FUNDAMENTALS OF TURBINE/ GENERATOR SPEED CONTROL

A graphical approach for islanding applications


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TO PROMOTE A better understanding of industrial turbine/generator speed control, the fundamentals of droop and isochronous turbine/generator control are discussed via graphical examples for typical industrial islanding applications with bus-connected generators. A mathematical analysis of several examples illustrates the validity of a practical graphical approximation approach. By comprehending these fundamental concepts, industrial application engineers can more thoroughly investigate advanced governor control topics, such as isochronous load sharing with communication lines between governors, manual operator control of multiple generators, and load sharing via automatic power-management systems.

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Discussion Outline

Simplified block diagrams with summing points show basic turbine/generator governor concepts of droop and isochronous control (Figure 1). Graphical examples of droop and isochronous governor control are provided to promote a better understanding of typically encountered industrial islanding applications.

The graphical approach discussions begin with isochronous control for one generator operating independently. A two-generator isochronous discussion illustrates why operating two generators in independent isochronous governor control mode is not recommended. Next, one generator is operated independently in droop mode, showing the resulting frequency change as load is applied; additionally, this one generator governor droop example shows the effect of changing the no-load frequency (NLF) above and below rated frequency. Two paralleled generator examples follow with identical generators operating with the same percent droop; the resulting system frequency is shown when the NLF is the same for both generators and also when the two generators have different NLFs.

Mathematical computations are included to illustrate that the graphical analysis and the analytical computations provide approximately the same results. Additional graphical illustrations show combined isochronous and droop operation and the change in power output as the droop line is shifted. Governor dynamic response capability limit discussions are beyond the scope of this article but are available in [1].

To better focus on the real power aspects related to governor actions, automatic voltage regulator (AVR) considerations are not included in this article; however, a future article with advanced governor control strategies will include AVR considerations.

STABLE OPERATION WITH THIS TYPE OF GOVERNOR CONTROL HAS BEEN APPLICABLE TO SINGLE ISLANDING GENERATOR APPLICATIONS.

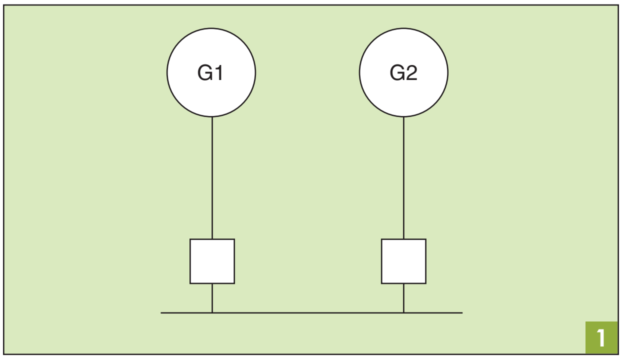
Fundamental Governor Speed Control—Droop and Isochronous

Droop and isochronous control are two fundamental methods of turbine/generator governor speed control. Droop control is a commonly implemented independent governor speed control method because it achieves stable electrical power system operation with multiple islanding system generators. A very rudimentary explanation of droop control is that an increase in megawatt power loading results in a linear decrease in speed, corresponding to the percent droop selected and NLF; this is described in more detail later in the article. It is imperative that droop control is well understood before proceeding to more advanced governor control concepts; therefore, droop control is the primary focus of this article.

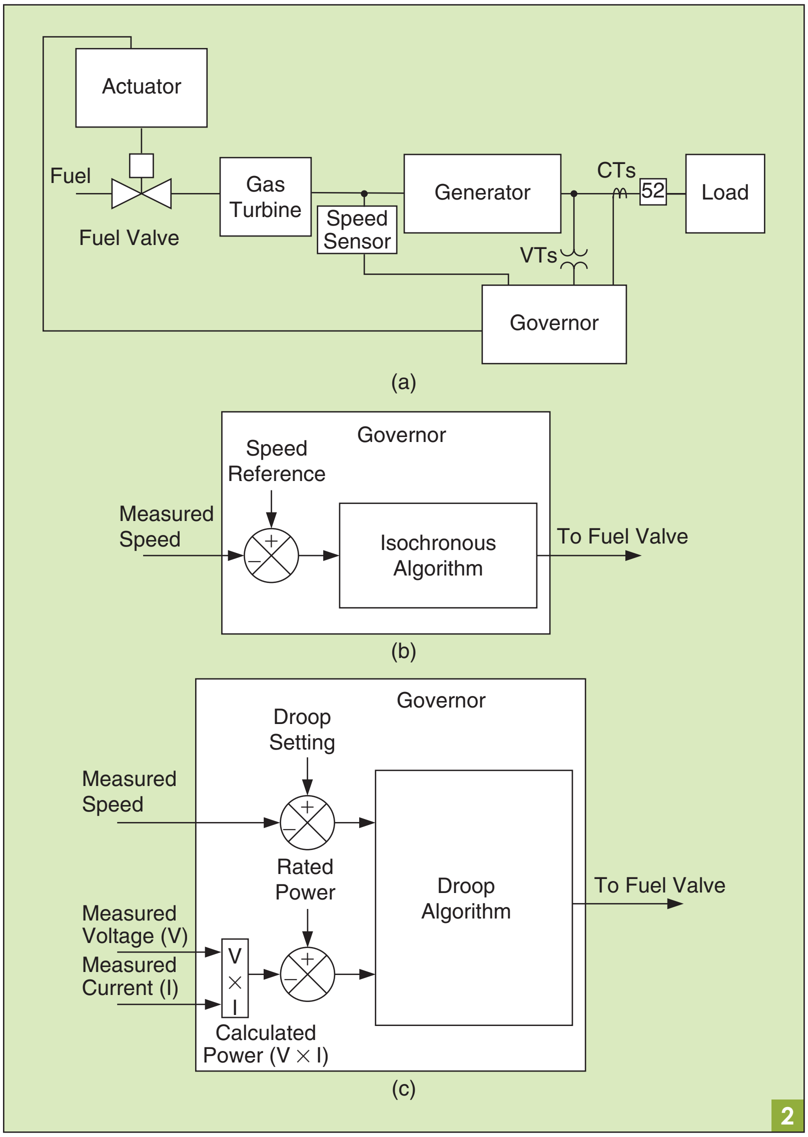
When the word "isochronous" is applied to turbine governor speed control, it means that changes in turbine/generator megawatt power loading result in no final speed change from a set reference; to accomplish this as load increases or decreases, immediate speed corrections via the fuel valve are made. Stable operation with this type of governor control has been applicable to single islanding generator applications. Although certain modern governors permit multiple bus-connected islanding generators to operate in isochronous load sharing via load-sharing lines, this control system strategy is considered an advanced type and is beyond the scope of this article. However, the authors plan to discuss isochronous load sharing and other advanced industrial turbine/generator control system strategies in a future paper.

Figure 2(a) is an example of a simplified turbine/generator governor control system that is the reference system diagram for the discussions here. Figure 2(a) shows a modern, simplified electronic governor control system with selectable droop/isochronous governor control. Voltage transformers, current transformers, and a turbine/generator speed sensor (tachometer) provide basic inputs to the modern electronic governor so that a selected fundamental control strategy (droop or isochronous) can be implemented. As indicated, the governor controls the turbine mechanical fuel valve so that the turbine can provide the generator megawatt output required by the electrical load.

Figure 2(b) shows a simplified block diagram of the governor speed summing point for basic isochronous control. The mechanical speed is measured by electrical/electronic speed transducers, converted to a usable format, and compared at the summing point with the isochronous speed reference (typically 60 or 50 Hz for industrial islanding systems). Deviation from the speed reference results in a fuel valve correction to adjust the turbine/generator frequency output until the system frequency is maintained at the speed reference and the summing point difference is theoretically zero. As load demand varies, system frequency is maintained as turbine/generator speed corrections are made, and turbine/generator power output provides the required load megawatt power output; this is isochronous speed control with the purpose of maintaining



The bus-connected islanding generators.



(a) A simplified turbine/generator governor control system. (b) A simplified isochronous governor control system. (c) A simplified droop governor control system.

a constant presettable speed as the load MW increases or decreases. This is a typical control strategy for a stand-alone, one-generator islanding application.

Figure 2(c) shows a simplified block diagram of the governor speed summing points for basic droop control, i.e., one summing point for speed comparison summation and a separate summing point for megawatt power comparison summation, so that an increase in load MW results in increased fuel to the turbine and a linear decrease in turbine speed based on the percent droop setting and NLF. As power must be measured, voltage and current transformer inputs are needed. Droop has been a typical governor control strategy when connecting to a utility infinite bus.

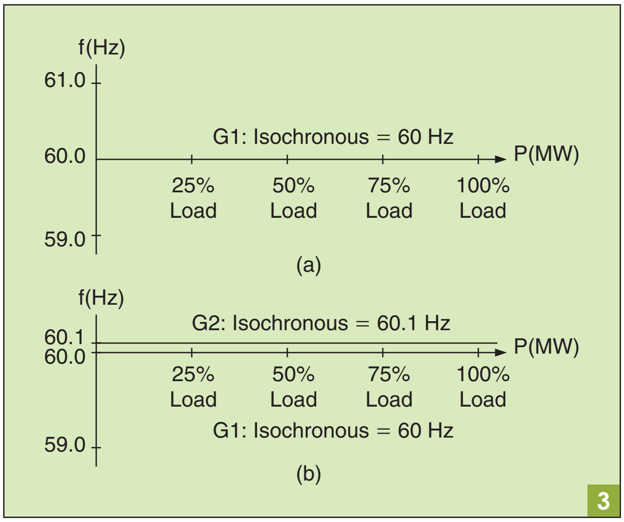
Understanding governor control fundamentals enables the application engineer to better comprehend governor control methodology during factory acceptance testing, initial commissioning and startup activities, and operational and maintenance conditions. The following discussions promote a better understanding of droop and isochronous governor control fundamentals for one- and two-generator applications. With this increased application background, the authors anticipate that when turbine/generator megawatt operation deviates from the expected, the operating conditions can be more readily understood, and appropriate corrective action can be taken by facility operations.

Isochronous Operation Examples

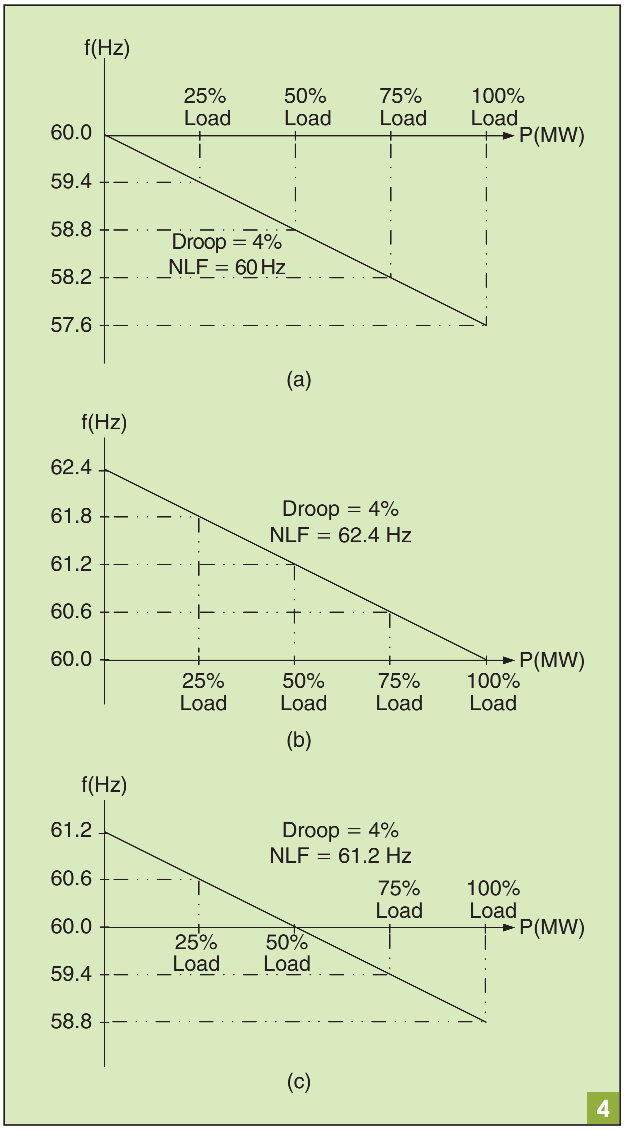
Consider an islanding electrical power system with one turbine/generator and associated governor operating in isochronous mode. Figure 3(a) is a steady-state graph of the generator megawatt output power versus frequency with an isochronous governor control strategy operating at 60-Hz frequency reference, ignoring response to transients. As the load increases from 0 to 100%, frequency is maintained at a constant steady-state magnitude of 60 Hz. As shown in Figure 2(b), the speed summation point compares the speed reference with the measured speed, and the fuel valve is modulated for load increases or decreases because the summation point output difference is maintained at zero after a load change. For this example, the isochronous control strategy maintains a constant speed and a 60-Hz frequency.

Figure 3(b) shows two generators in isochronous mode but with different frequency setpoints. The following discusses the process that occurs when two generators with different isochronous speed settings attempt to operate in parallel. Although it is not a detailed analytical analysis supported by a dynamic stability simulation, it attempts to explain why isochronous operation (without an additional control strategy of isochronous load sharing) is restricted to one islanding generator that powers all loads. The example assumes both generators are able to operate in a no-load condition.

Assume generator G1 is online, powering a load; generator G2 is offline. Typically, offline generators are operated at a slightly faster speed than online generators so that, when paralleled, the offline turbine/generator powers the load and does not trip on reverse power. Therefore, for this example, assume G1 is operating at 60 Hz and G2 is operating with 60.1-Hz frequency (speed) reference. When paralleled, the G2 governor senses a slightly greater than 60-Hz system frequency; therefore, the G2 summation point output is a negative number, which commands the G2 fuel valve to open with a resulting increase in turbine/generator speed. As system frequency increases, the turbine/generator G2 begins to power the load. The G1 summation point senses an increased speed and the summation point output is



(a) A one-generator (G1) example of power versus frequency with isochronous governor control. (b) A two-generator (G1 and G2) example of power versus frequency with different isochronous governor setpoints.



(a) A one-generator example with 4% droop and NLF = 60 Hz. (b) A one-generator example with 4% droop and NLF = 62.4 Hz. (c) A one-generator example with 4% droop and NLF = 61.2 Hz.

positive; this results in a command to close the G1 fuel valve, with a subsequent decrease of G1 megawatt power output. This iterative condition continues until G2 powers all loads and the G1 fuel valve closes to a minimum; eventually, G2 powers G1. With G1 in a motoring condition, the G1 reverse power protection device may trip the G1 generator circuit breaker, thereby tripping G1 offline.

Droop Operation Examples with One Generator

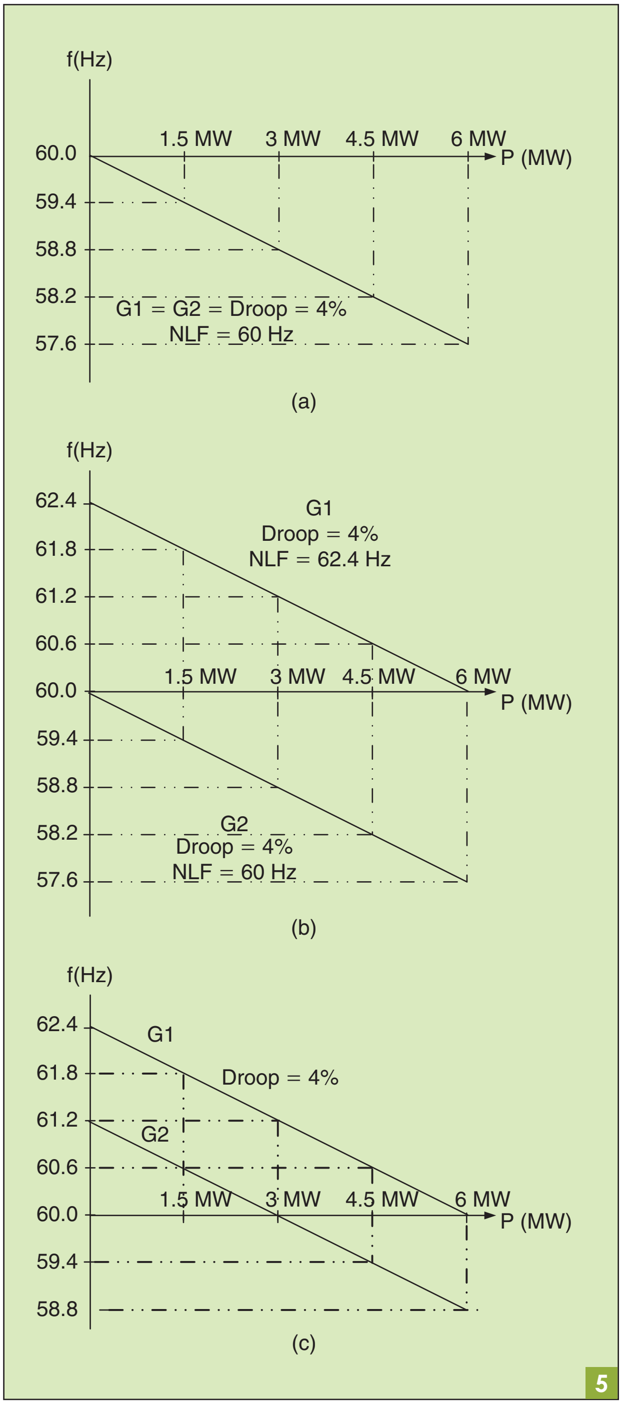
Figure 4(a) is an example of one generator operating in an island configuration supplying power to connected loads and a governor with a typical 4% droop setting. The 4% droop line starts at 60-Hz NLF, and as the load increases from no-load to turbine rated load (100% load), the generator output frequency decreases linearly from 60 to 57.6 Hz, a 4% frequency change, as shown in Figure 4(a). Figure 4(a) shows the turbine speed decreases proportionally from 0% speed reduction at no load to 4% speed reduction at 100% load.

The utility industry uses this proportional frequency (speed) reduction versus power output droop algorithm to maintain stable generator operation when connected to other system grid generators. From significant field experience, [2] indicates that a 3–5% droop setting is typical for gas turbine generators. However, when a droop setting is applied to an islanding generator, maintaining a system frequency of 58.2 Hz at 50% load or 57.6 Hz at 100% load is typically objectionable to industrial operating personnel because a reduced frequency decreases the output power of induction motors connected to pumps, compressors, fans, etc. Operating with a full-load frequency of 57.6 Hz may be objectionable to facility operations because traditional turbine/generator underfrequency alarm or trip limits (95% of rated) may be marginal.

Figure 4(a) illustrates the dilemma of accepting a reduced operating frequency when a 4% droop is applied with a 60-Hz NLF. Since there is a linear relationship between the droop setting and the NLF (speed), Figure 4(b) shows the result of changing the NLF from 60 to 62.4 Hz while retaining the same 4% droop setting and 4% droop line slope for a 60-Hz NLF.

Operating with an NLF of 62.4 Hz may be objectionable to operations because, at no load, traditional turbine overfrequency alarm or trip limits (105% × rated frequency) may be marginal. Turbine/generator frequency (speed) limits vary with size and manufacture of turbine/generator and should be reviewed. Only when 100% load is applied is the frequency reduced to 60 Hz; therefore, a compromise to reduce the NLF to less than 62.4 Hz could be considered.

Figure 4(c) shows the result of changing the NLF from 60 to 61.2 Hz with the same 4% droop setting and 4% droop line slope for 60-Hz NLF. With this operating condition, the NLF of 61.2 Hz presents a compromise for both



(a) A two 6-MW-generator example with 4% droop and NLF = 60 Hz. (b) A two 6-MW-generator example with 4% droop, generator G1 NLF = 62.4 Hz, and generator G2 NLF = 60 Hz. (c) A two 6-MW generator example with 4% droop, generator G1 NLF = 62.4 Hz, and generator G2 NLF = 61.2 Hz.

no-load and 100% loaded conditions because, at no load, the system frequency is 61.2 Hz (2% greater than rated operating frequency) and, at 100% load, the system frequency is 58.8 Hz (2% less than rated operating frequency). With the generator operating at 50% load, 60 Hz would be the operating frequency. If the generator operated at 75% load, this would result in an operating frequency of 59.4 Hz and could be considered as a frequency compromise when droop mode is selected in a system islanding configuration. As previously stated, isochronous load-sharing could be considered, but that discussion is reserved for a future article.

When two identical generators operate in parallel in an islanding configuration and have the same turbine/generator megawatt rating and governor percent droop setting at the same NLF, each turbine/generator should operate as described in this section, with the load shared equally between the generators.

Graphical Approach—An Approximation

The graphical approach is an approximation because the droop line slope is based on a 60-Hz (or 50-Hz) NLF and is used throughout the graphical analysis from 60- to 62.4-HZ NLF (or from 50- to 52-Hz NLF), rather than slightly adjusting the droop line slope for each NLF investigated.

Although this droop slope line approximation is used per turbine throughout the graphical illustrations, the mathematical comparison examples illustrate the very close approximation and minimal difference between the graphical approach and exact mathematical computations. This very close approximation is considered to be suitable for engineering evaluation because the graphical results are almost the same as the detailed calculations, and a visual, intuitive understanding provides a more in-depth comprehension of the application as well as the mathematical calculations.

Mathematical Analysis Approach

A graphical methodology is provided to make analyzing governor droop/isochronous controls concepts easier to explain and comprehend; a mathematical approach is presented below for validation of the practical graphical approach approximation used in the examples and also when a more rigorous analytical approach is needed.

The droop concept is a straight line that can be analyzed via a basic straight-line equation:

$$y = mx + b, \tag{1}$$

where y is the system frequency f_{SYSTEM}, m is the slope = rise/run = $[(f_{\mathrm{FL}} - f_{\mathrm{NL}})/(P_{\mathrm{FL}} - P_{\mathrm{NL}})]$, x is the system power P_{SYSTEM}, b is the straight line intercept with the y-axis, which is the droop line NLF f_{NL}, f_{FL} is the droop line full-load frequency, P_{NL} is the turbine/generator output power at no load, and P_{FL} is the turbine/generator output power at full load.

One Generator Droop Example

Figure 5(a) is an example of one generator with the following system and governor parameters:

Turbine rated power = P_{FL} = 6 MW
Power at no-load = P_{NL} = 0 MW
Droop setting = 4%

with f_{NL} = 60 Hz f_{FL} = 57.6 Hz.

Note that, except for f_{NL}, the parameters of the turbine/generator in Figure 5(a) are used for the examples in this section.

CALCULATIONS FOR FIGURE 5(A)

$P_{G1\ rated} = P_{G2\ rated} = 6\ MW$
G1 droop = G2 droop = 4%
$f_{G1NL} = f_{G2NL} = 60\ Hz.$

Determine P_{G1}, P_{G2}, and f_{SYSTEM} when the total system load is 6 MW:

$$P_{G1} = [(P_{G1FL} - P_{G1NL})/(f_{G1FL} - f_{G1NL})](f_{G1NL} - f_{SYSTEM}) \quad (S1)$$

$$P_{G2} = [(P_{G2FL} - P_{G2NL})/(f_{G2FL} - f_{G2NL})](f_{G2NL} - f_{SYSTEM}). \quad (S2)$$

Adding the two equations together provides the following resulting equation:

$$P_{G1} + P_{G2} = 6\ MW = [(P_{G1FL} - P_{G1NL})/(f_{G1FL} - f_{G1NL})] \times (f_{G1NL} - f_{SYSTEM}) + [(P_{G2FL} - P_{G2NL}) / (f_{G2FL} - f_{G2NL})](f_{G2NL} - f_{SYSTEM}) \quad (S3)$$

$$6\ MW = (6\ MW/2.4\ Hz)(60\ Hz - f_{SYSTEM}) + (6\ MW/2.4\ Hz)(60\ Hz - f_{SYSTEM}) \quad (S4)$$

$$f_{SYSTEM} = 58.8\ Hz$$

$$P_{G1} = P_{G2} = 6\ MW/2.4\ Hz \star (60\ Hz - 58.8\ Hz) = 3\ MW. \quad (S5)$$

Determine the operating frequency with a 3-MW load. From above and [3],

$$f_{SYSTEM} = [f_{FL} - f_{NL}/(P_{FL} - P_{NL})] \star P_{SYSTEM} + f_{NL} \quad (3)$$

$$f_{SYSTEM} = [(57.6\ HZ - 60.0\ Hz)/(6\ MW - 0\ MW)] \star 3\ MW + 60\ Hz = 58.8\ Hz. \quad (4)$$

When compared with Figure 5(a), approximately the same 58.8-Hz frequency with a 3-MW load is obtained.

Two-Generator Droop Example with Same f_{NL}

Figure 5(a) can also be utilized to illustrate load sharing with two identical 6-MW turbine/generators having the same parameters as the one-generator example.

Determine the power output of each generator and the system frequency when the total load is 6 MW. "Calculations for Figure 5(a)" shows $f_{SYSTEM} = 58.8$ Hz, and $P_{G1} = P_{G2} = 3$ MW. When compared with Figure 5(a), approximately the same 3-MW, 58.8-Hz result for each generator is obtained.

Two-Generator Droop Example—Acepting Load

Figure 5(b) shows the concept of Figure 5(a) generators with the same 6-MW full-load turbine/generator power rating and 4% droop setting but with different NLFs f_{NL}.

Initially, G1 and G2 are synchronized at 60 Hz; however, the G1 NLF setpoint is increased until $f_{G1NL} =$ 62.4 Hz. This example illustrates what could occur when it is desirable for an incoming droop generator to accept load.

Determine the power output of each generator and the system frequency when the total load is 6 MW. "Calculations for Figure 5(b)" shows $P_{G1} = 6$ MW and $P_{G2} = 0$ MW.

CALCULATIONS FOR FIGURE 5(B)

$P_{G1\ rated} = P_{G2\ rated} = 6\ MW$
G1 droop = G2 droop = 4%
$f_{G1NL} = 62.4\ Hz$, and $f_{G2NL} = 60\ Hz.$

Determine P_{G1}, P_{G2}, and f_{SYSTEM} when the total system load is 6 MW:

$$6\ MW = (6\ MW/2.4\ Hz)(62.4\ Hz - f_{SYSTEM}) + (6\ MW/2.4\ Hz)(60\ Hz - f_{SYSTEM}) \quad (S6)$$

$$f_{SYSTEM} = 60\ Hz$$

$$P_{G1} = (6\ MW/2.4\ Hz) \star (62.4\ Hz - 60\ Hz) = 6\ MW \quad (S7)$$

$$P_{G2} = (6\ MW/2.4\ Hz) \star (60\ Hz - 60\ Hz) = 0\ MW. \quad (S8)$$

CALCULATIONS FOR FIGURE 5(C)

$P_{G1\ rated} = P_{G2\ rated} = 6\ MW$
G1 droop = G2 droop = 4%
$f_{G1NL} = 62.4\ Hz$, and $f_{G2NL} = 61.2\ Hz.$

Determine P_{G1}, P_{G2}, and f_{SYSTEM} when the total system load is 9 MW:

$$9\ MW = (6\ MW/2.4\ Hz)(62.4\ Hz - f_{SYSTEM}) + (6\ MW/2.4\ Hz)(61.2\ Hz - f_{SYSTEM}) \quad (S9)$$

$$f_{SYSTEM} = 60\ Hz$$

$$P_{G1} = (6\ MW/2.4\ Hz) \star (62.4\ Hz - 60\ Hz) = 6\ MW \quad (S10)$$

$$P_{G2} = (6\ MW/2.4\ Hz) \star (61.2\ Hz - 60\ Hz) = 3\ MW. \quad (S11)$$

This confirms the graphical representation in Figure 5(b) because G1 accepts the load from 62.4 to 60 Hz, whereas G2 does not begin to accept load until the system frequency is reduced to 60 Hz or lower. Hence, G1 accepts loads from 0 to 6 MW (100% of G1) before G2 begins to provide megawatt power output.

Two-Generator Droop Example with Unequal Load Sharing

Figure 5(c) shows the concept of unequal load sharing when two identically rated 6-MW full-load turbine/generators (G1 and G2) have the same 4% droop setting and 4% droop line slope for 60-Hz NLF but different NLFs f_{NL}:

$$f_{G1NL} = 62.4\ Hz \text{ and } f_{G2NL} = 61.2\ Hz.$$

Determine the power output of G1 and G2 and the system frequency when the total load is 9 MW. "Calculations for Figure 5(c)" shows $f_{SYSTEM} = 60$ Hz, $P_{G1} = 6$ MW, and $P_{G2} = 3$ MW. What happens as the load is reduced from 9 to 6 MW? Inspection of Figure 5(c) shows that at 60.6 Hz, PG1 = 4.5 MW and PG2 = 1.5 MW. Hence, the load is reduced and divided between the two generators according to the droop line for each turbine/generator and the system frequency increases from 60 to 60.6 Hz. Further load reduction to 3 MW is shown at 61.2 Hz, where PG1 = 3 MW and PG2 = 0 MW. This example illustrates the unequal load sharing based on the droop line settings of G1 and G2.

Combined Droop/Isochronous Operation Example

Figure 6 shows two paralleled generators, with G1 operating in isochronous mode and G2 operating with 4% governor droop; both generators are initially operating at 60 Hz with no load.

Figure 6 shows G1 operating with an isochronous characteristic at 60 Hz and the G2 droop line with an NLF of 60 Hz. Because loading G2 results in a linear decrease in frequency less than 60 Hz, G1 powers the load from 0% load to 100% load of G1. G2 will not begin to provide output power until G1 has achieved maximum output power and the G1 fuel valve is fully open.

> AS SYSTEM FREQUENCY INCREASES, THE TURBINE/GENERATOR G2 BEGINS TO POWER THE LOAD.

For G2 to accept load from a fully loaded G1 isochronous generator without a decrease in system frequency, the G2 droop line must be slowly increased. Figure 6 shows G2 frequency increased in gradual increments with the 4% droop line slope for 60-Hz NLF used throughout the graph. As the G2 fuel valve is gradually opened and G2 accepts 25% load, the droop line NLF increases to 60.6 Hz. A continued opening of the G2 fuel valve until G2 powers 50% load results in a droop line shift to 61.2 Hz with no load. Further opening the G2 fuel valve to accept 75% load causes an additional droop line shift to 61.8 Hz with no load. To accept 100% load, the G2 fuel valve is opened further so that the G2 NLF is 62.4 Hz. This description is indicative of one method to parallel an in-plant droop generator with a utility grid and make the in-plant generator accept load. To unload G2, a reduction in the droop line NLF is required.

Conclusions

This article focused on the fundamentals of industrial turbine/generator governor control strategies of droop and isochronous control when applied to industrial islanding bus-connected generator systems. Simplified droop and isochronous block diagrams were presented to highlight the significance of the summation point for frequency and power parameters.

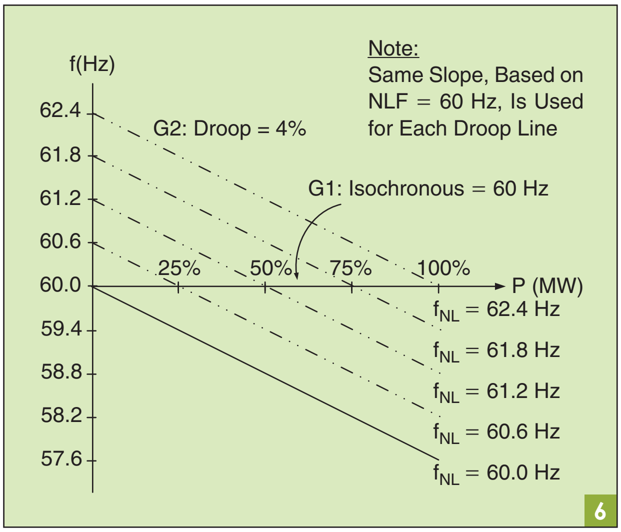
A graphical approach was used to more rapidly and easily illustrate fundamental droop and isochronous governor control concepts. A mathematical straight-line equation analytical approach was used to check the graphical example results and also to provide an analytical tool when a more complex and exacting computation or analysis is required.

One- and two-generator examples with various power and NLF combinations were selected for typical industrial applications. An example with one generator in droop and a second generator in isochronous illustrated load-sharing limitations with this type of governor control strategy.

Emphasis was placed on the droop line because this has been considered a stable governor operating mode for electrical power generating systems. The application practice of isochronous, droop, and other governor control strategies will be investigated in a future article.

It is imperative that fundamental governor concepts of droop and isochronous are thoroughly understood so that typical governor control operational strategies can be investigated, such as operating one turbine/generator in isochronous and the remaining turbine/generators in droop.

The authors intend to write an article about more advanced turbine/generator governor control strategies for typical islanding and grid-connected industrial applications; the purpose of that article would be to investigate control strategies having manual and automatic load-sharing control, isochronous load sharing via load-sharing lines, and turbine/generator governor control via a power-management system.



A two-generator example with droop line shift to accept load.

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