WOODWARD

Application Note 83403
(Revision B)
Original Instructions

Industrial Steam Turbine Control

Chapter 1.
General Information

Introduction

Industrial steam turbines represent one of the largest populations of prime movers in the world. They are found in many industries and utilized in a variety of applications. This report outlines the fundamentals of industrial steam turbine control that will be encountered throughout the world. Because of the interest in electronic control systems, this paper will focus on digital control schemes for turbine applications.

Types of Turbines

Fundamentally there are two basic types of turbines: condensing and back-pressure. Condensing turbines operate with exhaust pressures less than atmospheric pressure, while back-pressure turbines operate with exhaust pressures equal to or greater than atmospheric pressure. As a general rule, condensing turbines tend to be larger in physical size as well as power output. Back-pressure turbines are smaller in physical size than an equivalent condensing unit, and usually operate at much faster rotational speeds due to efficiency considerations. A hybrid of the basic condensing or back-pressure turbine is the extraction or induction turbine.

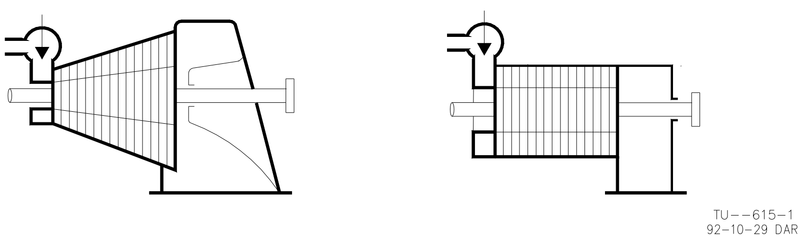

Figure 1. Condensing and Back-pressure Turbines

Extraction turbines get their name from the fact that steam is extracted at an intermediate point in the turbine casing, at a positive pressure. The extracted steam is utilized for some process requirement within the plant. Extraction turbines can be either condensing or back-pressure, depending on the particular application. By extracting steam from the turbine you avoid using a pressure reducing valve which is much less efficient. In effect an extraction turbine becomes the pressure let-down station for the plant. Extraction/back-pressure turbines are particularly effective when two or three process steam requirements exist.

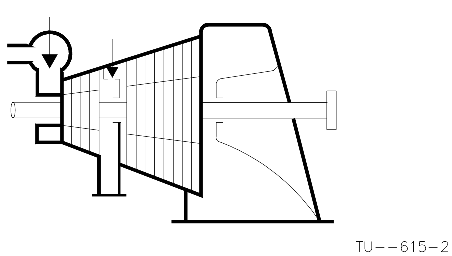

Figure 2. Extraction Turbine

Induction turbines work opposite their extraction counterparts. Instead of removing steam, the induction turbine receives steam into an intermediate stage of the turbine. The induction steam mixes with the steam in the turbine and increases the total steam flow through the remainder of the turbine. The induction steam is added to the turbine at a point where the steam pressures closely match. The induction steam comes to the turbine as a by-product of some process within the plant. It is a way to get additional work out of the steam before it is returned to the condensate system. Induction turbines are generally condensing units, although they could be back-pressure turbines if a demand for the exhaust steam exists.

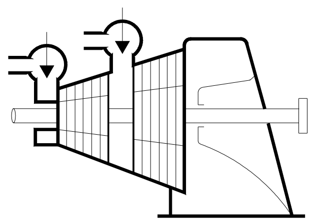

Figure 3. Induction Turbine

Type of Applications

Industrial steam turbines fit into one of two general categories; generator drives and mechanical drives. Generator drives include all turbines (non-utility) driving either synchronous or induction generators. These units vary considerably in power output, but are usually much smaller (less than 100 MW) than their utility counterparts. They can be direct-drive applications, but more often the turbine drives the generator through a speed reduction gear. This allows the turbine to be designed for optimum speed and efficiency. Generator drives can be either condensing or back-pressure; however, the larger percentage of them are condensing due to the increased efficiency and higher power output per pound of steam. Generator drive turbines can also have extraction or induction capability.

Mechanical-drive turbines can be applied in a variety of applications, but these usually fit into one of the following general categories of driven equipment:
- Fans (ID and FD)
- Blowers
- Compressors
- Pumps
- Mills
- Crushers/cutters
- Line shafts

Mechanical-drive turbines are drive options in lieu of electric motors. As a result, they tend to be considered when steam is readily available, steam has lower operating cost than electricity, or turbines are serving as pressure let-down stations in addition to powering the driven equipment. Mechanical drives can be condensing units, however more of them tend to be back-pressure. Most mechanical drives will not have extraction or induction capability, however some special applications do exist and nothing precludes this combination. Mechanical-drive applications can operate at rotational speeds that are considerably higher than would be found with generators; this is due to the driven equipment requirements.

General Control Variables

Industrial steam turbines can be controlled in a variety of ways dependent upon the application in question. However, all the possible control options can be categorized into one of the following general areas:

- Speed control
- Load control
- Turbine parameters
- Driven-equipment/process parameters
- Process parameters

The remainder of this report will be devoted to looking at each of these areas and how they can be utilized in steam turbine control.

Speed Control

Regardless of the steam-turbine application being considered, speed and/or load control will be required. Speed control is the primary control loop for all turbine applications, industrial as well as utility. Without speed control the turbine cannot be started or operated safely.

Industrial steam turbines typically have only one steam flow metering device, with the exception of extraction and induction designs. The inlet of industrial steam turbines will be controlled by a single valve, or a series of valves (multi-valve assembly) working in concert. Whether the turbine is of single or multi-valve design, a fundamental rule for governing applies:

> One steam control device can only control one parameter.

At first glance, this may seem restrictive. In general, only one parameter need be controlled for many applications. The applications flexibility is increased when the controlled parameter's setpoint is influenced as a function of a secondary parameter. For example, the turbine's inlet steam valve controls the turbine speed, but exhaust pressure can be used to bias the speed setpoint in order to maintain some level of exhaust pressure. This is an example of how parameters other than speed can come into play, but ultimately the speed control loop is the tie back to the inlet steam valve(s).

Speed control can be illustrated by use of a balance beam concept as illustrated. All systems requiring precise speed control need feedback. The actual speed must be weighed against the desired speed. The balance beam illustration shows how the actual speed weighs against the desired speed; adjustments are made to achieve speed balance which is the setpoint.

This balanced system is the heart of any control system. In mechanical-hydraulic governors the speeder spring exerts a force on the thrust bearing, while the flyweights exert an opposing force proportional to the rotational speed of the turbine. Depending on the speeder spring tension and the speed of the turbine, an equilibrium point is established.

In an electronic governor the same type of summations take place, however electronic currents and voltages are summed instead of forces. In either case, the system is continually giving feedback to the control so that it can adjust in an attempt to maintain the setpoint. This is a closed control loop and the heart of all turbine control systems, no matter the complexity.

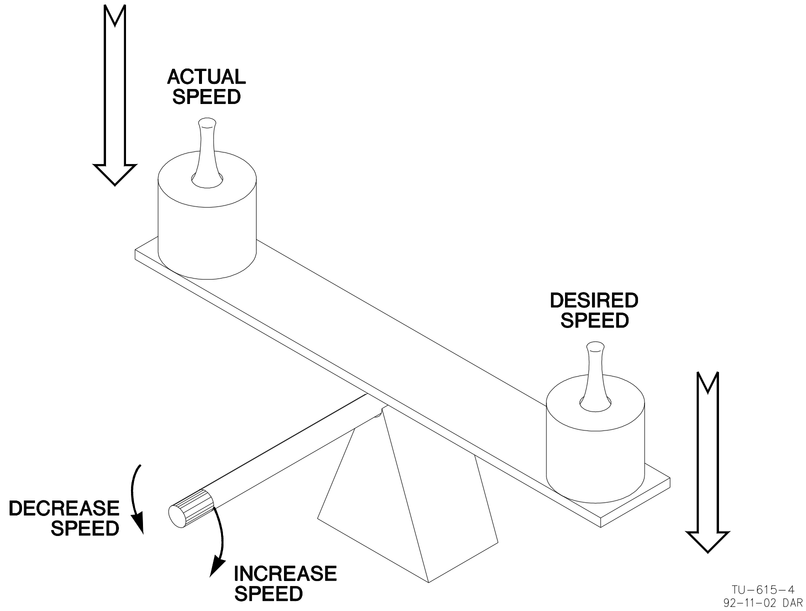

Figure 4. Speed Balance

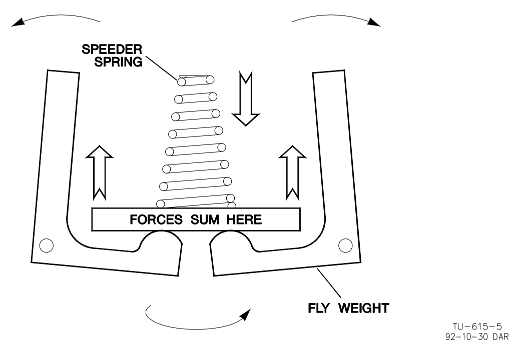

Figure 5. Ballhead Speed Balance

Load Control

For generator applications it is often desirable to control the turbine for load rather than speed. In most of these applications, the generator is feeding the electricity into a grid system. Once the turbine-generator has been synchronized to the grid and the breaker closed, the rotational speed of the turbine is locked to the frequency of the grid. Speed can no longer be influenced, but we can use the speed control loop to control load (kW) by raising or lowering the speed reference in order to open or close the inlet governor valves and influence the flow of steam through the turbine. The change in steam flow will not change speed; however, it will produce more/less power depending on the flow change.

For most generator applications the control of load is a primary consideration. In the case of back-pressure and/or extraction turbines, the control of load may be secondary, but will still be a controlling parameter. For condensing turbines load control is generally the primary parameter. Induction turbines also control on load, with the other consideration being the efficient use of the induced steam before it is returned to the condensate system.

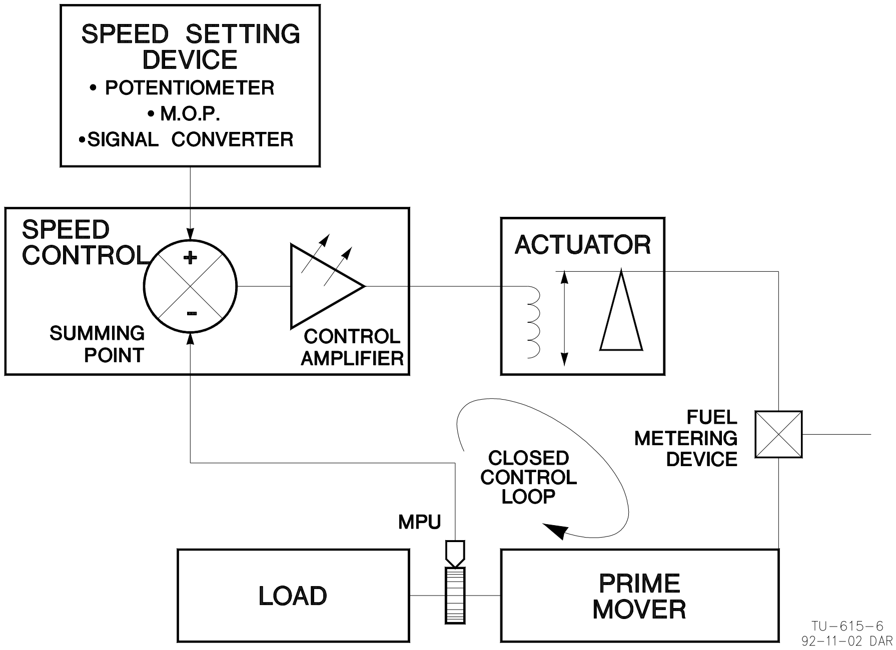

Figure 6. Closed-Loop Control

Turbine Parameters

There are four primary turbine-related parameters that are sometimes controlled as part of the turbine control system in addition to speed and/or load. In all four cases these relate to steam pressure; they are:

- Inlet pressure
- Extraction pressure
- Induction pressure
- Exhaust pressure

Inlet-Pressure Control

Inlet pressure is controlled by manipulating the inlet governor valve(s). In order to accomplish this, an output signal must be sent to the actuator via the control system. To control inlet pressure, a bias must be applied to the speed control loop that relates to inlet-pressure actual versus setpoint values. This bias of the speed loop is accomplished by incorporating cascade control into the system. Cascade control influences the speed reference setpoint by comparing a 4–20 mA pressure signal to a reference signal and sending a corrective signal to the speed reference. The change in speed reference in turn causes a corrective signal to the actuator which repositions the steam valve. In order to stabilize control, the cascade block incorporates deadband within which no corrective action is taken. The deadband window is small enough that pressure regulation is considered stable.

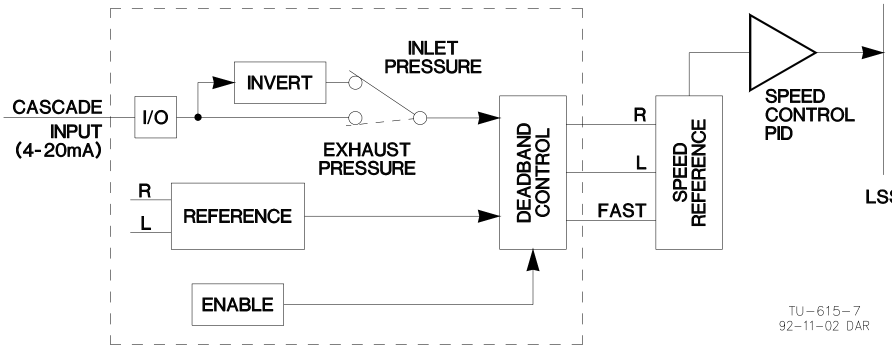

Figure 7. Cascade Control Inlet Pressure

The normal output signal to the actuator is an increasing signal for increasing speed or load. However, for inlet-pressure control the governor-valve position needs to be decreased in order to increase inlet pressure. Therefore the output control signal when controlling for inlet pressure must be inverted.

Extraction-Pressure Control
The control system of an extraction turbine plays an important role in determining the overall performance and reliability of the unit. An extraction turbine can be considered as being composed of two (or more) separate turbines operating in series. Automatic-extraction turbines can be found in three configurations; single, double, and triple. Single extraction are the most common, while double extraction aren't nearly as common. Triple extraction units are rare, but some exist. For purposes of this paper the focus will be on single-extraction turbines, since they are the most prevalent.

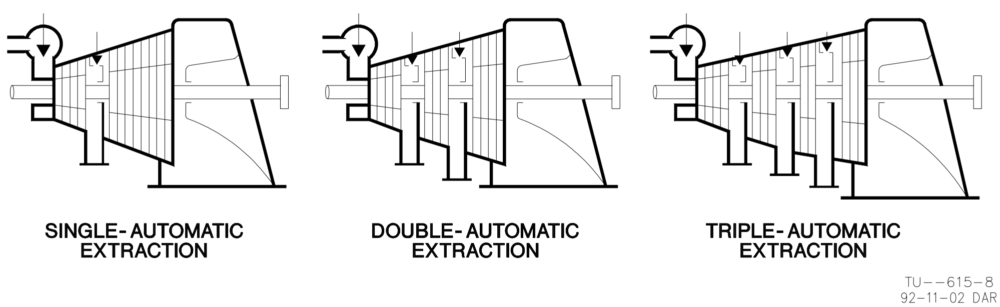

Figure 8. Extraction Turbine

Extraction-control valves are very similar to inlet control valve(s). Extraction valves control the flow of steam to the downstream stages of the turbine. Another way to view extraction control is, extraction valves regulate flow to the remainder of the turbine in an effort to maintain constant back-pressure at the exhaust of the preceding section.

Many industrial applications call for extraction turbines which regulate two or more parameters because economic benefits result from a more efficient use of energy. As stated previously, the number of controlled parameters requires an equal number of control devices.

The key to successful operation of automatic-extraction turbines is a control system which provides stable control of two parameters. The two parameters are usually speed/load and extraction pressure. Changing the position of the inlet or extraction valves affects both speed/load and extraction pressure. Or, if speed/load or extraction demand changes, both inlet and extraction-valve positions must be changed to re-establish speed/load and extraction setpoints. However, with generator drives in which load swings are acceptable, another parameter can be controlled (inlet or exhaust pressure) in addition to extraction pressure.

The governor for an extraction turbine must control (ratio) the inlet valves and the extraction valves in such a manner that both speed/load and extraction pressure are held at desired levels. The ratioing circuit, as shown, is the source of this control scheme. Speed/load and extraction controls receive two inputs each, a reference signal (desired) and a status signal (actual). The controls compare these signal voltages and send a correction signal to the ratioing circuit. The ratioing circuit has outputs to both the inlet and extraction final drivers which, in turn, control their respective actuators and steam valves. The ratioing circuit generates output signals so that both inlet and extraction valves move in a direction to correct the errors. Similarly, an error in extraction pressure will cause the inlet and extraction valves to move to correct the extraction pressure and not change load.

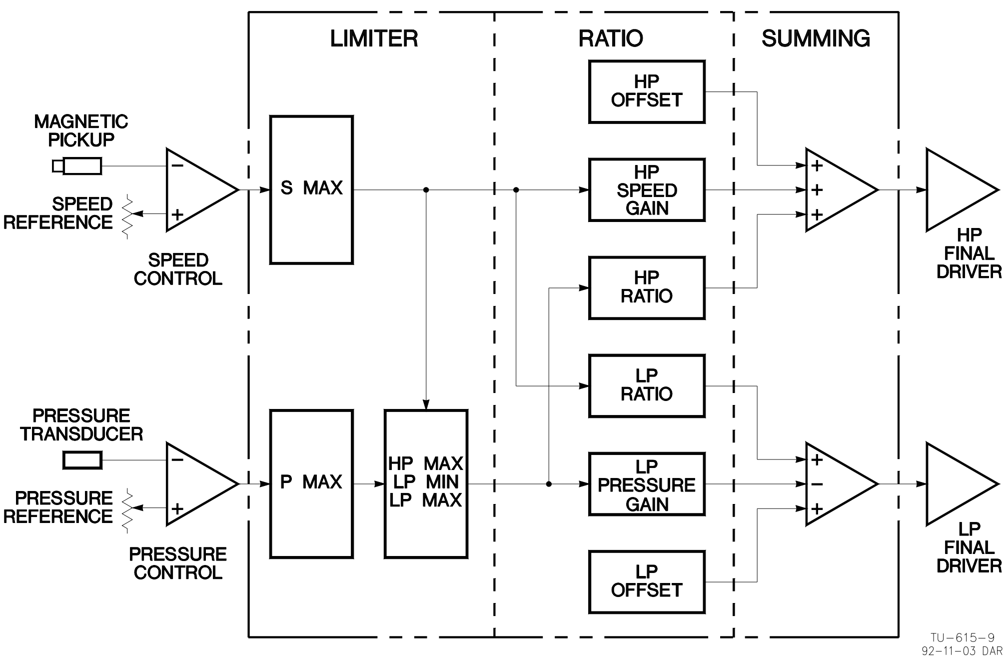

Figure 9. Ratioing

The movement of the inlet and extraction valves may be in the same direction or opposite direction depending on the change in condition for which a correction is taken. For an increase in speed/load demand, the inlet valve must open to allow more steam to enter the turbine. At the same time, the extraction valve must open to maintain constant extraction pressure. For an increase in extraction flow demand, the extraction valve closes to supply the additional extraction flow, and the inlet valve opens to maintain speed/load.

Extraction Steam Map

In order to make the ratioing circuit work properly, the control must contain particular data about the turbine performance. The steam map for an extraction turbine contains the data necessary for the ratio circuit to maintain proper control of the turbine. The steam map is a graphic description of the operating range of an extraction turbine. The map is often called a steam envelope, since normal turbine operation must be contained within the envelope lines.

The lines on the envelope define the operating characteristics of your turbine. Although these maps are constructed by the turbine vendor for purposes of depicting turbine performance to the customer, this map is also utilized by the control engineer to define the inlet (HP) valve to extraction (LP) valve relationships. In addition the map helps the control engineer to define the limits the control must keep the turbine from exceeding. The axis of the steam map represent power output along the horizontal, and throttle steam flow (or inlet valve position) along the vertical.

The first boundary line on the extraction map is the maximum throttle (inlet) flow line, referred to by the control engineer as HP=1 line. The reason the control engineer does so is because this line represents the point at which the inlet (HP) valve is at full open, which means the turbine is passing the maximum steam flow allowed with the design steam conditions.

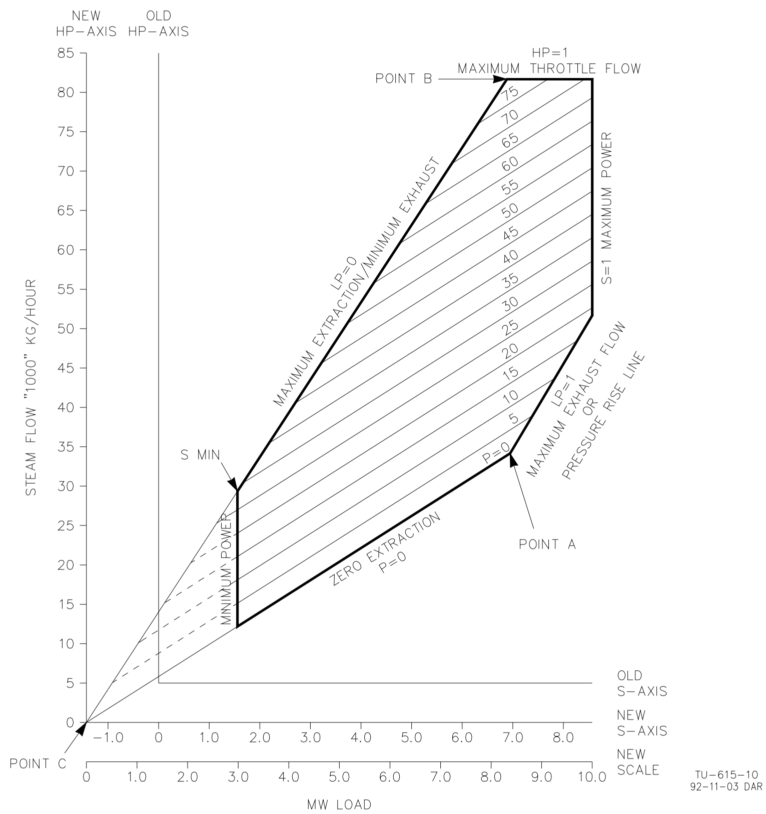

Figure 10. Extraction Map

The second boundary line is the maximum power line, referred to as S=1 by the control engineer. This line represents the maximum power output of the turbine with design steam conditions.

The next boundary line on the map is the maximum exhaust flow line, or LP=1 as designated by the control engineer. This line represents a real limit of the turbine in that greater exhaust flows would cause the turbine to operate at higher exhaust pressures. This line is also called the "pressure rise line" by some turbine vendors because operation to the right of this line will cause the turbine exhaust pressure to rise. Usually a limiter is applied in the control system to keep the turbine from operating outside this line. This means the turbine will be throttled back until the turbine returns to the area within the map.

The next boundary line is the zero extraction flow line, or P=0 as designated by the control engineer. This represents the throttle flow from minimum load to maximum exhaust flow, with no extraction steam flow demand. This also means the extraction (LP) valve would be fully open, hence P=0.

The minimum power line is next and is referred to the control engineer as S=min. This is not a hard limit because the turbine vendor usually chooses to cut the map off at some minimum power, below which the customer will most likely not operate the turbine, and prediction of turbine performance is difficult.

The final boundary line is minimum exhaust flow, or LP=0 as the control engineer refers to this limit. This line represents the combination of throttle and extraction flow, and associated power output, when minimum steam flow passes to the exhaust section of the turbine. In all turbines there must be a minimum amount of steam flowing through the exhaust in order to avoid overheating this section of the turbine. In effect, the extraction (LP) valve would be fully closed, which is why the control engineer designates this as LP=0.

Within the body of the map, bordered by the boundary lines just mentioned, are the combinations of throttle and extraction flow that result in various power output levels. With the boundary lines defined and the intersection points identified, the control engineer has all the data needed to design a control system with the proper ratioing and dynamics to provide precise and stable control.

Induction-Pressure Control

Just as the control system of an extraction turbine plays an important role, so to with induction turbine applications. An induction turbine utilizes waste steam by inducing it into the turbine at some intermediate stage. The induction steam increases the total mass flow through the remaining stages of the turbine which results in more power output.

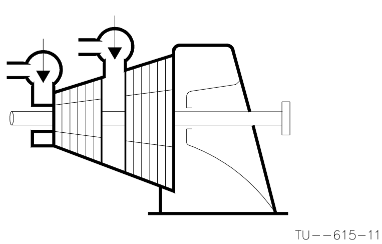

Figure 11. Induction Turbine

The control valve(s) for induction turbines are very similar, or the same hardware, as those used for extraction turbines. The purpose of induction valves is to control flow into the downstream stages of the turbine, while maintaining constant pressure at the induction opening. This accomplishes two important points; first it stabilizes the flow and pressure into the turbine which facilitates smooth transition of the two streams of flow in the turbine. It also provides stabilization of the steam line from which the induction steam comes from.

As with extraction turbines, the control system must ratio the positioning of the inlet valve and the induction valve such that speed/load and induction pressure are maintained and stable. The ratioing circuit for induction turbines is very similar to that of extraction control. In order to develop the ratioing of the two valves, the induction map must be incorporated in the control system.

Induction Steam Map

An induction performance map is very similar to an extraction map. As with extraction maps, the boundaries of the induction steam map represent the limiting factors of the turbine. The axis of the steam map represent power output along the horizontal and throttle steam flow (or inlet valve position) along the vertical.

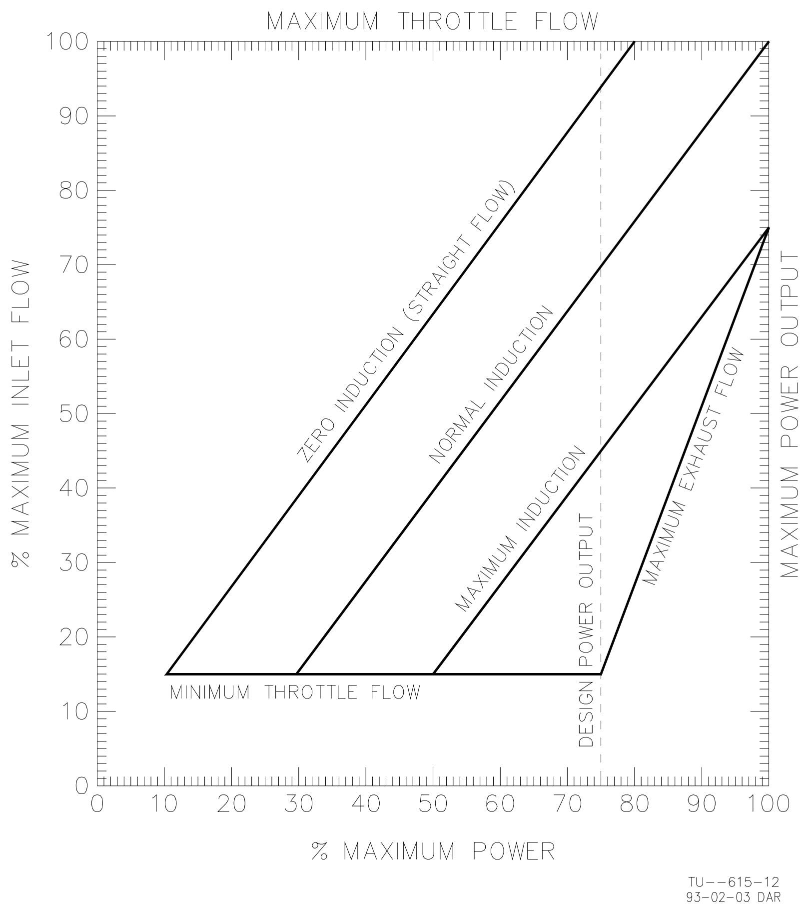

Figure 12. Induction Map

As with extraction maps, the first boundary line is the maximum throttle (inlet) flow line, again referred to as HP=1 by the control engineer. The second boundary line is also like an extraction map as it represents maximum power, called S=1 by control engineers. The third boundary is the maximum exhaust flow, or exhaust pressure rise line.

The next boundary line is unique to induction turbines, although extraction-turbine steam maps do have a similar limiter. In extraction turbines the potential exists that all steam could be demanded by the extraction line, leaving only enough steam to cool the exhaust section. With induction turbines the potential exists that all steam required could be supplied by the induction line, leaving only enough steam passing through the inlet section to cool the forward section of the turbine rotor. Therefore, this boundary line is defined as minimum throttle flow, designated as HP=0 by the control engineer.

The final boundary line is the zero induction line, or LP=0. This represents the condition of running on throttle (inlet) flow with no supplemental flow from the induction line. Because no flow is coming from the induction source, the induction (LP) valve is fully closed, hence LP=0.

Within these outer boundary lines are all the combinations of throttle flow and induction flow that can be achieved by the turbine. One other limit line needs to be identified which is not an outer boundary necessarily; this is the maximum induction flow line, or LP=1. This line represents the condition at which the induction (LP) valve is at its full open position. In some cases this line and the maximum exhaust flow line may be one in the same, depending on the sizing of the exhaust section of the turbine and available throttle (inlet) steam flow.

Exhaust-Pressure Control

The final turbine parameter to be discussed is exhaust-pressure control. This is utilized only with back-pressure turbines, and typically comes into play when the exhaust steam is being used in a process that requires close steam pressure control.

As with inlet pressure, exhaust pressure is controlled by manipulating the inlet governor valve(s). A bias must be applied to the speed control loop that relates to exhaust-pressure actual compared to the setpoint. As with inlet pressure, cascade control is incorporated into the control system. The exhaust-pressure control compares a 4–20 mA pressure signal to the reference setpoint and then sends a corrective signal to the speed reference. The change in speed reference in turn causes a corrective signal to the actuator, which repositions the governor valve. The deadband in the cascade provides a window of stability which keeps the turbine from reacting to minute changes in exhaust pressure.

Unlike inlet-pressure control, exhaust-pressure control does not require an inverted signal. To increase the pressure at the exhaust the inlet valve must increase position, and vice-versa. As with inlet pressure, exhaust pressure can be incorporated with extraction-pressure control, providing the speed/load of the turbine is allowed to fluctuate in response to pressure control changes.

Driven Equipment/Process Parameters

Industrial steam turbines are often employed in mechanical-drive applications involving driven equipment such as pumps, compressors, blowers, fans, etc. In many of these cases the purpose of the driven equipment is to provide a flow of some liquid or gas in response to the demands of the process involved. The process itself has parameters that directly affect the production of the final product. Driven equipment and/or process control parameters are generally one of the following:

- Pressure/flow
- Temperature/heat
- Level
- Speed

Control of the turbine based on driven equipment or process parameters can be accomplished in one of two ways. First, those parameters that are directly related to turbine rotational speed can be controlled by adjusting the actuator output signal in the control system. This would generally be limited to output parameters of the driven equipment, such as discharge pressure or flow. In this case, the process control resides inside the turbine control along side the speed control function. Each receives an input signal, compares that to the reference setpoint, and generates an corrective output signal. The two controllers then compete for control of the actuator through a low signal selector (LSS). The lowest corrective signal from either controller is selected and used to position the actuator and steam valve.

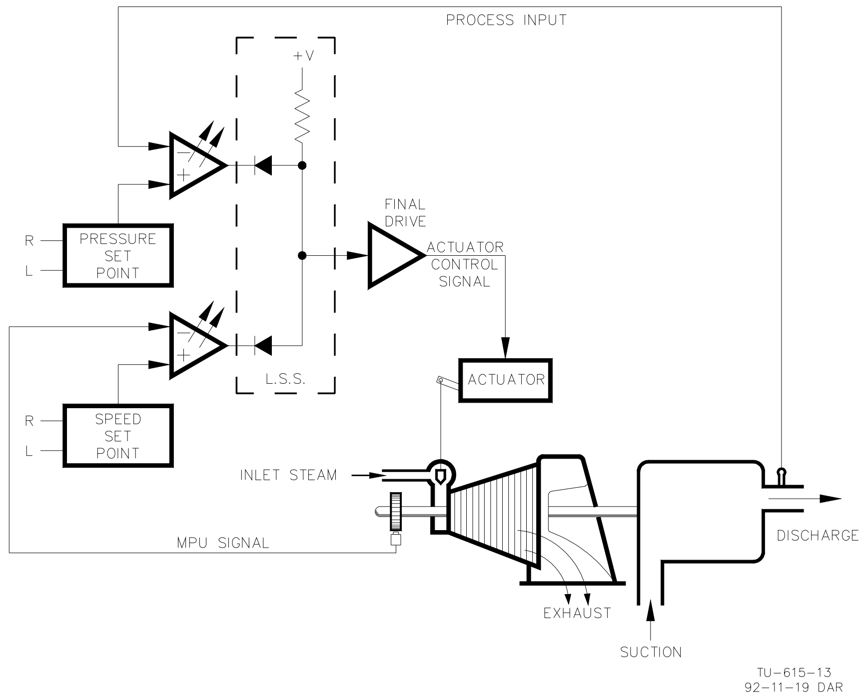

Figure 13. Low Signal Selector

The second option is to control the turbine speed via the remote speed setpoint. This is accomplished through a process controller or some remote control system that does the calculations and then sends a 4–20 mA corrective signal through the remote speed setpoint to adjust the speed reference. In this arrangement, all control algorithms relative to the process are external to the turbine control; the turbine control only receives the corrective speed signal. This type of arrangement is particularly common when the process is distanced from the turbine, or the turbine speed is indirectly related to the ultimate process under control.

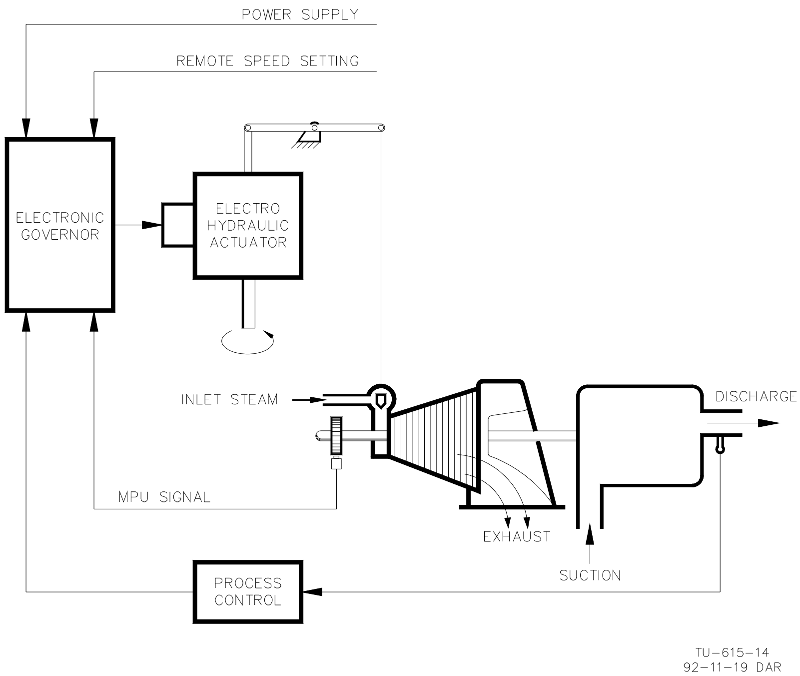

Figure 14.Remote-Process Control

Concluding Remarks

Industrial steam turbines offer a wide variety of control options to meet users' particular needs. The critical element in the success of a control is the development of clear understanding between the user and the control engineer.

If the control engineer understands the customer's requirements and plant operation, a control system can be developed to solve their problems and be cost-effective at the same time. The true test of any control system is whether it provides an effective solution and represents value-added to the customer. Value-added may be reduced downtime, improved operating efficiencies, reduced repairs or spares cost, etc. The bottom line is that value-added means better customer operation.

[Written by Ron Platz, Ph.D.]

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