UNDERSTANDING MODERN GENERATOR CONTROL

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ABSTRACT - Improvements in turbogenerator control have taken place at an accelerated pace with the introduction of microprocessor-based digital governors. Many innovative features are provided by these new control systems. However, old standby functions like "DROOP" and "SPEED/LOAD" are still used with the new controls.

Many of us are frustrated when the literature fails to define or mention "DROOP", "ISOCHRONOUS" or "SPEED/LOAD", and so on. There is thus a need for a simple discussion about generator control without the bode plots and other sophisticated references so necessary to equipment design but which are lost on those of us who need a simpler explanation.

INTRODUCTION

The control of synchronous generator drives is simple and straightforward if one is already familiar with the control principles involved as well as the peculiarities of synchronous generators and electrical transmission. When one does not have this background, however, the control of synchronous generators and the steam turbines driving them can be most confusing, to say the least.

Two kinds of control schemes are used for most generator drives. These are DROOP control and FREQUENCY control. Frequency control is the more sophisticated of the two but, oddly enough, seems to be the easiest for most people to understand. Unfortunately, most generator drives operate in DROOP control which, although simpler than frequency control, seems to be the more difficult for most people to grasp.

A good description of these control modes should begin with definitions; an area where different disciplines use different words for the same function. Rotating equipment people refer to "DROOP" control. However, controls or instrumentation types would call this "PROPORTIONAL ONLY" control and might not even recognize the term "DROOP" even though they have the same meaning. Frequently, utilities or powerhouse people will refer to this as "SPEED/LOAD" control and may not recognize either of the other terms.

Please remember, however, that "DROOP" control and "PROPORTIONAL ONLY" control and "SPEED/LOAD" control all refer to the same thing. The term "LOAD" control is also sometimes used and it also has essentially the same meaning.

By the same token, people with a rotating equipment background will refer to "ISOCHRONOUS" control. Those with a controls-oriented background will call this "PROPORTIONAL PLUS RESET" or "PID" control. And utilities or powerhouse people will call the same thing "FREQUENCY" control.

Probably the reason most people find "FREQUENCY" or "ISOCHRONOUS" control easier to understand is that it more closely resembles human response where we as controlling devices will continue to adjust our outputs until the measurement matches the setpoint precisely. We use our bodily responses to "reset" our outputs so long as an error (the difference between measurement and the setpoint) exists.

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DROOP CONTROL

Visualizing "DROOP" control can be somewhat difficult at first until we realize just how simple (and useful) it is. A good analogy is a float-controlled level in a tank.

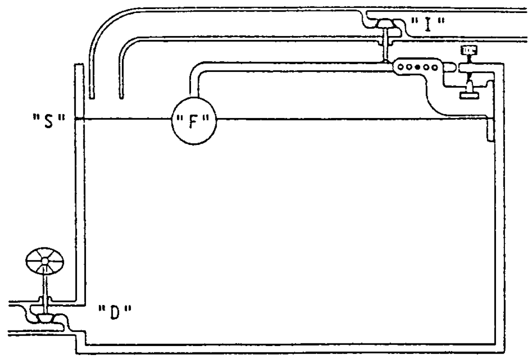

FIG. 1

In figure 1, the the drain valve "D" has been completely closed. The inlet valve "I" will let water flow into the tank until the float "F" rises to the setpoint "S", where the float causes the inlet valve "I" to shut off completely.

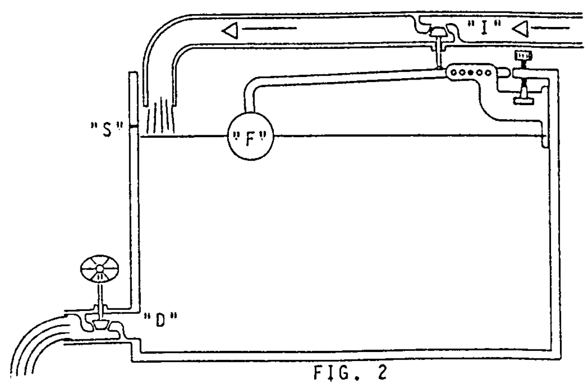

FIG. 2

If, now, we partly open the drain valve "D" as shown in figure 2, water will begin to drain from the tank. The float will begin to fall with the water level thus opening inlet valve "I" until the volume of water flowing in exactly matches the volume flowing out, at which point the level (and float) will stabilize at some intermediate level below the setpoint.

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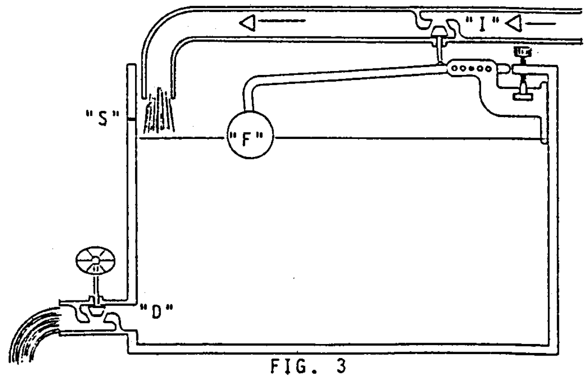


FIG. 3

If the drain valve is now opened fully, the level will fall even more until the inlet water flow equals the out flow again. The level (or measurement) will now stabilize at an even lower level, offset still further from the setpoint.

It is important to understand that the level will never return to the setpoint (or reference) so long as there is demand at the drain valve. The only time the level will be at the reference is when the load is zero

There will be a different level corresponding to each set of load conditions. The system does not automatically "reset" to eliminate the offset or measurement error caused by the load change.

There are other types of load change which can affect the level. These might include a higher water supply pressure, a leak in the tank, and so on.

THE "FLYBALL" GOVERNOR

An analogy which demonstrates DROOP control well and is closer to rotating equipment is the "archaic" flyball governor. Although the flyball governor is shown simplistically, bear in mind that the flyball governor is connected to the turbine shaft and that the flyball rotation is proportional to turbine speed.

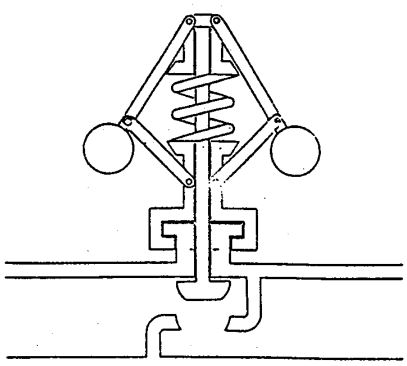


FIG. 4

In figure 4, we see a flyball governor at rest. The spring, which opposes the centrifugal force of the flyballs when turning, has forced the steam valve fully open. The valve will remain in this position until the centrifugal force of the flyballs becomes strong enough to overcome the spring and start to close the valve.

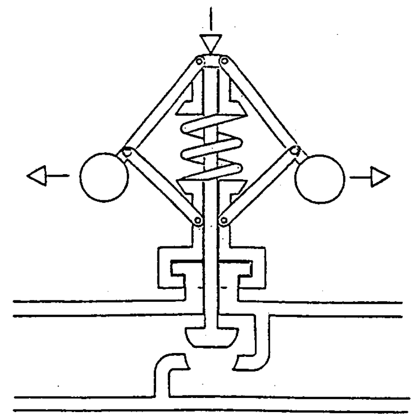


FIG. 5

In figure 5, centrifugal force of the flyballs is high enough to depress the spring partially and close the valve about half-way. Observe that turbine speed must stabilize at some RPM higher than that required to just barely compress the spring.

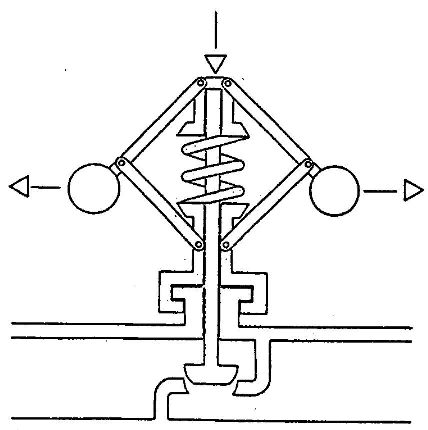
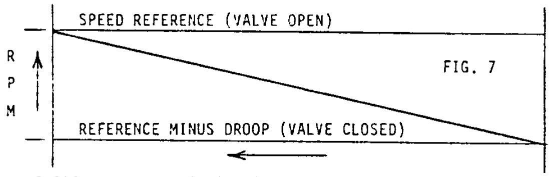


FIG. 6

In figure 6, centrifugal force of the flyballs has compressed the spring sufficiently to almost close the governor valve. (BALLS-OUT) This would be a low load (high speed) condition where speed will keep the governor valve almost closed. If the load should increase, speed must fall. This in turn will cause the governor valve to open some. RPM will then stabilize at some lower value.

The level control and the flyball governor are both examples of PROPORTIONAL ONLY or DROOP control. Figure 7 perhaps shows more clearly how a governor valve will open as the speed falls (droops) and how the governor valve will close as the speed rises. The mechanical characteristics of the governor valve (the linkage, spring tension, etc.) will determine maximum and minimum operating speeds of the turbine. The total speed range (reference) can be adjusted up or down a small amount as limited by mechanical construction of the governor.



If the speed does not change but the speed range rises then the governor valve must open more. If the speed does not change but the speed range falls then the governor valve must close more.

DROOP CONTROL AND SYNCHRONOUS GENERATORS

As explained in more detail later, a natural characteristic of synchronous generators is that they must turn at a fixed (synchronous) speed. If two or more synchronous generators are connected to the same electrical system (utility grid), they will be electrically locked together as if they were on the same shaft.

The typical utility grid may have dozens or even hundreds of generators so synchronized. Since there is no way an individual generator can affect the speed of the whole grid, it is pointless to try to use speed control under these conditions. Isochronous speed control would only cause the individual turbine to load up completely if its reference is slightly higher than that of the utility grid or to totally unload if its reference is slightly lower than that of the utility grid.

DROOP control is a different matter. Since there is no "automatic reset" in DROOP control, the governor will open the steam valve a fixed amount determined by the relationship between speed (frequency) and speed reference.

ENTER "LOAD" CONTROL

Now, we cannot change turbine speed when driving a synchronous generator locked to the grid but we can change the speed reference of the governor. When we raise the reference the governor valve will open, increasing load, and when we lower the reference the governor valve will close, decreasing load. Thus, we find that the "archaic" mechanical governor may be pretty useful, after all, as a "LOAD" controller. What was previously a "poor" speed control now becomes a useful load control when the generator is synchronized and is locked to the grid. Thus arises the term "SPEED/LOAD" as commonly used by powerhouse people.

DROOP STABILIZES THE GRID

Yet this is not the only useful feature of DROOP control. We mentioned that dozens or even hundreds of synchronous generators may be connected to the utility grid. Most of these are in DROOP control mode. Here is a marvelous thing. Although these turbines will control load when the speed is fixed, they will change load if the speed (frequency) of the utility grid should fall (droop). Therefore, all of these load controlled machines will pick up load if the grid frequency falls and will drop load if the grid frequency rises. This provides a magnificent stabilizing influence to the frequency of the whole utility grid.

This demonstrates that DROOP control is not archaic at all; only the one-hundred year old mechanical governor is archaic because of its mechanical limitations. DROOP control is, therefore, a very useful mechanism and by incorporating DROOP control performance in modern digital control devices we can preserve the useful functions of DROOP yet at the same time eliminate the objectionable limitations of the mechanical governor.

The best modern digital governors then include provisions for operating in DROOP mode when required, particularly when they are controlling synchronous generators connected to a utility.

BEST OF BOTH WORLDS

Now, other, better features are possible. Since we sometimes find our generator disconnected from the utility grid, we would like to be able to switch operation when this happens. We would like to operate in FREQUENCY control when disconnected from the grid. Not only that, we would like to be able to switch back to DROOP control whenever the generator is resynchronized and reconnected to the grid with a minimum of disturbance.

The modern digital governor easily gives us the capability to automatically switch from FREQUENCY control to DROOP control and back as required by operation. The governor can backcalculate the DROOP reference that is required to hold output or valve position at a constant value and thus make the transfer with no bump or change in control output.

DROOP-ON-OUTPUT OR DROOP-ON-KILOWATTS

However, this is still not all. The digital governor has the capability to DROOP on control output. (the DROOP function we have been discussing until now) The digital governor also has the capability to DROOP-ON-KILOWATTS. This involves using the kilowatt output signal as feedback for the control algorithm instead of using control output as a feedback signal as shown.

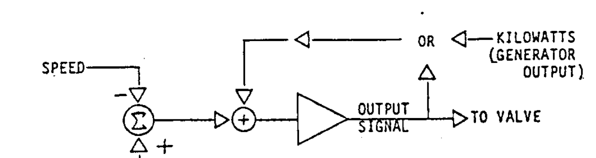


FIG. 8

TRUE LOAD CONTROL

When the governor is configured for DROOP-ON-KILOWATTS, the speed reference becomes a "load setpoint". That is, if the DROOP speed reference is set at midpoint (halfway up the speed range), the control output will drive open or closed as necessary to provide one-half generator load (kilowatts) since the control feedback is now the kilowatt signal, the generator output, not the output of the controller.

This function will then hold generator output at 50% or whatever the reference has been set for despite changes in steam pressure. Note that the reference to speed relationship will still stabilize the grid.

PIP DROOP

There is one other difficulty with DROOP control. It is a strictly displacement function. That is, if load (or speed) should change suddenly, the control output (valve position) will change just as suddenly. This characteristic causes some instability of control due to the abrupt change in control output. This requires a DROOP setting of some six to ten percent (of full governor speed value) in order to obtain stable operation of the turbogenerator.

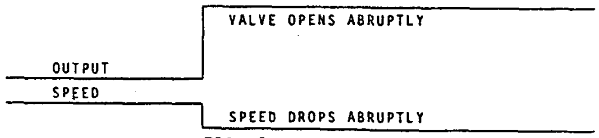


FIG. 9

PIP DROOP provides short term stability based on the PI value (proportional plus reset) while DROOP (the other P) is maintained independent of stability. With this control mode, DROOP settings of three or four percent are commonly used and will furnish much more stable control of the turbogenerator than plain DROOP.

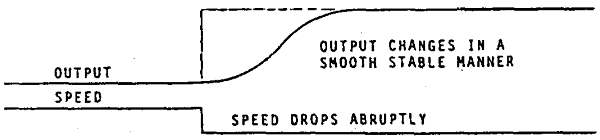


FIG. 10

Again, the modern digital governor will provide superior and flexible performance. This includes PIP DROOP control.

IMPROVED STARTUP SEQUENCING

One more valuable feature can be provided by the modern digital governor. If the governor is configured for DROOP control, the startup sequence, acceleration and synchronizing to the utility bus can be somewhat awkward in that the speed (RPM) is never at the DROOP reference when using DROOP control. The digital governor easily solves this problem by operating in ISOCHRONOUS speed control through the startup and synchronizing phases and then automatically switching to DROOP control when the generator load breaker closes. Even "startup tuning" can be employed to make synchronizing easier if the actual running tuning constants are not quite satisfactory for no-load conditions.

SYNCHRONOUS GENERATORS VS INDUCTION GENERATORS

Two types of electrical generators are found in common use today. These are synchronous generators and induction generators. Their characteristics differ considerably. Most special digital governor programs are designed to be used with synchronous generators. They are not appropriate for use with induction generators. Induction generators should be operated with plain speed control as described in more detail later. Modern digital governors are capable of operating in a generator control mode or in straight speed (isochronous) control with only minor changes in the configuration.

SYNCHRONOUS GENERATORS

Synchronous generators require a source of D. C. power which is used to create the magnetic field in the rotor (the part that turns) of the generator. This magnetic field rotates with the rotor and as the magnetic field passes through the stator windings (the shell of the generator that does not turn) creates alternating current that is precisely coordinated with the rotation (RPM) of the rotor.

Speed (RPM) of the synchronous generator thus creates an alternating current whose frequency is a function of the rotational speed. This is referred to as "synchronous speed". If two or more synchronous generators are connected to the same electrical system (grid) they will be electrically locked together as if they were on the same shaft. They must be carefully coordinated and must be electrically "in-phase" before the generator load breaker is closed. Severe damage can result if a generator load breaker is closed when a synchronous generator is out-of-phase.

INDUCTION GENERATORS

Induction generators are not self-excited. The magnetic field of the rotor is created (induced) when the rotor "SLIPS" in relation to synchronous speed. If the induction generator turns slower than synchronous speed it will act as an induction motor; if it turns faster than synchronous speed, it will act as an induction generator. Most induction generators are in fact induction motors that are being driven above synchronous speed by a steam turbine or by a water wheel. If the induction generator turns exactly at synchronous speed, it will be inert and will generate no electricity at all.

The magnetic field in the rotor of the induction generator is caused by the alternating current which flows in the stator. Therefore, if the utility grid fails, this current ceases to flow and the induction generator will cease to generate electricity as well.

The more negative the "SLIP" (when actual RPM is greater than the synchronous speed) the more electricity will be generated by the induction generator. A turbine driving an induction generator should use plain isochronous speed control because the induction generator application is more closely related to driving a centrifugal pump or a compressor than the DROOP "LOAD" control required for driving a synchronous generator which is tied to a utility grid.

Typically, induction generator "SLIP" will range from about 10RPM to as much as 40 or 50RPM. Once the rated output of the induction generator has been reached, driving the generator to a higher speed can damage the generator just as overloading an induction motor will cause overheating and damage to the motor.

DIFFERENCES IN CONTROL

The control schemes used with synchronous and induction generators must then be quite different.

The synchronous generator control scheme should use PIP DROOP when connected to a utility grid but should at the same time be capable of switching to isochronous (FREQUENCY) control and back when required. It should also be able to switch bumplessly (without bumping the control output) back to DROOP control mode when the generator is reconnected to the grid.

Changing the DROOP speed reference of a governor controlling a synchronous generator will change the load, not the speed, when the generator is connected to the grid. However, changing the speed reference when disconnected from the grid will change the local frequency, not the load. The load is determined by the connected electrical load of the "isolated" (local) electrical bus.

In contrast, the induction generator control scheme should always be isochronous (proportional plus reset) speed control. Here, changing the speed reference does change the load , just as if the turbine were driving a compressor or a centrifugal pump. The induction generator will require a much smaller speed range, however, than a centrifugal pump or a compressor in order to match the "SLIP" of the induction generator.

GRID FREQUENCY CONTROL

Although one of the generators in a large utility grid may be set to control frequency of the grid, it can be seen that the frequency controlled turbogenerator may not be absolutely necessary. This is because an operator can raise or lower the DROOP reference of one or of several large generators in the grid in order to maintain frequency.

Likewise, a computer may be programmed to provide the same type of adjustable control for several or for many machines on a priority basis. Factors such as efficiency, condition of the equipment, proximity to loads, etc. of each machine might influence the priorities set by an individual or by a computer.

SMALL POWER HOUSES

The situation may be relatively more complicated for the small power house (20 to 50 Megawatts) which is usually associated with a papermill, a refinery or a chemical plant. The operator may have to contend with many variables like extraction pressure control, backpressure control and some steam balance manipulation until suddenly the utility grid is lost and he is faced also with controlling the frequency within his plant or in part of it.

Older controls do not make his job easy. It is sometimes tedious and awkward to switch from backpressure control to controlling frequency. Older extraction controls may not work well or may be broken. And synchronizing the machine (and his plant) to reclose the utility tie breaker when the grid is again available may be akin to tight-rope walking. This same operator may also be trying to run several boilers and their accessories at the same time. He may have forgotten or confused some of the procedures in the mean time. Training is difficult and mistakes can be costly. Better understanding of the control principles can help a lot. Better control can help a great deal more.

SMALL COGENERATION

A whole forest of trash burners, wood-chip burners and chipped tire burners has sprung from the ground while we weren't looking. These plants are frequently designed and operated by people with good construction backgrounds and who may be controls knowledgable but who are weak in the area of power house operation. One might guess there have been problems.

COMES THE MICROPROCESSOR

Suddenly the world is computer conscious. A late entry into rotating equipment control by the microprocessor is providing revolutionary solutions to some of the problems already mentioned. This revolution has also left some of the old timers in a state-of-shock and in need of a better understanding of the control principles used in the newer equipment even if some of the control principles have been around for a long time.

SUMMARY

The modern digital governor has made vast improvement in generator drive control. However, time-proven functions like DROOP and SPEED/LOAD control are still in use and are incorporated into the control schemes of these newer governors. It is incumbent on those of us who design, apply, operate and manage these systems to better familiarize ourselves with the control principles residing in our old equipment and that will be provided in the newer equipment we are either now installing or will surely be installing in the future.

BIOGRAPHY

Robert M. Wright was born July 14, 1921 in St. Stephen, New Brunswick, Canada but is a native-born U. S. Citizen since St. Stephen had the nearest hospital to Eastport, Maine, his real hometown. He has lived mostly in the South, however, graduating from High School at El Dorado, Arkansas in 1938. Study at the University of Oklahoma before and after WWII finally produced a BSME in 1948 after spending four years as an airplane mechanic in North Africa, Italy and the U. S. He and his wife Catherine currently reside in Dickinson, Texas, south of Houston.

He spent about a year designing helicopters for McDonnell Aircraft in St. Louis before moving to the Amoco Refinery in El Dorado, Arkansas in 1949. This time was spent in engineering and refinery heavy maintenance before accidentally falling into the controls business with Amoco in 1960. During 1966 he went to Karachi, West Pakistan to assist in starting up a new refinery there. In 1968 he was transferred by Amoco to Texas City where he tried to fill the job of Supt. of Instrument and Electrical maintenance at the Texas City refinery. Retiring from Amoco in 1981, he went to work for TRI-SEN SYSTEMS of La Marque, Texas where he is presently Applications Consultant.

Wright is a member of ASME and participates on the ASME Gas Turbine Institute - Controls and Diagnostics Committee. He has been a Senior Member of the Instrument Society of America since 1969. He has written a number of published articles, primarily on the application of rotating equipment controls and holds several patents.

DISCUSSION

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This paper is an excellent piece of writing for training, and it is a good exposition of the coordination between modern computer-based governing systems and conventional governing as used in interconnected power systems. Because of its excellent analogies and figures and its easy writing style, this paper is well suited for training. Since this discussor intends to use this paper in both classroom and on the job training, this discussion points out some appropriate industry and national standards and includes some observations from the point of view of a large, interconnected utility.

The title of the paper is misleading; the paper falls within the broad category of governing control. Governors necessarily are associated with the prime mover that drives the generator shaft and provides the power which the generator converts to electrical power. Without the prime mover, the generator cannot generate power.

With regard to the author's comment about lack of definition of terms, this discussor would like to call attention to several standards, which address this issue. There are standards for operating generators; Standard 67 [Reference 1] is a broad example that cites other relevant standards. Governing control is also covered by standards. Depending upon the type of the prime mover, different standards are appropriate [References 2-4]. These provide formal definitions of the terms droop, reset, isochronous, etc.

There is no isochronous governing within large utility power systems. If a unit were put on isochronous control, it would act to change its power output to balance the generation-load power imbalances of the entire interconnection; in the eastern U.S./Canadian connection, of about 400,000 MW capability, this would require one very large turbine generator set. Instead, frequency is maintained by overriding automatic generation control systems (AGC). The design control of AGC systems is another entire subject, with its own literature, standards, and terminology.

Prime movers in U.S. large electric utility networks have droop that is universally set at 5%. The 5% droop implies that each unit will have a governing characteristic which changes power output linearly as speed changes, as shown in the author's Figure 7. The 5% droop corresponds to the 5% change in speed or frequency that is required to shift from valves closed to valves open. As the author points out, this provides an automatic means for sharing frequency error and power imbalance among all interconnecting units, each unit will change power in proportion to its MW rating.

As a final observation, there are very few large (greater than 50 MW) induction generators on the electric utility systems. This is largely because of economics. The costs involved with providing reactive power to excite the generator and the losses associated with the generator slip make it economically unattractive. A recent EPRI report describes a study which re-evaluated the economics [Reference 5].

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