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Automatic Control Systems

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CHAPTER 1

Introduction

1-1 INTRODUCTION

The objective of this chapter is to familiarize the reader with the following subjects:

1. What a control system is.
2. Why control systems are important.
3. What the basic components of a control system are.
4. Some examples of control system applications.
5. Why feedback is incorporated into most control systems.
6. Types of control systems.

One of the most commonly asked questions by a novice on control system is: What is a control system? To answer the question, we can cite that in our daily life there are numerous "objectives" that need to be accomplished. For instance, in the domestic domain, we need to regulate the temperature and humidity of homes and buildings for comfortable living. For transportation, we need to control the automobile and airplane to go from one point to another accurately and safely. Industrially, manufacturing processes contain numerous objectives for products that will satisfy the precision and cost-effectiveness requirements. A human being is capable of performing a wide range of tasks, including decision making. Some of these tasks, such as picking up objects and walking from one point to another, are commonly carried out in a routine fashion. Under certain conditions, some of these tasks are to be performed in the best possible way. For instance, an athlete running a 100-yard dash has the objective of running that distance in the shortest possible time. A marathon runner, on the other hand, not only must run the distance as quickly as possible, but in doing so, he or she must control the consumption of energy and devise the best strategy for the race. The means of achieving these "objectives" usually involve the use of control systems that implement certain control strategies.

• Control systems are in abundance in modern civilization.

In recent years, control systems have assumed an increasingly important role in the development and advancement of modern civilization and technology. Practically every aspect of our day-to-day activities is affected by some type of control systems. Control systems are found in abundance in all sectors of industry, such as quality control of manufactured products, automatic assembly line, machine-tool control, space technology and weapon systems, computer control, transportation systems, power systems, robotics, MicroElectroMechanical Systems (MEMS), nanotechnology, and many others. Even the control of inventory and social and economic systems may be approached from the theory of automatic control.

has forced manufacturers to design and test an entire system in a computer environment before a physical prototype is made. Design tools such as **MATLAB** and **Simulink** enable companies to design and test controllers for different components (e.g., suspension, ABS, steering, engines, flight control mechanisms, landing gear, and specialized devices) within the system and examine the behavior of the control system on the virtual prototype in real time. This allows the designers to change or adjust controller parameters online before the actual hardware is developed. Hardware in the loop terminology is a new approach of testing individual components by attaching them to the virtual and controller prototypes. Here the physical controller hardware is interfaced with the computer and replaces its mathematical model within the computer!

Steering Control of Automobile

As a simple example of the control system, as shown in Fig. 1-1, consider the steering control of an automobile. The direction of the two front wheels can be regarded as the controlled variable, or the output, y; the direction of the steering wheel is the actuating signal, or the input, u. The control system, or process in this case, is composed of the steering mechanism and the dynamics of the entire automobile. However, if the objective is to control the speed of the automobile, then the amount of pressure exerted on the accelerator is the actuating signal, and the vehicle speed is the controlled variable. As a whole, we can regard the simplified automobile control system as one with two inputs (steering and accelerator) and two outputs (heading and speed). In this case, the two controls and two outputs are independent of each other, but, there are systems for which the controls are coupled. Systems with more than one input and one output are called **multivariable systems**.

Idle-Speed Control of Automobile

As another example of a control system, we consider the idle-speed control of an automobile engine. The objective of such a control system is to maintain the engine idle speed at a relatively low value (for fuel economy) regardless of the applied engine loads (e.g., transmission, power steering, air conditioning). Without the idle-speed control, any sudden engine-load application would cause a drop in engine speed that might cause the engine to stall. Thus the main objectives of the idle-speed control system are (1) to eliminate or minimize the speed droop when engine loading is applied, and (2) to maintain the engine idle speed at a desired value. Figure 1-2 shows the block diagram of the idle-speed control system from the standpoint of inputs–system–outputs. In this case, the throttle angle α and the load torque T_L (due to the application of air conditioning, power steering,

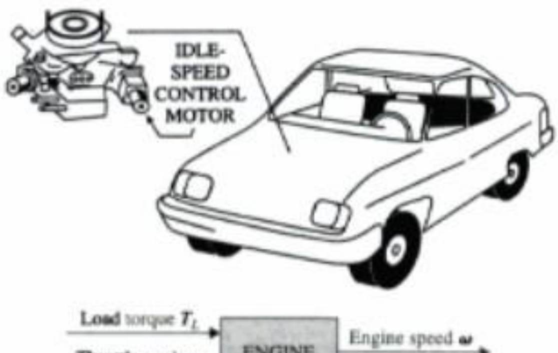

Figure 1-2 Idle-speed control system.

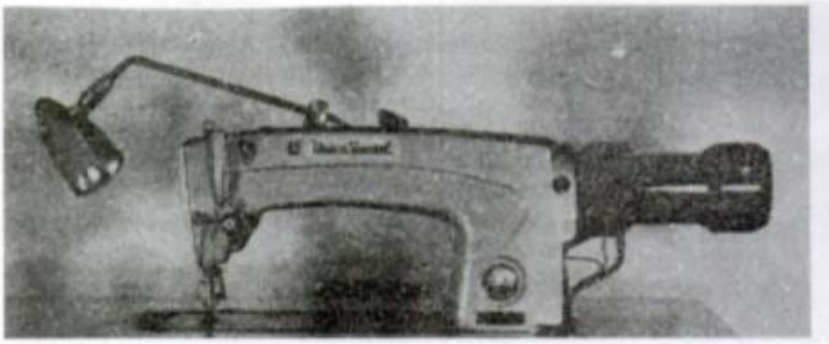

Figure 1-3 Industrial sewing machine.

transmission, or power brakes, etc.) are the inputs, and the engine speed ω is the output. The engine is the controlled process of the system.

Industrial Sewing Machine

Sewing, as the basic joining operation in a garment-making process, is in principle a rather complicated and laborious operation. For low cost and high productivity, the sewing industry has to rely on sophisticated sewing machines to increase the speed and accuracy of the sewing operations. Figure 1-3 shows a photograph of a typical industrial sewing machine, which, compared to household machines, is strictly a single-purpose, high-precision device. It can produce only one type of stitch, but is extremely fast, with a typical rate of over 100 stitches per second. One stitch corresponds to one revolution of the machine main shaft, which translates to top speeds of as high as 8000 rpm. An ideal velocity profile of one start-stop cycle of the machine is shown in Fig. 1-4. Typically, there

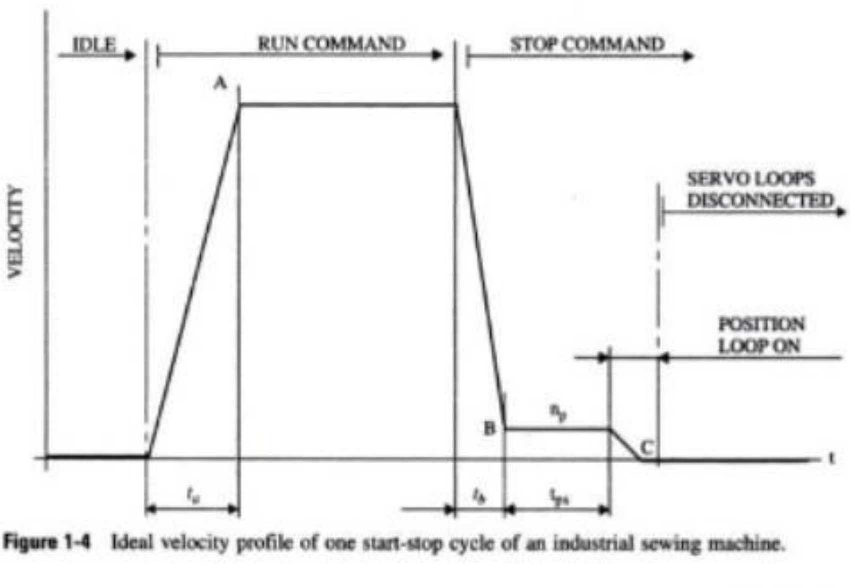

Figure 1-4 Ideal velocity profile of one start-stop cycle of an industrial sewing machine.

Figure 1-5 Solar collector field.

should be no velocity overshoot at point A and no undershoot at point B. Acceleration time t_a, deceleration time t_b, and position search time t_p, should be as short as possible. When the machine reaches the stopping point, C, there should be zero or negligible oscillations. To achieve these performance objectives, the control system in the machine should be designed with stringent requirements.

Sun-Tracking Control of Solar Collectors

To achieve the goal of development of economically feasible non-fossil-fuel electrical power, the U.S. government has sponsored many organizations in research and development of solar power conversion methods, including the solar-cell conversion techniques. In most of these systems, the need for high efficiencies dictates the use of devices for sun tracking. Figure 1-5 shows a solar collector field. Figure 1-6 shows a conceptual method of efficient water extraction using solar power. During the hours of daylight, the solar collector would produce electricity to pump water from the underground water table to a reservoir (perhaps on a nearby mountain or hill), and in the early morning hours, the water would be released into the irrigation system.

One of the most important features of the solar collector is that the collector dish must track the sun accurately. Therefore, the movement of the collector dish must be controlled by sophisticated control systems. The block diagram of Fig. 1-7 describes the general philosophy of the sun-tracking system together with some of the most important components. The basic philosophy of the control system is that a predetermined desired rate

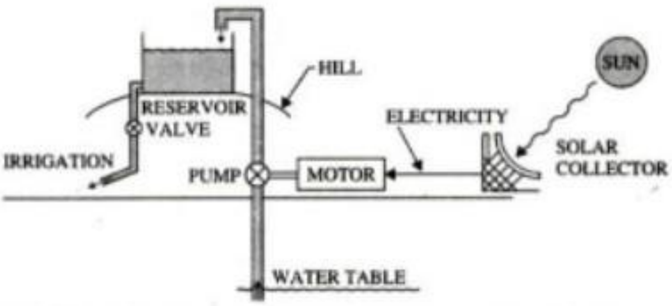

Figure 1-6 Conceptual method of efficient water extraction using solar power.

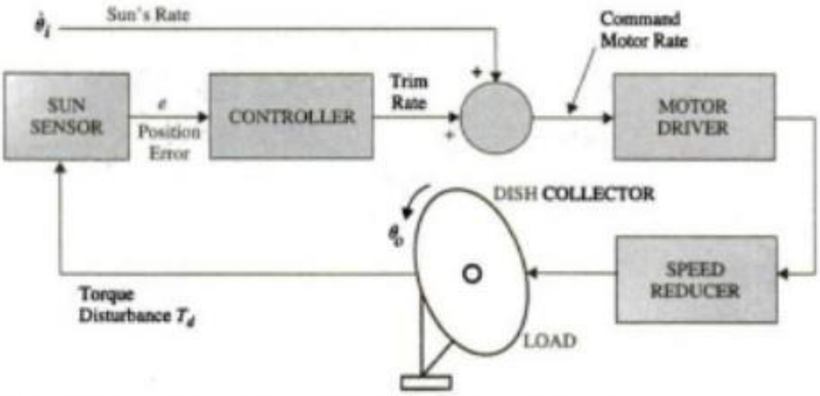

Figure 1-7 Important components of the sun-tracking control system.

is modified or trimmed by actual position errors determined by the sun sensor. The controller ensures that the tracking collector is pointed toward the sun in the morning and sends a "start track" command. The controller constantly calculates the sun's rate for the two axes (azimuth and elevation) of control during the day. The controller uses the sun rate and sun sensor information as inputs to generate proper motor commands to slew the collector.

1-1-3 Open-Loop Control Systems (Nonfeedback Systems)

• Open-loop systems are economical but usually inaccurate.

The idle-speed control system illustrated in Figs. 1-2 is rather unsophisticated and is called an **open-loop control system**. It is not difficult to see that the system as shown would not satisfactorily fulfill critical performance requirements. For instance, if the throttle angle α is set at a certain initial value that corresponds to a certain engine speed, then when a load torque T_L is then applied, there is no way to prevent a drop in the engine speed. The only way to make the system work is to have a means of adjusting α in response to a change in the load torque in order to maintain ω at the desired level. The conventional electric washing machine is another example of an open-loop control system because, typically, the amount of machine wash time is entirely determined by the judgment and estimation of the human operator.

The elements of an open-loop control system can usually be divided into two parts: the **controller** and the **controlled process**, as shown by the block diagram of Fig. 1-8. An input signal or command r is applied to the controller, whose output acts as the actuating signal u; the actuating signal then controls the controlled process so that the controlled variable y will perform according to some prescribed standards. In simple cases, the controller

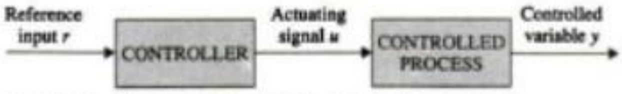

Figure 1-8 Elements of an open-loop control system.

the entire operating life of the system. For instance, the winding resistance of an electric motor changes as the temperature of the motor rises during operation. Control systems with electric components may not operate normally when first turned on, because of the still-changing system parameters during warmup. This phenomenon is sometimes called "morning sickness." Most duplicating machines have a warmup period during which time operation is blocked out when first turned on.

In general, a good control system should be very insensitive to parameter variations but sensitive to the input commands. We shall investigate what effect feedback has on sensitivity to parameter variations. Referring to the system in Fig. 1-11, we consider G to be a gain parameter that may vary. The sensitivity of the gain of the overall system M to the variation in G is defined as

$$S_G^M = \frac{\partial M/M}{\partial G/G} = \frac{\text{percentage change in } M}{\text{percentage change in } G} \tag{1-3}$$

• Note: Feedback can increase or decrease the sensitivity of a system.

where ∂M denotes the incremental change in M due to the incremental change in G, or ∂G. By using Eq. (1-1), the sensitivity function is written

$$S_G^M = \frac{\partial M}{\partial G}\frac{G}{M} = \frac{1}{1 + GH} \tag{1-4}$$

This relation shows that if GH is a positive constant, the magnitude of the sensitivity function can be made arbitrarily small by increasing GH, providing that the system remains stable. It is apparent that in an open-loop system, the gain of the system will respond in a one-to-one fashion to the variation in G (i.e., $S_G^M = 1$). Again, in practice, GH is a function of frequency; the magnitude of $1 + GH$ may be less than unity over some frequency ranges, so feedback could be harmful to the sensitivity to parameter variations in certain cases. In general, the sensitivity of the system gain of a feedback system to parameter variations depends on where the parameter is located. The reader can derive the sensitivity of the system in Fig. 1-11 due to the variation of H.

1-2-3 Effect of Feedback on External Disturbance or Noise

All physical systems are subject to some types of extraneous signals or noise during operation. Examples of these signals are thermal-noise voltage in electronic circuits and brush or commutator noise in electric motors. External disturbances, such as wind gusts acting on an antenna, are also quite common in control systems. Therefore, control systems should be designed so that they are insensitive to noise and disturbances and sensitive to input commands.

• Feedback can reduce the effect of noise.

The effect of feedback on noise and disturbance depends greatly on where these extraneous signals occur in the system. No general conclusions can be reached, but in many situations, *feedback can reduce the effect of noise and disturbance on system performance*. Let us refer to the system shown in Fig. 1-13, in which r denotes the command signal and n is the noise signal. In the absence of feedback, that is, $H = 0$, the output y due to n acting alone is

$$y = G_2 n \tag{1-5}$$

With the presence of feedback, the system output due to n acting alone is

$$y = \frac{G_2}{1 + G_1 G_2 H} n \tag{1-6}$$

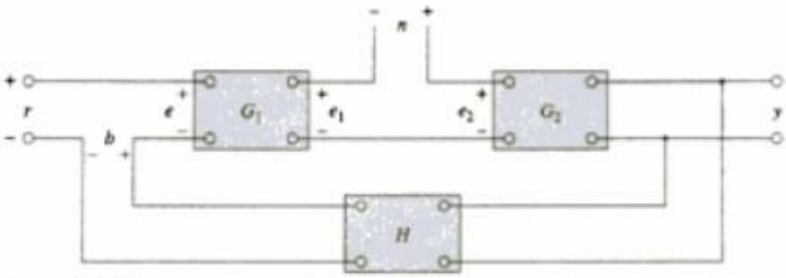

Figure 1-13 Feedback system with a noise signal.

• Feedback also can affect bandwidth, impedance, transient and frequency responses.

Comparing Eq. (1-6) with Eq. (1-5) shows that the noise component in the output of Eq. (1-6) is reduced by the factor $1 + G_1G_2H$ if the latter is greater than unity and the system is kept stable.

In Chapter 10 the feedforward and forward controller configurations are used along with feedback to reduce the effects of disturbance and noise inputs. In general, feedback also has effects on such performance characteristics as bandwidth, impedance, transient response, and frequency response. These effects will become known as we continue.

1-3 TYPES OF FEEDBACK CONTROL SYSTEMS

Feedback control systems may be classified in a number of ways, depending upon the purpose of the classification. For instance, according to the method of analysis and design, control systems are classified as **linear** or **nonlinear**, and **time-varying** or **time-invariant**. According to the types of signal found in the system, reference is often made to **continuous-data** or **discrete-data** systems, and **modulated** or **unmodulated** systems. Control systems are often classified according to the main purpose of the system. For instance, a **position-control system** and a **velocity-control system** control the output variables just as the names imply. In Chapter 7, the **type** of control system is defined according to the form of the open-loop transfer function. In general, there are many other ways of identifying control systems according to some special features of the system. It is important to know some of the more common ways of classifying control systems before embarking on the analysis and design of these systems.

1-3-1 Linear versus Nonlinear Control Systems

• Most real-life control systems have nonlinear characteristics to some extent.

This classification is made according to the methods of analysis and design. Strictly speaking, linear systems do not exist in practice, since all physical systems are nonlinear to some extent. Linear feedback control systems are idealized models fabricated by the analyst purely for the simplicity of analysis and design. When the magnitudes of signals in a control system are limited to ranges in which system components exhibit linear characteristics (i.e., the principle of superposition applies), the system is essentially linear. But when the magnitudes of signals are extended beyond the range of the linear operation, depending on the severity of the nonlinearity, the system should no longer be considered linear. For instance, amplifiers used in control systems often exhibit a saturation effect when their input signals become large; the magnetic field of a motor usually has saturation properties. Other common nonlinear effects found in control systems are the backlash or dead play between coupled gear members, nonlinear spring characteristics, nonlinear friction force or torque between moving members, and so on. Quite often, nonlinear characteristics are intentionally introduced in a control system to improve its performance or provide more effective control. For instance, to achieve minimum-time control, an on-off (bang-bang or relay) type controller is used in many missile or spacecraft control systems. Typically in these systems, jets are mounted on sides of the vehicle to provide reaction torque for attitude control. These jets are often controlled in a full-on or full-off fashion, so a fixed amount of air is applied from a given jet for a certain time period to control the attitude of the space vehicle.

• There are no general methods for solving a wide class of nonlinear systems.

For linear systems, a wealth of analytical and graphical techniques is available for design and analysis purposes. A majority of the material in this text is devoted to the analysis and design of linear systems. Nonlinear systems, on the other hand, are usually difficult to treat mathematically, and there are no general methods available for solving a wide class of nonlinear systems. It is practical to first design the controller based on the linear-system model by neglecting the nonlinearities of the system. The designed controller is then applied to the nonlinear system model for evaluation or redesign by computer simulation. The Virtual Lab introduced in Chapter 11 is mainly used to model the characteristics of practical systems with realistic physical components.

1-3-2 Time-Invariant versus Time-Varying Systems

When the parameters of a control system are stationary with respect to time during the operation of the system, the system is called a **time-invariant system**. In practice, most physical systems contain elements that drift or vary with time. For example, the winding resistance of an electric motor will vary when the motor is being first excited and its temperature is rising. Another example of a time-varying system is a guided-missile control system in which the mass of the missile decreases as the fuel on board is being consumed during flight. Although a time-varying system without nonlinearity is still a linear system, the analysis and design of this class of systems are usually much more complex than that of the linear **time-invariant systems**.

Continuous-Data Control Systems

A **continuous-data system** is one in which the signals at various parts of the system are all functions of the continuous time variable t. The signals in continuous-data systems may be further classified as ac or dc. Unlike the general definitions of ac and dc signals used in electrical engineering, **ac** and **dc control systems** carry special significance in control systems terminology. When one refers to an ac control system, it usually means that the signals in the system are *modulated* by some form of modulation scheme. On the other hand, when a dc control system is referred to, it does not mean that all the signals in the system are unidirectional; then there would be no corrective control movement. A **dc control system** simply implies that the signals are *unmodulated*, but they are still ac signals according to the conventional definition. The schematic diagram of a closed-loop dc control system is shown in Fig. 1-14. Typical waveforms of the signals in response to a step-function input are shown in the figure. Typical components of a dc control system are potentiometers, dc amplifiers, dc motors, dc tachometers, and so on.

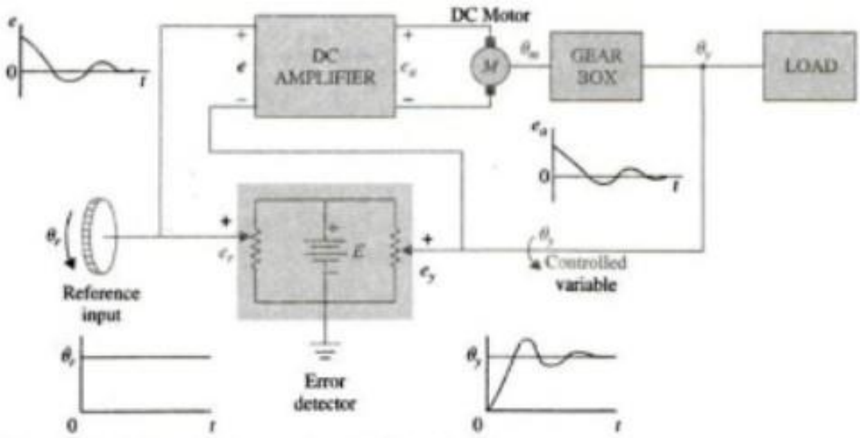

Figure 1-14 Schematic diagram of a typical dc closed-loop system.

Figure 1-15 shows the schematic diagram of a typical **ac control system** that performs essentially the same task as the dc system in Fig. 1-14. In this case, the signals in the system are modulated; that is, the information is transmitted by an ac carrier signal. Notice that the output controlled variable still behaves similarly to that of the dc system. In this case, the modulated signals are demodulated by the low-pass characteristics of the ac motor. Ac control systems are used extensively in aircraft and missile control systems in which noise and disturbance often create problems. By using modulated ac control systems with carrier frequencies of 400 Hz or higher, the system will be less susceptible to low-frequency noise. Typical components of an ac

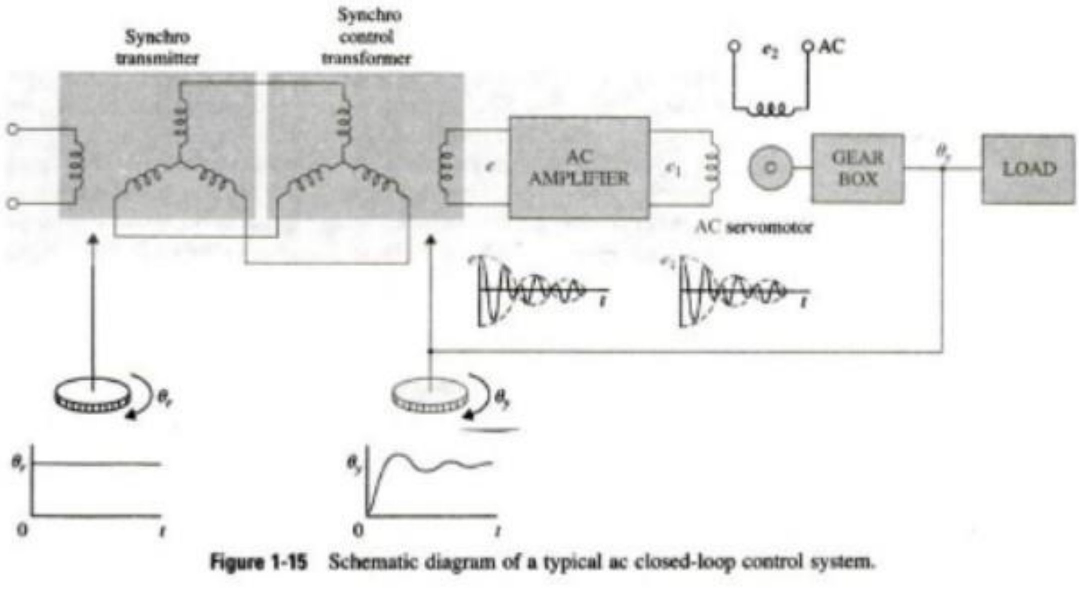

Figure 1-15 Schematic diagram of a typical ac closed-loop control system.