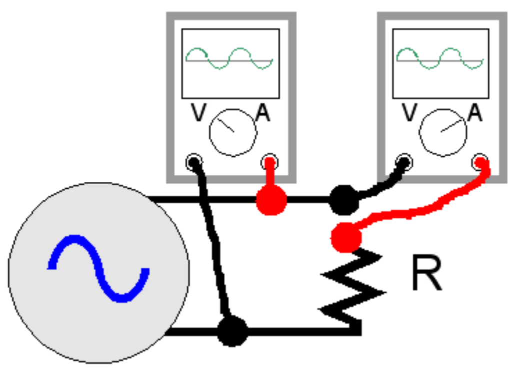
Reactive loads such as inductors and capacitors dissipate zero power, due to the 60 Hz sine wave of the generator. Yet the fact that they drop voltage and draw current gives the deceptive impression that they do dissipate power. This "Phantom Power" is called reactive power, and it is measured in a unit called Volt-Amp-Reactive (VAR). The mathematical symbol for reactive power is the capital letter Q. The actual amount of power being used in a circuit is called true power and it is measured in watts, symbolized by the capital letter P. The combination of reactive power and true power is called apparent power, and it is the product of the voltage and current, without reference to phase angle. Apparent power is measured in the unit of Volt-Amps (VA) and is symbolized by the capital letter S. Voltage is symbolized by the capital letter E, R is for resistance and I equals current.

The equations for P = true power are: $P=I^2R$ or $P=E^2/R$, measured in watts

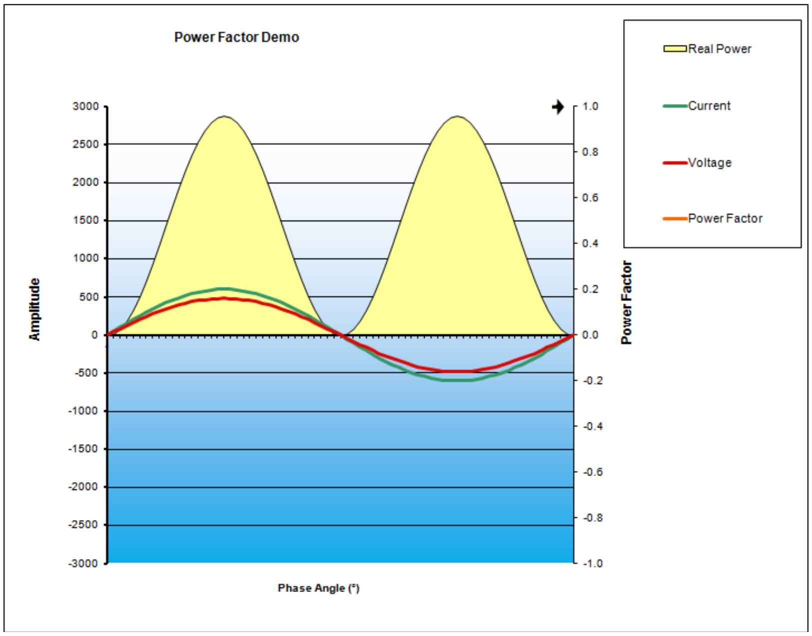
The equations for Q = reactive power are: $Q=I^2X$ or $Q=E^2/X$, where X=capacitive reactance and measured in volt-amps-reactive

The equations for S = apparent power are: $S=I^2Z$ or $S=E^2/Z$ or $S=IE$, where Z=inductive reactance and measured in volt-amps.

Here is an analogy on how to understand reactive power. You can then demonstrate it on the model. If you have a generator with a resistive load

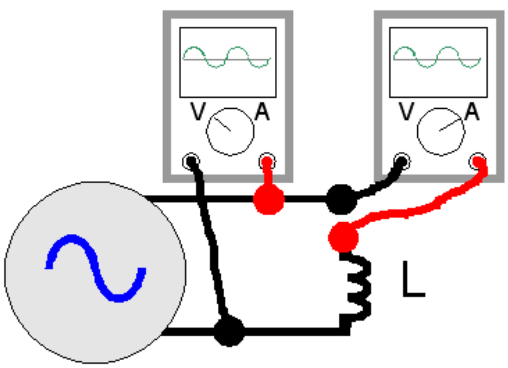


and plot the voltage across the resistor and the current through it, you will get this result:

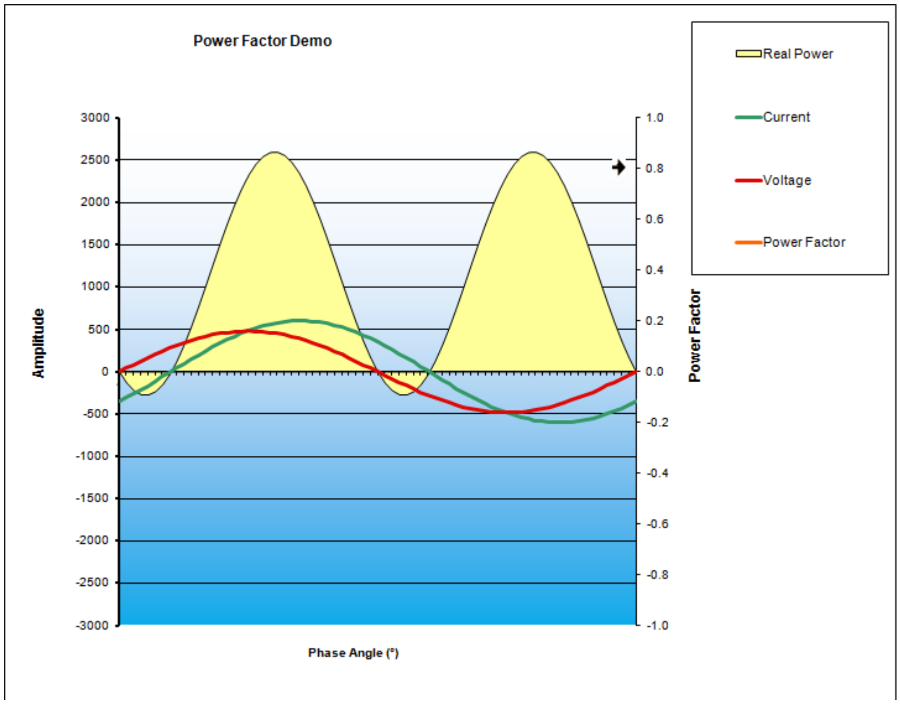


Notice that the voltage (green line) and current (red line) cross the zero reference at the exact same time. If you multiply the voltage and the current together, you get the real power curve, which is always positive. Multiplying two negative numbers together is a positive number. The average of this curve is the average power. The phase difference between the voltage and current is zero. Cosine of zero = 1.0 which is Unity Power Factor.

If we take the same generator with a coil or inductor across it:

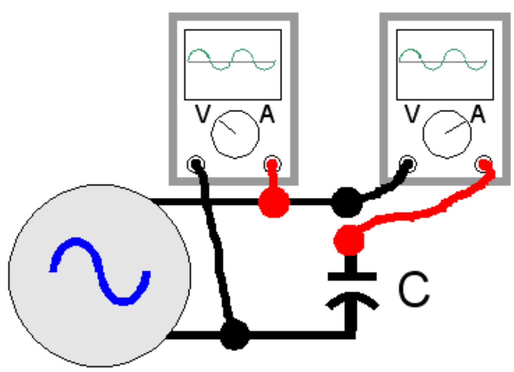


The waveform changes to this:

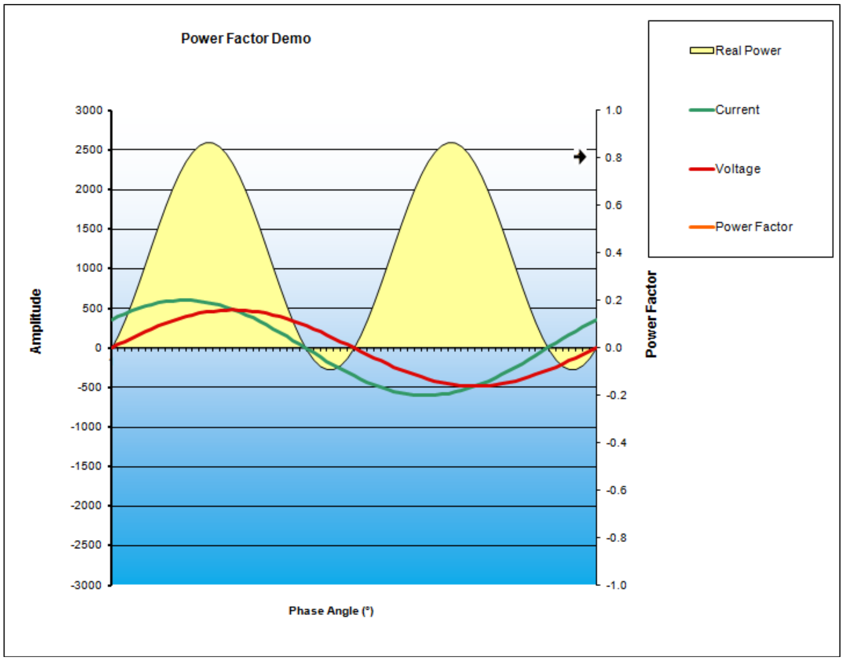


Notice that the voltage leads the current by a specific number of degrees. Also notice that there is a certain amount of power that is below zero (yellow curve below zero). This is the Reactive Power component. This chart shows the phase difference between the voltage and the current at about a 0.8 Power Factor.

If we take the same generator with a capacitor across it:



The waveform changes to this:



Notice that current leads the voltage by a specific number of degrees. The same reactive current can be seen. This condition is not seen very often as most Power Factors are lagging and not leading, like this is shown.

Power Factor and Reactive power is caused by the load on a generator in a system that is not tied to the Utility Grid. The reason that it is typically lagging is due to the fact that most electrical loads are inductive in nature. The Power Factor equation is given as PF = Cos θ. If the load is resistive and the phase difference between the voltage and current is zero, the Cosine of 0.0 degrees equals 1.0, therefore unity power factor. If the load is inductive at about 37 degrees, the Power Factor is about a 0.8 Power Factor.

Exercise

Let’s demonstrate some of these concepts on the model. Navigate to the System Overview page, Start Engine # 1 and close Generator Breaker #1 by selecting the “Enable Synchronizer and Close Gen Breaker #1” button. The generator breaker should close. Select the “Close Load Breaker” button on the Load Bank to close the Load Bus to the Load Bus. Close all three of the 50 kW Load Steps on the load bank. Navigate to the Engine / Generator #1 Page. The generator load should be at 150 kW. Since the real load steps are all resistive, the Power Factor should be at 1.0 or Unity Power Factor and the Reactive Power should be at zero. Add 100 kVAR of Reactive Load from the Reactive Power Load Steps and watch the current and VARs increase and the Power Factor decrease. The Power Factor should drop down to 0.83 and the current should increase to 180 A. The kW load stays the same, only the current increases as the Power Factor decreases. Most generators are sized to handle a 0.8 Power Factor.

Remove all of the loads, open all of the breakers and shutdown the engine.

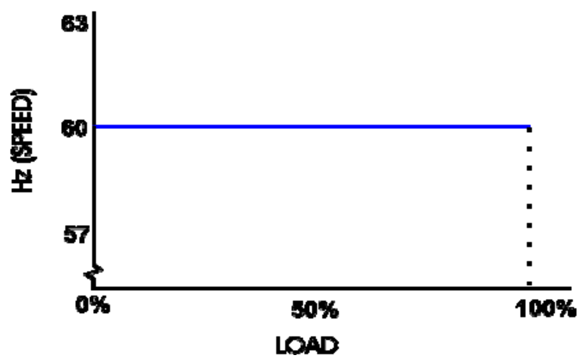
Chapter 6. Isochronous Load Control—Single Engine, Isolated Operation

The word “Isochronous” means “Constant Speed” and is defined as “No change in speed for a change in load”. Isochronous is the preferred operating mode for a generator or generators that are isolated or islanded from the Utility Grid (Mains).

Isochronous operation is used in many applications, such as:

- Emergency generators used in hotels, hospitals, data centers, etc.
- Ships at sea,
- Oil rigs on the ocean,
- Many towns in Northern Canada and Alaska and remote locations that are not capable of connecting to the Utility Grid.

Below is a graph of an isochronous generator. No change in speed, throughout the load range of the generator:



Exercise

Navigate to the Engine / Generator #1 page. Click on the “Start Engine #1” button. Monitor the Engine Speed, the Generator Frequency and Generator Voltage. The synchronous speed of the engine is 1800 rpm, with a four pole generator equates to 60.0 Hz. This equation used to determine the synchronous speed is:

$$\text{Generator Frequency (Hz)} = (\text{Engine Speed (RPM)} * \#\ \text{Gen Poles}) / 120$$

Example: $60\ \text{Hz} = (1800\ \text{RPM} * 4\ \text{Poles})/120$

Click on the “Enable Synchronizer and Close Gen Breaker” button, under the Load Control title. Since the Load Bus is dead, the breaker will close automatically. Click on the “Close Load Bank Breaker” button. The Load Bank breaker will close allowing the generator to tie to the Load Bank. Close one of the 50 kW buttons under the Real Power Load Steps. The generator will drop down in frequency temporarily and return to 60 Hz. The kW meter will show 50.0 kW and the Current Meter will show 60 A. Continue adding both 50 kW switches for full load operation. The generators are rated for 150 kW.

The speed controls are in isochronous, and you can see from the model, that the engine speed and generator frequency always comes back to 1800 rpm and 60.0 Hz as load is applied and removed. This meets the definition of “Isochronous – No change in speed for a change in load”.

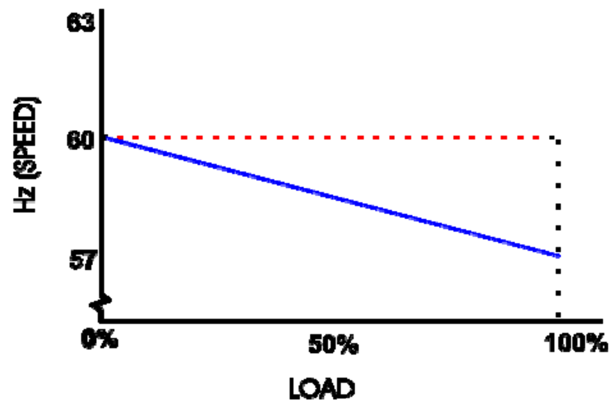
Remove all of the loads, open all of the breakers and shutdown the engine.

Chapter 7.
Droop Load Control—Single Engine, Isolated Operation

Droop, for the speed control, is defined as: “A decrease in speed reference, for an increase in real load”.

Droop, for the voltage regulator, is defined as: “A decrease in voltage reference, for an increase in reactive load”

The chart below shows the effect of speed droop in an isolated system:



Exercise

The effects of droop can be seen during this exercise. Navigate to the Engine #1 Parameter page, start Engine #1, close the Generator Breaker and the Load Bank Breaker. Push the “Select For Droop” button. This will put the speed control from running Isochronous Mode into the Droop Mode. The droop percentage is fixed at 5%. This means that with full load on the generator, the speed will drop by 5%. Example; 1800 rpm * 5% = 90 rpm or 60 Hz * 5% = 3 Hz. Put on the first 50 kW load step and watch the frequency drop to 59 Hz. Put on the second load 50 kW step and watch the frequency drop to 58 Hz. Put on the last 50 kW load step and watch the frequency drop to 57 Hz. The speed control is acting per the definition: “A decrease in speed reference, for an increase in load”.

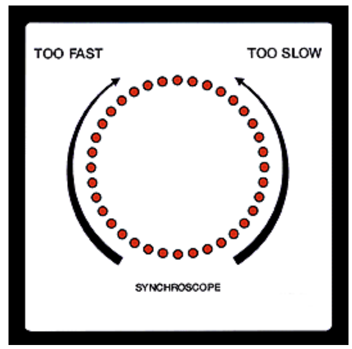
Voltage droop can also be seen in the voltage regulator, which is also in the droop mode. As Reactive Load is increased, the voltage decreases at a rate of 5%. Close the 20 KVAR Reactive Power Load Bank load step and watch the voltage drop in voltage. Continue to add Reactive Power Load Bank load steps until 100 KVAR is closed. The voltage drops down to about 474 Vac. The voltage regulator is acting per the definition: “A decrease in voltage reference, for an increase in reactive load”.

This exercise shows the affect of speed and voltage droop, but does not explain why and where droop is required? This will be explained in Chapter 9.

Remove the load from the system and open all of the breakers. Shutdown all of the Engines.

Chapter 8. Synchronizing

What does Synchronizing mean? Synchronizing, sometimes called paralleling, as applied to the generation of electricity, is the matching of the voltage output waveform of one alternating current (AC) electrical generator with the voltage waveform of another alternating current system. This could mean that two or more generators are being connected together or a generator to the utility grid. Some systems utilize synchroscopes to detect the phase difference across a breaker:



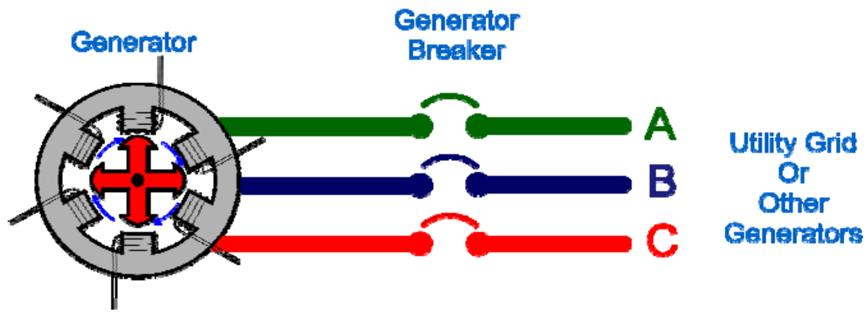
For two systems to be synchronized, five conditions must be met:

1. The number of phases in each system must be the same
2. The direction of rotation of each system must be the same
3. The voltage amplitudes of the systems must be closely matched
4. The frequencies of the systems must be closely matched
5. The phase angle of the voltage waveforms must be closely matched

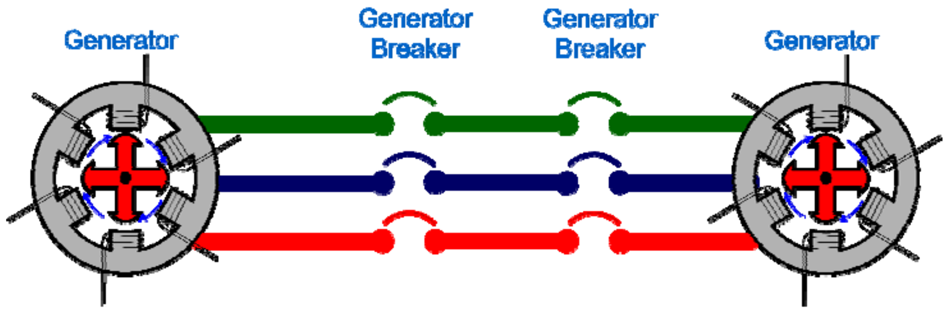
The first two of these conditions are determined when the equipment is specified, installed and wired. The output voltage of the generator is controlled by an automatic voltage regulator (AVR). The two remaining conditions, frequency matching and phase matching, are controlled by the speed control.

Here are the conditions that must be met:

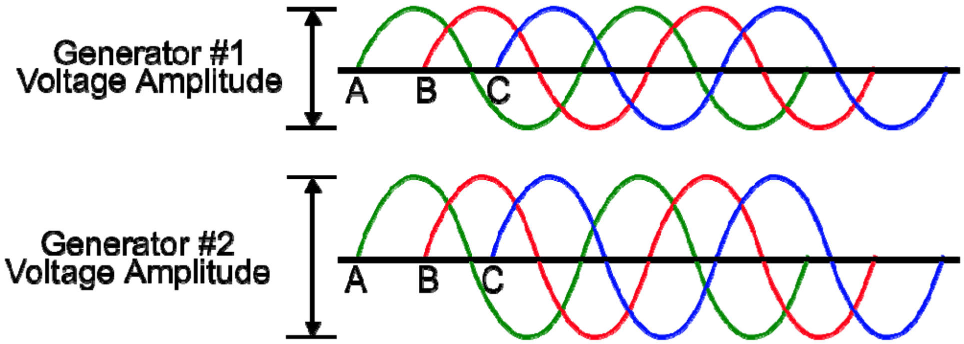
1. The number of phases in each system must be the same. A three phase system must be tied to a three phase system:



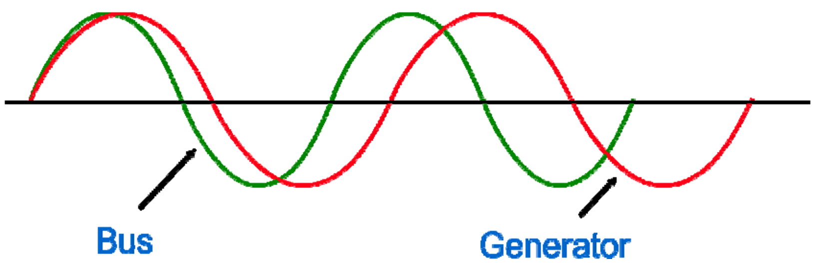
2. The direction of rotation of each system must be the same. A phase, B phase and C phase must be the same rotation:



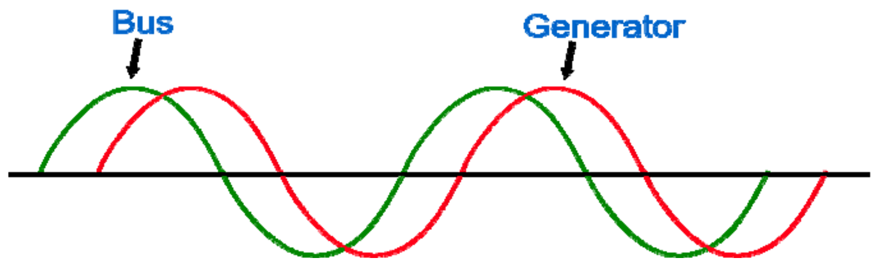
The voltage amplitudes (controlled by the voltage regulator) of the systems must be closely matched (usually between 1-5 %) before the generator breaker is closed. If they are not closely matched, the generator could produce large amounts of Reactive Power:



3. The frequencies of the systems must be closely matched, usually within 0.2%. The 60 Hz of the generator must match the 60 Hz of the other generator or utility grid. The following diagram shows the Bus at 60 Hz and the Generator at 58 Hz:



4. The phase angle of the voltage waveforms must be closely matched, usually plus or minus 10%. Therefore, the sine waves will be practically on top of each other. If the phases are not close, and the breaker closes, damage can be seen on the engine / generator. It can also cause very high voltage across the breaker resulting in arcing in the breaker. The following diagram is showing the Bus and the Generator about 70 degrees out of phase. The synchroscope is the device that measures phase difference.



When two or more electrical generating sets or systems are paralleled to the same power distribution system, the power sources must be synchronized properly. Without proper synchronization of the oncoming unit or system, power surges and mechanical or electrical stress will result when the tie breaker is closed. Under the worst conditions, the voltages between the two systems can be twice the peak operating voltage of one of the systems, or one system can place a dead short on the other. Extremely high currents can result from this, which puts stress on both systems. These stresses can result in bent drive shafts or broken couplings. Under some conditions, power surges can be started which will build on each other until both generating systems are disabled. These conditions are extreme. Stress and damage can occur in varying degrees. The degrading effects depend on the type of generator, the type of driver, the electrical load, and on how poorly the systems are synchronized when the breakers are closed.

Exercise

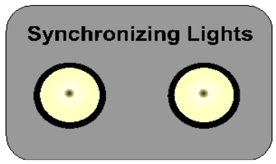
This exercise demonstrates synchronizing between the engines on the model. From the System Overview page, start Engine #1 and Engine #2. Close the “Enable Synchronizer and Close Gen Breaker #2”. The breaker will close immediately due to the fact that the load bus is dead or at zero potential. Once the breaker closes the “Load Bus” becomes active. Any other generator that connects to this bus must follow the synchronizing properties listed above.

Navigate to the Engine / Generator #1 page. In order to watch the synchronizing process in action, increase the speed of the engine, by a small amount, by selecting the “Raise Speed / Load” button. The engine speed should be running at approximately 1800.3 rpm. The synchroscope, in the lower right hand corner should be rotating clockwise slowly. This is what is called “going slow in the fast direction”. Wait until the needle is out of phase and push the “Enable Synchronizer and Close Gen Breaker #1” Button. The Automatic synchronizer will activate and pull the needle to 0.0 degrees (12:00 o’clock). Once the phases are within ±10 degrees, the breaker will close. Generator #1 and Generator #2 breakers are now closed and the generators are electrically locked together.

To watch the process again, select the “Open Gen Breaker” button. This time, decrease the speed of the engine by a small amount. The engine speed should be running at 1799.6 rpm or so. Push the “Enable Synchronizer and Close Gen Breaker #1” Button. The Automatic synchronizer will activate and pull the needle to 0.0 degrees (12:00 o’clock). Once the phases are within ±10 degrees, the breaker will close.

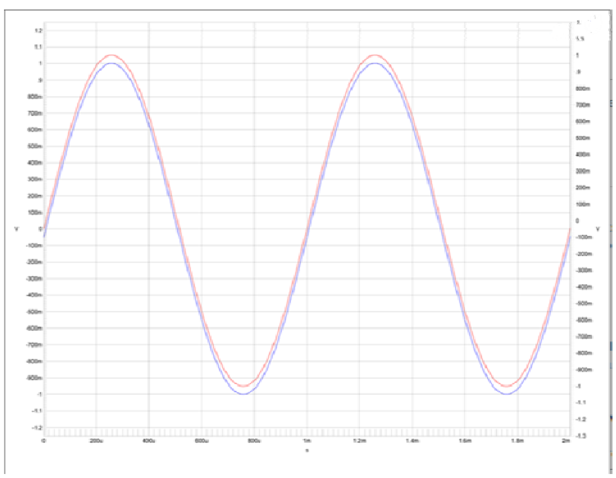
This is called “Automatic Synchronization”. There are many facilities that do not have an automatic synchronizer available and still rely on an operator to manually synchronize the generators together manually. Open the generator breaker #1. Increase the speed of the engine a small amount. This time, by using the Raise and Lower Speed buttons, try and get the synchroscope to Zero Phase. Most operators will get the oncoming generator slightly faster than the other unit, again getting the synchroscope going slow in the fast direction. Once the two phases are within the phase window of ±10 degrees, they will manually close the breaker.

In much older systems, synchroscopes were not available, and the older systems used phasing lights for synchronizing.



These usually consisted of two or three light bulbs across one phase or across all phases, on the generator. When the phase of both generators were 180 degrees out of phase, the light bulbs were on bright. As the phases of the generators got closer and closer, the voltage across the light bulbs became less and less. Until the phases were directly on top of each other, when the voltage between the two are close to zero.

The following graph illustrates two sine waves that are in phase with each other:



Remove the load from the system and open all of the breakers. Shutdown all of the Engines.

Chapter 9.
Droop Baseload to the Utility Grid

Chapter 7 explained the effects of droop. This chapter will explain why you need droop in a governor or speed control system and will show you why you cannot tie two generators together without using some kind of Load Sharing or use Droop between the speed / load controls. When two generators are electrically tied together or a generator to the utility grid, the phases of the generators are electrically locked together and the voltages are electrically locked together. This is an important concept to remember. This means that they ***have to*** be running at exactly the same speed / frequency, and the voltages must be close before closing the breaker. The exercise below will tie an isochronous controlled speed controlled engine / generator to the Utility Grid. The Utility Grid (Mains) is basically a very large isochronous source. In North America, the frequency of the electrical grid changes very little. The North American electrical grid consists of large Hydro Turbines, Large Nuclear Power Plants, Large Coal Fired Power Plants, Large Gas and Steam turbines and many other power sources all paralleled together into one network / grid. Therefore the Utility Grid (Mains) frequency is very stable.

Exercise

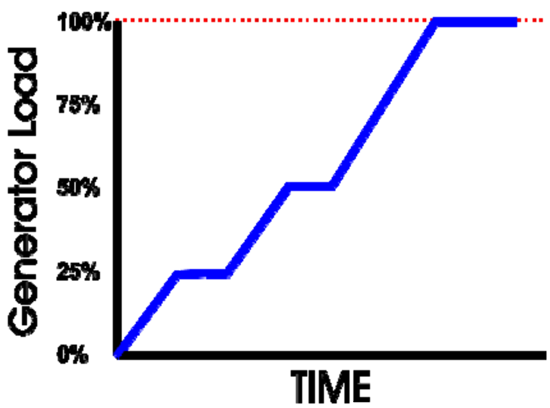
This exercise will demonstrate what happens if you tie an isochronous controlled engine / generator to the isochronous utility grid. Start Engine #1 and close the Generator Breaker. Select Isochronous on the Engine #1 page. Navigate to the Overview Page and select the Enable Synchronizer and Close the Utility Breaker button. The synchronizer will bring the phases of the generator and the utility into phase and the breaker will close. Once closed, since the speed governor was running slightly faster than the Utility Grid (Mains) frequency, engine #1's speed control was slowed down (due to electrically locking the generator to the utility grid). The engine's speed control seeing a slight decrease in speed wants to try and increase the speed back to where it was (that is the whole function of the speed control). The fuel demand is increased, adding fuel to the engine. This increase in fuel increases the torque from the engine to generator and current starts increasing and is exported to the utility (as seen from the Generator #1 kW meter). The load will continue to integrate up, since the speed control is never satisfied, and eventually will max out. The generator breaker has a current limit on it and if reached for a period of time will open the breaker. If the engine speed were slightly slower than the utility grid, the generator would be motored, sending current from the Utility Grid (Mains) back into the generator. This is called reverse power and the generator reverse power relay should open the breaker.

This above example shows why you cannot tie two isochronous controlled generators together, without some kind of load sharing, load control or droop. Although you should not do this on live generators, the model is very realistic and a live generator will perform exactly as seen in the model.

Now, let's get back to why we need frequency and voltage droop. Remember the definition of frequency droop: "A decrease in speed reference for an increase in load", and the definition of voltage droop is " A decrease in voltage for an increase in reactive load". Let's run through that scenario again this time with the speed control and the AVR (Automatic Voltage Regulator) in droop. Start Engine #1 and close the Generator Breaker. Select Droop on the Engine #1 page. Select the Overview Page and select the Enable Synchronizer and Close the Utility Breaker button. The synchronizer will bring the phases of the generator and the utility into phase and the breaker will close. Once the breaker closes, and since the speed governor was running slightly faster than the Utility Grid (Mains) frequency, engine #1's speed control was slowed down (due to electrically locking the generator to the utility grid). The engine's speed control seeing a slight decrease in speed wants to try and increase the speed back to where it was. The fuel demand is increased, adding fuel to the engine. This increase in fuel increases the torque from the engine to generator and current starts increasing and is exported to the utility (as seen from the Generator #1 kW meter). This is where the droop comes in. As real load is increased, the speed reference is decreased until the speed of the engine and the frequency of the generator match. It should be a small amount of power. Everything will be satisfied.

To increase the power of the generator, select the Speed / Load Raise button on the Engine #1 page. ***Remember the speed of the engine will not change***, all you are doing is increasing the speed reference, thus adding more fuel to the engine. This in turn increases the torque of the engine and more power is produced in the generator. You can manually increase or decrease the power output to where ever you want to set it. This is how many power plants test their emergency diesel engines once a month. Set the generator output to 100 kW.

The chart below illustrates a generator tied to the utility grid. The operator can choose to produce (export) as much power out of the generator as they want.



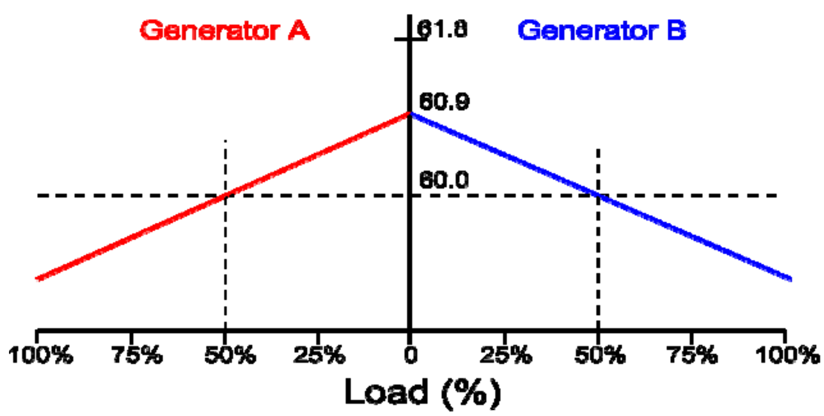
You can also see the effects of changing the voltage excitation at this time. While the engine / generator is connected to the utility grid in droop, and with a kW load of 100 kW, increase the excitation to the generator by selecting the Raise Voltage / PF button. As you push the Raise Voltage / PF down, watch the VARs meter and the Power Factor meter on Engine / Generator #1 page. As the voltage excitation is increased, the power factor decreases from 1.0 (unity power factor) to a lagging power factor. The reactive power and VARs increase.

If the Lower Voltage / PF button is pushed, the power factor will increase towards 1.0, and if you continue to lower the excitation, the power factor will go leading. This is not normal practice in the field.

Remove the load from the system, open all of the breakers and shutdown all of the engines.

Chapter 10. Droop / Droop Load Sharing—Isolated Operation

Droop is typically used in mechanical style governors although it is available in electronic controls for back up purposes. Droop is required, in the mechanical governors, to tie two or more generators together or a generator to the utility grid. In the electronic speed controls, Isochronous Load Sharing (described in Chapter 11 – Isochronous Load Sharing chapter) is most often used. As stated in the previous chapter, when two generators are tied together or a generator to the utility grid, the phases of the generators are electrically locked together. This means that they ***have to*** be running at exactly the same speed / frequency. Now consider this, if two generators are connected together and each one of those generators is being controlled by a separate speed governor, and if the two speed governors were not set to exactly the same speed reference, the instant the tie breaker closes (and the generators are electrically locked together), one governor is going to have to speed up and the other will slow down a small amount. Even by a minute amount. The governors are unable to control the speed to exactly where they were before the breaker was closed and they will start to change their fuel settings. The slower one will increase fuel and the faster one will decrease fuel. When you increase fuel on the engine you're basically changing the torque on the engine's output shaft into the generator and it will produce more power. If you decrease fuel you will decrease the power. Eventually one engine will be carrying the entire load and the other will go into reverse power and trip open the breaker. This is where droop comes into play. Droop is defined as "A decrease in speed reference for an increase in load". When both speed controls are in droop, as soon as the load increases on one unit, the droop function comes into play and reduces the speed reference. As long as both speed control / governors have the same droop percentage, the speed controls will balance out the load. Below is a graph of two generators running Droop – Droop load sharing and each generator carrying 50% of the system load. If more load were applied to the system, the generators would follow the Droop Curve and continue to share the load, albeit the frequency would drop.



Exercise

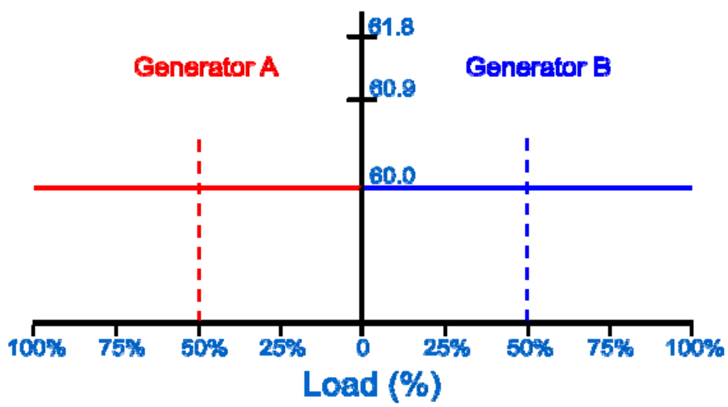
The exercise will demonstrate Droop – Droop Load Sharing. Navigate to the System Overview and start all of the engines. Navigate to each of the Engine / Generator pages and select Droop on all of the engine speed controls. Synchronize the generators together by closing the Enable Synchronizer and Close Generator Breakers on the System Overview page. Once the generator breakers are closed, close the Load Bank Breaker and add some resistive load from the load bank. The loads will be sharing. This is called Droop – Droop Load Sharing. The problem with Droop – Droop Load Sharing on an isolated or islanded system is that as load is increased, the frequency is decreased. Therefore an operator was usually stationed by the governors to increase the speed / frequency back up to 60 Hz. As you increase the speed of engine-generator #1, it will not only increase the frequency but will also increase the load. You have to move back and forth to all engine governors to increase the speed and also keep the load balanced. Two engines are fairly easy to keep balanced, three or more engines are harder. This was used quite extensively in the Navy in the days before electronic control systems and mechanical governors were used.

Remove the load from the system and open all of the breakers. Make sure to put the Isochronous / Droop switches on all of the Engine / Generator pages back to Isochronous. Shutdown all of the Engines.

Chapter 11. Isochronous Load Sharing—Isolated Operation

Isochronous Load Sharing is defined as two or more generators paralleled or connected together each generator carrying an equal percentage of its full load rating on an isolated bus. This is done where the system load is physically larger than one generator can handle and to provide backup power in case an engine does not start or has faults. The speed controls are kept in Isochronous, thus maintaining 60 Hz on the bus. Load sharing is done through percentages, thus equal size or unequal size generators can be load shared together. There must some kind of load controller on both generators that are communicating information together, sharing the load information. Load sharing information can be communicated across all of the units using analog signals, CAN bus, Ethernet, or a variety of communication protocols.

Below is a graph of two engines performing isochronous load sharing. Each generator is carrying 50% of the system load. As the system load increases or decreases, system frequency stays at 60 Hz, and the two units share their share of the load proportionally.



Exercise

This exercise will demonstrate the function of isochronous load sharing. From the System Overview page, start Engine #1, Engine #2, and Engine #3. Close the “Enable Synchronizer and Close Gen Breaker #1”. The breaker will close immediately due to the fact that the load bus is dead or at zero potential. Once the breaker closes the “Load Bus” becomes active. Any other generator that connects to this bus must be synchronized. Close the “Close Load Bank Breaker”. Add all three of the Real Power Load Steps to 150 kW.

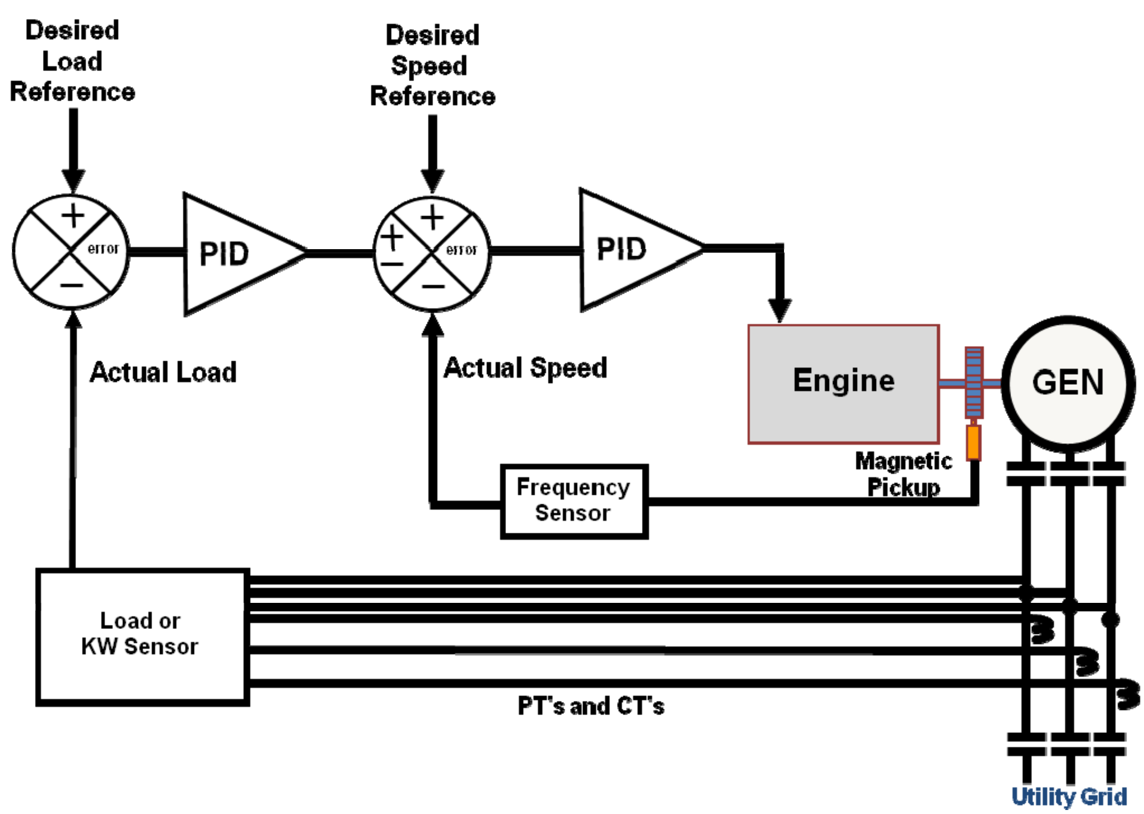
Close the “Enable Synchronizer and Close Gen Breaker #2”. The generator will synchronize and close its breaker. Once the breaker is closed, the load sharing device will see that one generator has 100% load and the other has 0% load. The two will slowly ramp the load together until each generator is carrying 50% of the load, or 75 kW each. The act of slowly bringing the generators into load sharing is called “Soft Loading”. Soft Loading helps prevent frequency variations in due to the load changing.

Close the Real Power Load Steps until there is 300 kW on the load bus. Each engine should be carrying 150 kW each. Close the “Enable Synchronizer and Close Gen Breaker #3”. The generator will synchronize and close its breaker. Once the breaker is closed, the load sharing device will see that the other two generators have 100% of the load and it has 0% load. Number three generator will slowly ramp the load together until each generator is carrying 33% of the load, or 100 kW each.

To remove a generator from the load sharing bus, switch to one of the engine pages and de-select the “Select to Unload Generator” button. The unit will softly unload and when the load gets down to an unload trip point will open the breaker. Make sure to re-select the “Select to Load Generator” button before synchronizing and bringing the generator back on-line. Remove the load from the generators, open the breakers and shut the engines down.

Chapter 12. Isochronous Baseload to the Utility Grid

Isochronous Baseload Mode is similar to the Droop Baseload mode, discussed in Chapter 9. From that chapter, you learned that the effects of droop on the speed control is what keeps the generator from carrying the entire load, or tripping out on reverse power when connected to an Infinite Bus (Mains). Isochronous Baseload is used when the speed control / load control is measuring the real load. As you learned earlier, once a generator is synchronized to the utility grid, the generator and the Utility Grid (Mains) are electrically locked together. The speed control has no effect anymore on speed. This is why a load control is required. This mode is used quite often to test an emergency generator on a monthly basis. The following diagram illustrates a simple block diagram of closed loop speed control and closed loop load control. You already learned in Chapter 3 about the Speed Control. A load control is added to calculate the real generator power and compare it to a desired load reference. This load error is sent to a PID algorithm and is then sent to the summing point of the speed control. You can see from the diagram below that there are two control loops. The Speed Control loop and the Load Control Loop.



Exercise

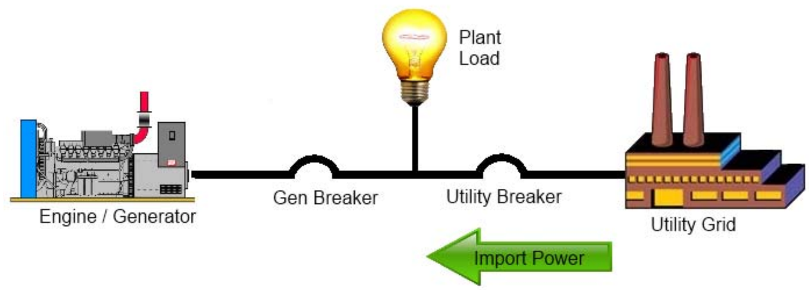
This exercise will demonstrate Isochronous Baseload. Start Engine #1 and close the generator breaker by selecting the “Enable Synchronizer and Close Gen Breaker 1” button. Go to the ENGINE / GENERATOR #1 page and select the “Select for Baseload” button. Notice that the Baseload Reference is preset to 5.0 kW. Navigate back to the SYSTEM OVERVIEW page and close the Utility Tie breaker by selecting the “Enable Synchronizer and Close Utility Breaker” button. The Utility Tie breaker will synchronize and close the breaker. The load on the generator will increase to approximately 5.0 kW. To increase the Baseload Reference, select the Raise Speed / Load or Lower Speed / Load to the desired Baseload Reference. The operator can control this Baseload Reference to the desired level. This information could also come from a PLC that sets the Baseload Reference level. Increase and decrease the load level to show that the generator will export the amount of power that the operator sets it to.

Remove the entire load, open up the breakers and shutdown the engine.

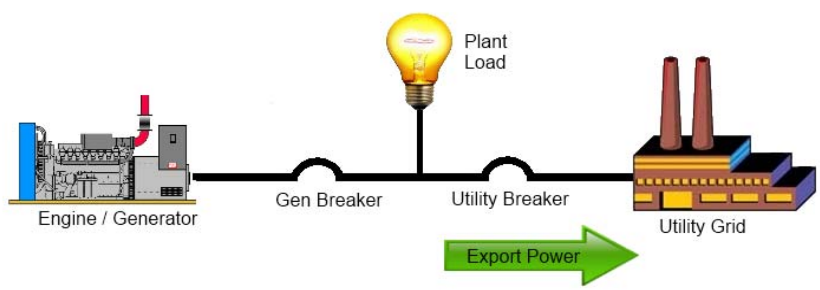
Chapter 13.
Import / Export Control to the Utility Grid

Import or Export Load control is utilized where a certain amount of load / power is controlled across the utility tie breaker to the Utility Grid or Mains. This can be used where a contract is written with the local utility to import a specific amount of power. Likewise the contract could be written to export a specific amount of power and export it to the utility grid. A specific control mode of the Import or Export control of power across the utility tie breaker is called “Zero Power Transfer”. Zero Power Transfer (ZPT) is where a single engine or a bank of engines are paralleled to the utility grid, but zero power flows across the utility tie breaker. This special case is used where the load is very critical. In this case, if the engines were to fail or the Utility Grid (Mains) were fail, the load would still have power.

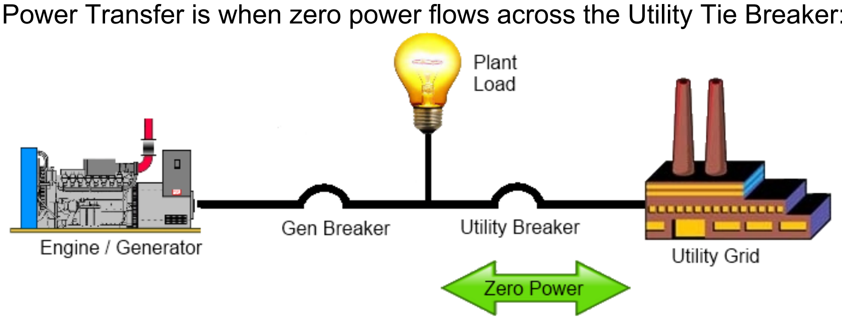
Import power comes from the Utility Grid (Mains) to the Plant:



Export power comes from the Generator to the Utility Grid:



Zero Power Transfer is when zero power flows across the Utility Tie Breaker:



Exercise

Zero Power Transfer Mode

This exercise will demonstrate import, export, and zero power transfer modes of operation. Start Engine #1 and close the generator breaker by selecting the "Enable Synchronizer and Close Gen Breaker 1" button. Navigate to the Utility page and select the "Select for Import / Export Control" button. The Import / Export setpoint is defaulted to 0.0 kW. This is the Zero Power Transfer value. Select the "Enable Synchronizer and Close Utility Breaker" button. This will synchronize the generator and close the Utility Tie Breaker. The power across the Utility Tie Breaker will be essentially zero. Select the "Close Load Breaker" and select one of the 50 kW Real Power Load Step buttons. Engine #1 will immediately pick up the 50 kW, thus maintaining zero power across the Utility Tie Breaker. There will be a momentary jump in kW from the Utility Grid, as the Utility Grid (Mains) is faster than the engine. This momentary import and export of power from the Utility Grid (Mains) is normal and acceptable.

Start Engine's #2 and #3 and synchronize and close their generator breakers. The generators will share the load off the load bank and keep zero power across the utility tie breaker. Increase the load on the generators. As the load changes, the load across the Utility Tie Breaker will always go back to zero.

Constant Level Export Mode

From the Utility page, increase the Import / Export setpoint to 100 kW (Positive number is export). View the System Overview screen and notice that the Export level on the Utility Bus kW meter is approximately 100 kW of Export. Change the load bank load and the Export level will always control back to approximately 100 kW. Be careful! While exporting power, it would be easy to overload the engines. Leave off the last 100 kW load bank step, to maximize the generator loads.

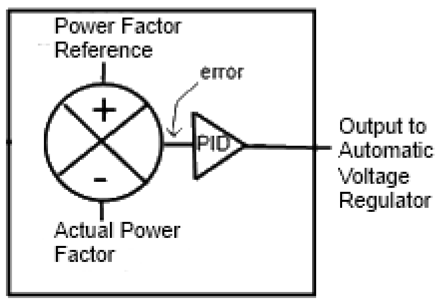
Constant Level Import Mode

From the Utility page, decrease the Import /Export setpoint to –100 kW (negative number is import). View the System Overview screen and notice that the Import level on the Utility Bus kW meter is approximately 100 kW of Import. (It might take a little time for the load ramp to get to the new level). Change the load bank load and the Import level will always control back to approximately –100 kW. Be Careful! While importing power, it would be easy to Reverse Power (motor) the generators. Leave on at least 100 kW of Load Bank steps.

Leave the engines running in this mode for the next chapter.

Chapter 14. Constant PF / VAR Control to the Utility Grid

When a generator is controlling the load on an isolated or islanded load, the Power Factor (PF) or VARs cannot be controlled. The type of load (inductive or capacitive) determines the Power Factor or VARs. This was learned in Chapter 5. When a generator is paralleled to the Utility Grid, the Power Factor / VARs can be varied and controlled. This is done through the excitation of the generator field current with the Automatic Voltage Regulator (AVR). As you increase the generator field excitation (excite the generator), you would expect the voltage to increase. But, remember the generators voltage is electrically locked to the voltage of the Utility Grid. The control the Power Factor or VARs is very similar to the control of the Speed and Load. Comparing the Power Factor Reference to the Actual Power factor, the error between the two is sent to a bias input on the AVR to control the Power Factor or VARs. Some AVRs already have this feature built in. See simple diagram below for a PF Controller.



Exercise

PF Control

With the generators all running and paralleled to the Utility Grid (Mains) in the Import Load Mode (from the previous exercise) with 100 kW import level and 150 kW of Load Bank Load, navigate to the Utility Page. The current mode of Voltage Control is in the Voltage Droop mode. Change the voltage control from Droop to PF Control by changing the PF / VAR / VOLTAGE DROOP number to #3 – PF Control. Decrease the PF setpoint to 0.8 Lagging Power Factor. The Power Factor will slowly change to 0.8 Lagging Power Factor. The control of Power Factor and VARs is usually a slow control process. It may 20-40 seconds to come back into control. Change the Reactive Power Load Steps on the Load Bank. As the Reactive Load is changed, the Power Factor will react, but will always come back to 0.8 Lagging Power Factor.

Change the PF setpoint back to 1.0. The Power Factor will slowly move back towards Unity Power Factor (1.0). Although electrically possible, the PF setpoint was limited (in this model) to only work in the Lagging direction. The Utility Grid (Mains) will usually restrict any Leading Power Factor.

VAR Control

Change the voltage control mode from PF Control to VAR Control by changing the PF / VAR / VOLTAGE DROOP number to #2. Increase the VAR setpoint to 72 VARs. The VAR Controller is now looking at the VAR Reference and the Actual VARs are making a correction to the AVR to control at that reference.

This should give you the relationship between Power Factor and VARs.

Return the VAR setpoint to 0 VARs, open all breakers and shutdown the engines.

Chapter 15. Fully Automatic Mode—Emergency Power Standby

Many newer type control systems will allow a fully automatic control system that incorporates many of the above mentioned functions. Let's use the example of three emergency diesel engine / generators at a hospital. Typically the hospital get is power from the local utility grid. In case the Utility Grid (Mains) fails, the following scenario would incur:

1. The Utility Grid (Mains) fails
2. The failure is sensed and the Utility Breaker opens.
3. A start all command is given to all three engines.
4. The first engine / generator to reach voltage and frequency would block the others from closing their breakers and it would close its breaker to the dead bus. Thus picking up the hospital load.
5. The next generators would synchronize to the live bus and once their generator breakers close will go into Isochronous Load Sharing.
6. All three engines should be in Isochronous Load Sharing carrying the hospital load.
7. Some controllers (not in this model) will use a group breaker for two or more engines. This would allow two engines to parallel together first before the group breaker closes. This would take into account that there was more load on the hospital than the one generator could handle.
8. At this time some controllers (not in this model) will go into the Load Management control mode and based on hospital load levels, could cycle one of the engines off. This is done to keep from lightly loading the diesel engines. As the load of the hospital changes, engines could be started or shutdown based on the hospital load levels.
9. As the Utility Grid (Mains) returns, the generators will automatically synchronize back to the utility grid; softly unload the generators load back to the utility grid.
10. The engine / generators will open their generator breakers, cool down and shutdown.

Exercise

From the System Overview Page, close the Utility Tie Breaker and the Load Bank Breaker. Close two of the 50 kW Load Steps on the Load Bank to simulate hospital load. The hospital is importing 100 kW from the Utility Grid. Select the "Enable Automatic Mode" button, below the Utility Grid (Mains), to select the Automatic Mode. Select the "Shutdown Utility Grid" button to shutdown the Utility Grid (Mains) voltage and frequency. Here is the scenario that will happen:

1. Once the Utility Grid (Mains) is failed, the Utility Breaker will open. The hospital will go in the dark.
2. All three engines will start.
3. Whichever engine / generator starts the fastest will close its generator breaker.
4. The other engine / generators will synchronize and close their breakers.
5. The control systems will go into Isochronous Load Sharing and will share the load proportionally.
6. Add more load and watch the engines share the load.
7. Press the "Restore Utility Grid (Mains)" button to activate the Utility Grid voltage and frequency.

8. The control system usually waits a specific amount of time, to verify that the Utility Grid is stable.
9. The control system will synchronize all three generators back to the Utility Grid (Mains).
10. The control system will slowly unload the generators, transferring the load back to the Utility Grid.
11. Once the generators get down to an unload trip level, they will open their breakers.
12. The engines will then cool down and shutdown.
13. This completes a fully automatic Utility Grid (Mains) failure and the starting and stopping of the engine / generators.

Press the “Enable Manual Mode” to de-select the Automatic Mode.

Chapter 16.
Acronyms, Definitions, and Trademarks

Acronyms and Definitions

AC	Alternating current. A current which reverses in regularly recurring intervals of time and which has alternately positive and negative values, and occurring a specified number of times per second. The number is expressed in hertz.
Ammeter	An instrument for measuring the magnitude of an electric current.
Ampere (A)	The unit of measurement of electrical current produced in a circuit by 1 volt acting through a resistance of 1 Ω.
Apparent Power	The product of the voltage (in volts) and the current (in amperes). It comprises both active and reactive power. It is measured in "volt-amperes" and often expressed in "kilovolt-amperes" (kVA) or "megavolt-amperes" (MVA).
Artificial Load (reactive)	Load banks to which devices that operate at a lower power factor have been added. Generally, variable reactors are used so that the amount of reactance can be adjusted to match the power factor of the actual load. Air core reactors provide the most stable operation for testing purposes.
Artificial Load (resistive)	Load banks usually consisting of heater coils or strip heaters which operate only at a unity power factor.
ATS	Automatic Transfer Switch. A switch designed to sense the loss of one power source and automatically transfer the load to another source of power.
AVR	Automatic Voltage Regulator.
Baseload	The minimum amount of electric power delivered or required over a given period of time at a steady rate.
Capacitance	The property of any system of conductors and dielectrics or any device to store electrical potential energy. See capacitor. The unit of measure of capacitance is farads and its symbol is "C".
Capacitor	A device consisting of two conducting surfaces separated by a dielectric material capable of storing electric energy.
CAN	Controller Area Network, a digital communications link between control modules.

Capacity	The amount of electric power delivered or required for which a generator, turbine, transformer, transmission circuit, station, or system is rated by the manufacturer.
Circuit Breaker	A mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time, and automatically breaking currents under specified abnormal circuit conditions such as those of short circuit.
Circulating Currents	When paralleling generators together and the voltage excitation of one generator is higher or lower than the others, will produce excess VARs and circulating currents.
Closed-Transition Switch	Transfer switch which provides a momentary paralleling of both power sources during a transfer in either direction. The closed transition is possible only when the sources are properly interfaced and synchronized.
Conductor	A wire, cable or bus bar designed for the passage of electrical current.
Continuous Power	An electric generating set which is operated for an unlimited number of hours per year, where there is a constant non- varying load, or a dedicated load.
Cross Current Compensation	A series differential connection of the various generator parallel current transformer secondaries which act to modify generator excitation so as to minimize its differential reactive current with the end result, that reactive load sharing among generators is obtained without voltage droop. Its effect on voltage is similar to that of parallel isochronous governors operation effect on speed or frequency. Also called reactive differential compensation.
Current (electric)	A flow of electrons in an electrical conductor. The strength or rate of movement of the electricity is measured in amperes.
Current Transformer (CT)	A transformer that produces a secondary current proportional to the primary current.
Demand (electric)	The rate at which electric energy is delivered to or by a system, part of a system, or piece of equipment, at a given instant or averaged over any designated period of time.
DC	Direct current.
Electric Plant	A facility containing prime movers, electric generators, and auxiliary equipment for converting mechanical, chemical, and/or fission energy into electric energy.

Electrical Degree	One 360th part of a cycle of an alternating current or wave.
Electromagnetic Field	An induced magnetic field generated by the passage of an electric current through a conductor (commonly used in conjunction with a pole structure).
Emergency Power	An independent reserve source of electric energy which, upon failure of the normal source, provides electric power for safety to life circuits.
Engine Speed	The rotating velocity of the engine flywheel, measured in revolutions per minute (rpm).
Energy	The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatt-hours, while heat energy is usually measured in British thermal units.
Excitation	The dc power supplied to the field coils of a synchronous generator, producing the magnetic flux required for inducing voltages in the opposing member.
Exciter	A device for supplying excitation to the generator field. It may be a rotating dc, ac with rectifiers, or a static device converting ac to dc.
Field	A region of magnetic lines of flux. The field may be produced by electrical current or permanent magnet.
Flux	Magnetic lines of force.
Frequency Meter	An instrument that indicates frequency of the alternator output in hertz.
Frequency Transient	The frequency deviation resulting from a sudden change in load.
Full Load Current	The greatest load that a circuit or device is designed to carry continuously at rated conditions. Also known as rated current.
Generation (electricity)	The process of producing electric energy by transforming other forms of energy; also, the amount of electric energy produced, expressed in watt-hours (Wh).
Generator	A machine that converts mechanical energy into electrical energy.

Gigawatt (GW)	One billion watts.
Governor	A device that regulates prime mover speed by adjusting the fuel input to maintain constant speed.
Grid	The layout of an electrical distribution system.
Ground	A connection, either intentional or accidental, between an electric circuit and the earth or some conducting body serving in place of the earth.
Harmonic	Deviations from the fundamental frequency which are a multiple of the generated frequency. They are expressed as second, third, fourth, fifth, etc. harmonics, denoting their frequency as a multiple of the fundamental frequency.
Hertz (Hz)	A unit of frequency(formerly cycles per second).
HMI	Human-Machine Interface.
Impedance	The total opposition offered by a circuit to the flow of alternating current. It is composed of resistance and reactance (inductive and/or capacitive) and its symbol "Z" is expressed in ohms.
Independent Power Producers	Entities that are also considered nonutility power producers in the United States. These facilities are wholesale electricity producers that operate within the franchised service territories of host utilities and are usually authorized to sell at market-based rates. Unlike traditional electric utilities, Independent Power Producers do not possess transmission facilities or sell electricity in the retail market.
In-rush Current	The inrush current of a machine or apparatus is the maximum current which flows after being suddenly and fully energized.
Internal Combustion Plant	A plant in which the prime mover is an internal combustion engine. An internal combustion engine has one or more cylinders in which the process of combustion takes place, converting energy released from the rapid burning of a fuel-air mixture into mechanical energy. Diesel or gas-fired engines are the principal types used in electric plants. The plant is usually operated during periods of high demand for electricity.
IR Drop	The voltage drop across a resistance. The IR drop is equal to the current in amperes multiplied by the resistance in ohms.
I/O	Input/output.
Isochronous	Defined as no decrease in speed for an increase in real power. Zero Droop.

kilovolt-amperes (kVA)	1000 volt-amperes (apparent power).
kilovolt-amperes reactive (kVAR)	1000 volt-amperes reactive (reactive power).
kilowatt-hour (kWh)	Unit of electric energy. 1 kW x 1 hr = 1 kW h.
kilowatt (kW)	One thousand watts.
Lagging Power Factor	The power factor caused by inductive loads, such as motors and transformers, in which the current lags behind the voltage in an alternating current network. See power factor.
Load (electric)	The amount of electric power delivered or required at any specific point or points on a system. The requirement originates at the energy-consuming equipment of the consumers.
Mains	The mains is the utility grid, is the system of distribution lines that delivers electrical power energy.
Megawatt (MW)	One million watts.
Megawatt-hour (MWh)	One million watt-hours.
Modbus	A communications protocol developed by Gould Modicon.
MPU	Magnetic pickup—A variable reluctance passive device used to pickup or sense a ferrous gear and produce a signal that represents the speed of the sensed gear.
Neutral	The point in a polyphase system where the voltages to all phases are equal.
Ohm (Ω)	The unit of measurement of electrical resistance. The resistance of a circuit in which a potential difference of 1 volt produces a current of 1 ampere.
Outage	The period during which a generating unit, transmission line, or other facility is out of service.
Out-of-Phase	A condition in which AC voltage waves of two generating systems do not coincide.
Overload Power	Overload power is that load in excess of rated load which the generator set is capable of delivering for a specified period of time. It should be recognized that the voltage, frequency and operating temperature may differ from normal rated values.
Overspeed Device	A mechanical, or electrical, speed-sensitive device that through mechanical or electrical action acts to cause a shut down of the engine or limit the speed by cutting off fuel and/or air supply should the engine speed exceed a preset maximum.

Parallel Operation	Two or more generators, or other power sources, of the same phase, voltage and frequency characteristics supplying the same load.
Paralleling	The procedure used to connect two or more generators to a common load.
Peak Demand	The maximum load during a specified period of time.
Peaking Capacity	Capacity of generating equipment normally reserved for operation during the hours of highest daily, weekly, or seasonal loads. Some generating equipment may be operated at certain times as peaking capacity and at other times to serve loads on an around-the-clock basis.
Peaking Power Plant	An electric generating set that assumes all or part of the load during peak-load periods. This is sometimes referred to as "limited running time power", and generally is operated for a defined time interval.
Peak Shaving	Process by which utility customer minimizes utility charges by either generating power and eliminating excessive demand charges or by shedding load.
Phase	The winding of a generator that determines the number of complete voltage and/or current sine waves generated per 360 electrical degrees, as in three phase.
Phase Rotation	The sequence in which the phases of a generator or network pass through the positive maximum points of their waves. Typically 1-2-3 or 3-2-1 (sometimes referred to as ABC or CBA).
PID	Proportional-Integral-Derivative (feedback control parameters). A known algorithm used for many types of control systems.
Pole, Magnetic	A part of a magnetic structure, there being two such parts, called a north pole and a south pole. Since neither pole can exist without the corresponding opposite, they are always present in pairs. A generator always has an even number of poles.
Power	Rate of expending energy per unit of time. Mechanical power can be measured in horsepower; electrical power in kilowatts. One horsepower equals 746 watts.

Power Factor (also cos θ)	In AC circuits, the inductances and capacitances may cause the point at which the voltage wave passes through zero to differ from the point at which the current wave passes through zero. When the current wave precedes the voltage wave, a leading power factor results, as in the case of a capacitive load or over-excited synchronous motors. When the voltage wave precedes the current wave, a lagging power factor results. The power factor expresses the extent to which voltage zero differs from the current zero. Considering one full cycle to be 360 electrical degrees, the difference between the zero points can then be expressed as an angle, θ. Power factor is calculated as the cosine of θ between zero points and expressed as a decimal fraction (0.8) or as a percentage (80%). It can also be shown to be the ratio of kW, divided by the kVA. In other words, kW = kVA $\times$ PF.
Prime Mover	The engine, turbine, water wheel, or similar machine that drives an electric generator; or, a device that converts energy to electricity directly (such as photovoltaic solar and fuel cell(s)).
Prime Power	An electric generating set which is operated as the primary source of power. It may be primary because it is the sole source or because it provides a special type of power. (The load is considered to be a normal varying utility type load.)
Protective Relay	A device used to detect defective or dangerous conditions and initiate suitable switching or give warning. The IEEE assigns device numbers to various types of protective relays.
PWM	Pulse Width Modulation—A variable duty cycle signal.
Reactive Current	The component of a current in quadrature with the voltage.
Reactive Power	The portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment. Reactive power must be supplied to most types of magnetic equipment, such as motors and transformers. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences electric system voltage. It is a derived value equal to the vector difference between the apparent power and the real power. It is usually expressed as kilovolt-amperes reactive (kVAR) or megavolt-ampere reactive (MVAR).

Real Power	The component of electric power that performs work, typically measured in kilowatts (kW) or megawatts (MW)--sometimes referred to as Active Power. The terms "real" or "active" are often used to modify the base term "power" to differentiate it from Reactive Power and Apparent Power. See Apparent Power, Power, Reactive Power.
Resistance (R)	The non-reactive opposition which a device or material offers to the flow of direct or alternating current.
Spinning Reserve	That reserve generating capacity running at a zero load and synchronized to the electric system.
Speed Droop	Defined as the decrease of speed for an increase in real power.
Standby Power	An electric power generating system which is on "standby alert," ready to assume the load when the normal power source fails.
Synchronizer, Automatic	A device which will synchronize an on-coming electric set with the bus or another electric set and will automatically close the circuit breaker which connects the multiple power sources in parallel.
Synchronous Generator	A synchronous alternating-current machine that transforms mechanical power into electric power. A synchronous machine is one in which the speed of normal operation is exactly proportional to the frequency of the system to which it is connected. A synchronous generator has field poles excited with direct current or permanent magnets.
Synchroscope	An instrument that provides a visual indication of proper time for closing the switch when synchronizing generators are connected in parallel to the load.
Tau (τ)	Time constant (such as for a filter).
Transfer Switch	A switch designed so that it will disconnect the load from one power source and reconnect it to another source. Both automatic and manual transfer switches are available.
Unity Power Factor	A power factor of 1.0, characteristic of a resistive load.
Utility Grid	The Utility Grid or sometimes call the Mains, is the system of distribution lines that delivers electrical power energy.

Voltage Droop	Defined as a decrease in excitation for an increase in reactive power. reactive droop compensation. A voltage regulator circuit that acts to affect generator excitation so as to create a droop in generator voltage proportional to the inductive reactive current. This characteristic is used to obtain reactive load sharing among generators operating in parallel. Its effect on voltage is similar to the effect that a droop type governor has on speed or frequency.
Watt (W)	The electrical unit of power. The rate of energy transfer equivalent to 1 ampere flowing under a pressure of 1 volt at unity power factor.
Watt-hour (Wh)	An electrical energy unit of measure equal to 1 watt of power supplied to, or taken from, an electric circuit steadily for 1 hour.

Trademarks

Chapter 17.
Troubleshooting and Contact Information

Troubleshooting

Here are some problems that you might run into while operating the model:

Problem:	Solution:
The model is acting erratic or not behaving properly.	Re-start the model. Close down everything and start the NetSim model and ToolKit up again.
Toolkit won't connect to the model.	Toolkit communicates with the model through an IP address on your computer. This is done using either your local LAN (Local Area Network) IP address or the internal loopback IP address of 127.0.0.1. If using Windows 7, you have to enable this feature. Follow this link to install this feature: http://www.windowsreference.com/windows-7/how-to-install-a-loopback-adapter-in-windows-7/
Engine #1 is running unstable or the load is not being controlled at the right rate.	Return the PID settings back to default values on the ENGINE #1 TRENDS page.

Contact Information

For support / questions / concerns for this product, please send an email to **powergenhelpdesk@woodward.com**.

We appreciate your comments about the content of our publications.

Send comments to: icinfo@woodward.com

Please reference publication 26736.

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