Control Engineering

Noel Morris

2nd edition

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Noel M. Morris

Principal Lecturer
North Staffordshire Polytechnic

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Control Engineering

Consulting Editor

M. R. WARD, B.Sc.(Eng.), C.Eng., F.I.E.E.

Vice-Principal

South East London Technical Colleg

Preface to the Second Edition

In this edition the opportunity has been taken to update the contents to keep abreast of developments in the field of control engineering. This edition covers the needs of a wide variety of courses in control engineering, including Part II and Part III of the City and Guilds of London Institute, the H.N.C. and H.N.D., the O.N.D. in Technology (Engineering), and the C and G Electronic and Electrical Craft Studies Course (Course 519). It also provides valuable background reading for many other courses.

The work on semiconductor devices and circuits has been completely revised and expanded. The additional work in chapter 13 on the operation and programming of digital computers reflects the trends in control engineering. Information on transducers, rewritten and expanded, is introduced in the form of an additional chapter at an early point in the book. The chapter on frequency response diagrams is extended to provide coverage of testing techniques and also of recording devices, and throughout the book valve circuits have been replaced either by semiconductor circuits or by operational amplifiers.

I have taken the opportunity to replace many of the problems in the book with more recent ones, and I express my thanks to the City and Guilds of London Institute for permission to reproduce their examination problems.

I am grateful to Mr F. W. Senior, M.Sc., for checking the manuscript, to Mr J. K. Davis, M.Sc., for constructive comments on the penultimate and final chapters, and to Mr L. A. Meredith, M.Inst. M.C., for his helpful suggestions. Once again, thanks are due to my wife for help and assistance in completing this edition.

I would also like to thank the McGraw-Hill reviewers for their valued assistance, and the production and editorial staff for maintaining the quality of the book.

N. M. MORRIS

Preface to the First Edition

The continued and explosive growth of industrial control engineering has prompted the author to write this book for both the practising engineer and the young technician. The mathematical level of the book has been regulated to allow the reader to obtain a grasp of the physical operation of systems rather than to present him with a number of advanced design tools. The author makes no apologies for limiting the mathematical level, since young men approaching the subject for the first time often find it clouded in abstract theory. The practising engineer is largely concerned with the installation and maintenance of control systems rather than with design principles.

The author has attempted to build up the book in a logical form, giving the background theory of devices before going on to consider specific systems in detail. The emphasis in the early parts of the book is on electrical and electronic techniques, since the majority of all systems employed today utilize them at some stage. Analogue and digital computing techniques are exerting considerable influence on control engineering, and each of these topics has a chapter devoted to it with special emphasis on its use in control systems.

Together with the growth of the study of control systems, special methods have been developed for the study of system stability. A chapter on frequency response diagrams has been included to give the reader background information to enable him to visualize the effects of various components on system stability. A simplified statement of Nyquist's stability criterion has been given in the chapter on frequency response diagrams, and this, together with the carefully regulated mathematical level, is an attempt to simplify the approach to the subject.

The general academic level of the book is that of the final and endorsement years of the electrical, mechanical, and instrumentation technicians' courses. While it is not possible to cover the whole range of all the courses in one book, the author has endeavoured to cover the ground common to them. A great deal of work common to the subjects of industrial electronics and electrical power equipment in the final and endorsement years of the electrical technicians' course will also be found between the covers of this book. The book will also appeal to undergraduate, H.N.D., and H.N.C. students in their final and penultimate years, in providing background information lacking in a course of formal lectures. A bibliography is provided at the back of the book for further reading.

Much of the information in this book has been gleaned from engineers in industry and other industrial sources. The author would particularly like to thank Messrs. Standard Telephones and Cables Ltd, Mullard Ltd, International General Electric Company of New York, and Newmarket Transistors Ltd for information on semiconductors. Iliffe Electrical Publications Ltd have kindly given the author permission to publish circuits based on articles in the *Wireless World* written by the author. The author is indebted to his colleagues at the North Staffordshire Polytechnic for the many profitable discussions he had with them which helped to clarify points arising during the preparation of the book; and to my wife for the valuable assistance she has rendered in checking and typing the manuscript.

I also wish to thank Dr W. E. Lewis, Deputy Director of the North Staffordshire Polytechnic, for

permission to publish examination questions from past H.N.D. and H.N.C. papers. The City and Guilds of London Institutes have kindly given the author permission to reproduce problems which have appeared in past examination papers; the responsibility for the accuracy of the solutions is solely the author's. A key to the examination papers referred to is given on page xiii.

Finally, the author would like to thank past students for their unwitting aid in guiding him in the presentation of his subject.

N. M. MORRIS

Key to Examination References

H.N.D.	Higher National Diploma in Electrical and Electronic Engineering.
H.N.C.	Higher National Certificate in Electrical and Electronic Engineering.
ET4	Electrical Technicians' Final Year.
ET5	Electrical Technicians' Endorsement Year.
C	Industrial Control Systems.
I	Instrumentation.
EPE	Electrical Power Equipment.
IE	Industrial Electronics.
TM(P)	Testing Methods (Power).
TM(E)	Testing Methods (Electronics).
G	Generation of Electrical Energy.
U	Utilization of Electrical Energy.
MET – C	Mechanical Engineering Technicians, Control Systems Technology.

Contents

1.

An Introduction to Control Engineering

1.1 Introduction

Man has transformed his world by his ability to control the other occupants of the planet. Progress was painfully slow at first, but was later accelerated by a series of stupendous discoveries. An early landmark was the wheel, a more modern example the transistor.

Countless civilizations have developed things we now regard as commonplace. The first faltering steps in electrical engineering have led to the gigantic power stations of today.

Elementary experiments in early laboratories have materially contributed to the present generation of electronic computers. The development of modern production techniques and theories have led directly to a state of control engineering where fully automatic factories can be contemplated.

There is a limit to the accuracy and speed at which a human operator can work. The problems associated with designing a machine or plant which will work automatically to provide consistent accuracy, finish, and production rate is a challenge to technicians and engineers alike. A control engineer must be a 'complete' engineer with a knowledge of electrical power plant, mechanical components, and electronic circuits. Above all, he must fully appreciate their effect in *closed-loop systems.*

1.2 Requirements of an Automatic Control System

Before any variable can be controlled accurately, it must first be measured. The device used to measure the output is generally known as a *trans-*

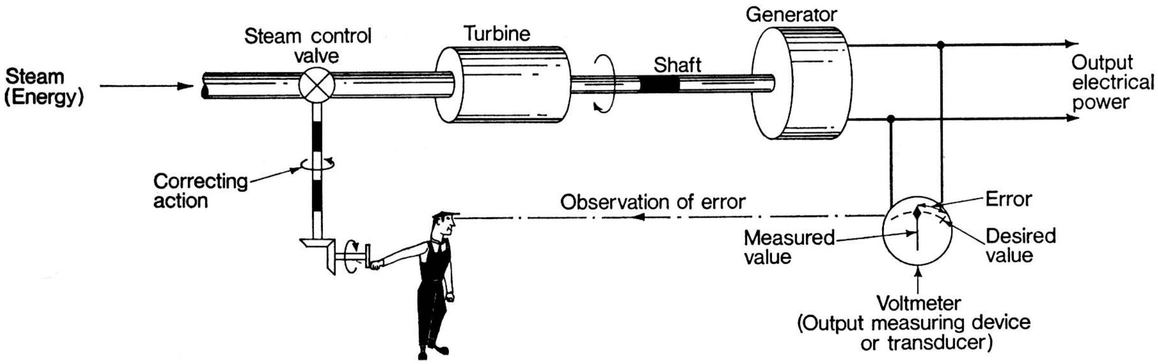

Fig. 1.1 Rudimentary control system.

ducer. [BS 1523 defines a transducer as a device for converting a signal or physical quantity of one kind into a corresponding physical quantity of another kind. A potentiometer is a transducer, being commonly used in position control systems to convert angular displacement (position of shaft) into an electrical voltage.]

In fact, any piece of equipment used to convert a signal of one kind into a signal of another kind is known as a transducer. Figure 1.1 shows a crude voltage regulator embodying the basic elements of a *closed-loop* or *closed-cycle* system. The figure shows a direct current generator which is driven by a steam turbine, its speed being controlled by a valve coupled to a handwheel. The output is measured by a voltmeter, and the operator notes visually the difference between the *measured* or *output value* and the *desired* or *reference value*. This difference is known as the *error* or *deviation*.

The operator acts on these data, and alters the steam control valve in such a manner as to *reduce the error to zero*. The output power may be many megawatts, but this is controlled by a human operator whose output power is only a fraction of a horsepower. To effect the desired control, the closed-loop system must therefore be capable of *amplifying signals*, this being more frequently referred to as *amplification*. Automatic control systems embody the principle of *negative feedback*, in which the measured value is subtracted from the reference value. Correcting action is taken, depending on the magnitude of the error and whether or not the measured value is less or greater than the desired figure, i.e., if the error is positive or negative.

An essential principle of any control system is that output is dependent on the control operation, i.e., the system is error actuated.

It is convenient to use a number of 'black boxes' to represent automatic systems, a *block diagram* of the elementary voltage regulator being shown in Fig. 1.2(*c*). The system is first reduced to the basic requirements:

(*a*) Output measurement (sometimes known as the *reset* signal).

(*b*) Input or reference signal (sometimes called the *set* signal).

(*c*) A means of comparing input and output signals (the *error detector*).

(*d*) The controller.

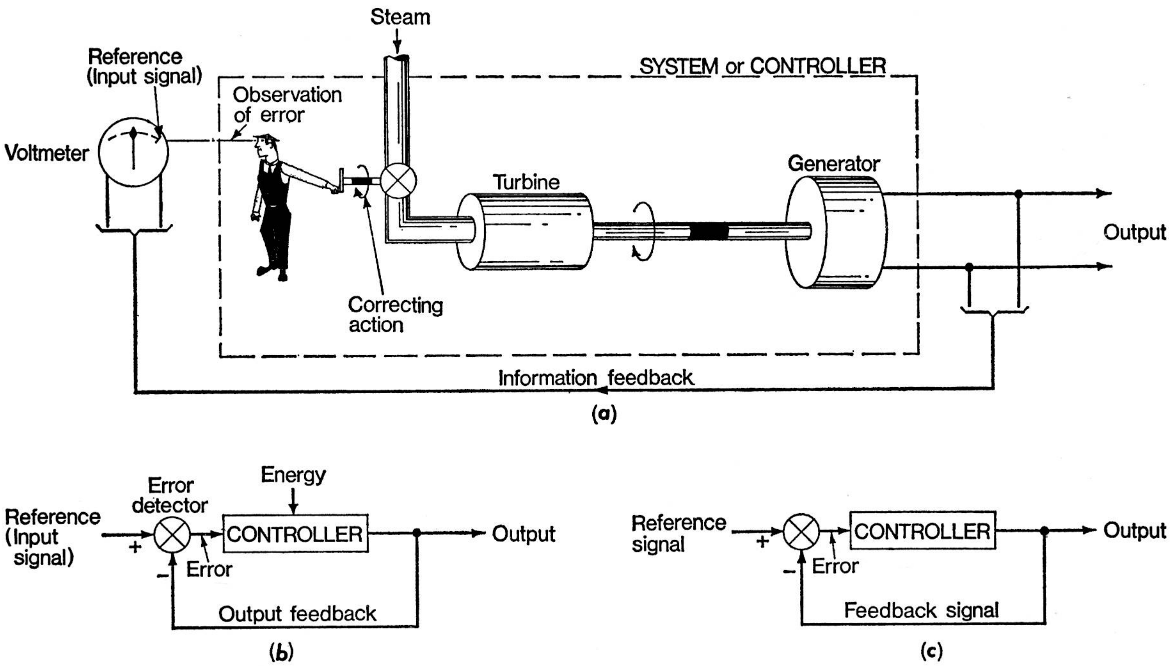

Fig. 1.2 (*a*) Shows a more convenient version of the rudimentary voltage regulator, which is reduced to its basic 'block' diagram in (*b*). A more conventional block diagram is shown in (*c*).

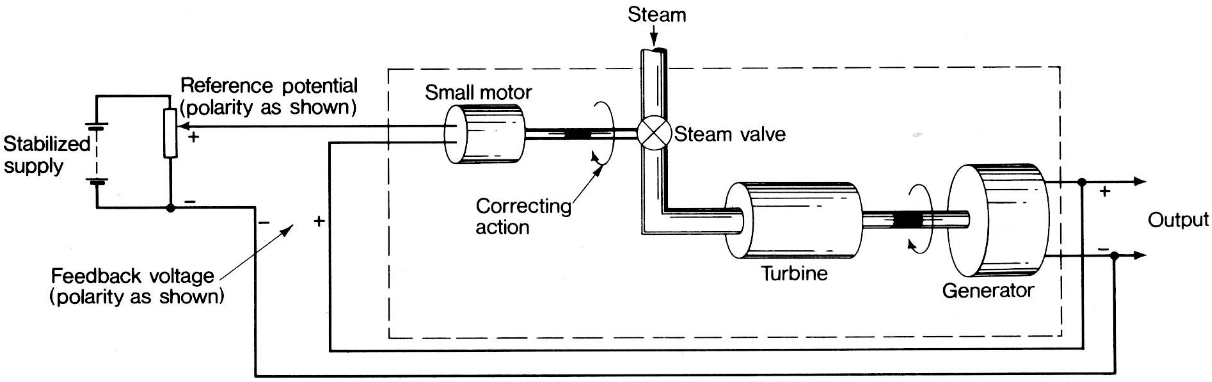

Fig. 1.3 A simple regulator with automatic error correction.

The operator must be included in the closed-loop, but in practical systems he would be replaced by an automatic error detecting and correcting device. One possible method is shown in Fig. 1.3. The operator is replaced by a stabilized source of power supply, a potentiometer, and a small motor. The input signal is now an electrical voltage, which is compared directly with the output signal. The error is no longer the difference between a pointer and a mark on a scale, but is a voltage. This is applied to a small electric motor, which drives the steam valve in such a direction to make the error zero. This is in essence a modern version of the James Watt governor.

In practice, systems are subject to both external and internal *disturbances*. A typical internal disturbance might be a sudden variation in steam pressure, which would cause the turbine to change speed and alter the output voltage. An external disturbance would be the sudden application or removal of a large electrical load. These and other random disturbances could occur simultaneously; but the regulating system would be required to produce a reasonably constant output irrespective of any variations. If the system was operated as an *open-loop* one, i.e., the output was not monitored and correcting action taken, all the random disturbances would produce unchecked variations in output voltage. With a closed-loop, negative feedback system, the output is monitored and correcting action applied to keep the output at its desired level. **It should be appreciated at this stage that while negative feedback has many merits, it cannot correct every defect of the system.**

Some applications require the use of *positive feedback*, in which the output signal is *added to* the input signal. In general, this has the opposite effect of negative feedback, and finds special application in magnetic amplifiers and where the output impedance of amplifiers has to be reduced. This is discussed in more detail in the appropriate sections.

1.3 Transfer Functions

The elementary system discussed above contained a turbine, a generator, a steam generating plant, and either a voltmeter and operator or a stabilized power supply, a potentiometer, and a motor. A full knowledge of each of these covers a whole range of technological subjects, and in combination represents a formidable task for any engineer or student to attempt. In order to simplify the problem, engineers have devised *transfer functions* for many items of plant. The transfer function of a section of a system gives an indication of how it will perform with different types of input signal; e.g., if a sinusoidal signal is applied, it gives an indication of the ratio of the magnitude of output to input (the *gain*) and the *phase-shift* (lag or lead). This knowledge is vital to correct operation when the plant is commissioned. At the design stage, the complete plant is usually simulated on a computer to see how it will perform, the design being based on the transfer functions of the elements involved.

It is difficult to obtain the transfer functions of some items of plant due to peculiar effects such as *saturation* and *hysteresis*. When an amplifier saturates (and they all do!), the output signal is unchanged even if the input is increased (Fig. 1.4),

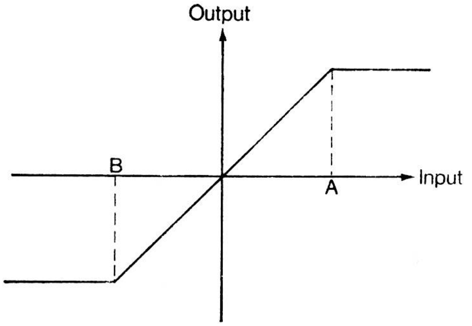

Fig. 1.4 Typical 'saturation' characteristic.

resulting in a *non-linear* characteristic for large values of input signal. [The output of a *linear device* is proportional to its input. Since most devices have some degree of non-linearity, the linear working range is often specified (AB in the case of Fig. 1.4).] Some mechanical components, gears for example, have an output–input characteristic not unlike the B–H curve of a magnetic circuit, and are said to produce hysteresis effects (Fig. 1.5). The latter characteristic results from the use of gears with teeth which are not in contact all the time.

These and other non-linear problems limit the application of 'linear' theory, to the extent that theoretical predictions and measured values may differ significantly. Electrical devices which produce an output in the form of pulses, square waves, rectified sine waves, etc., are difficult to deal with using simple transfer functions. Typical examples are mercury-arc convertors, thyristors, and magnetic amplifiers. Fortunately, many of these non-linear problems are masked by other properties of the system and it is often possible to use relatively simple techniques. The theoretical difficulties are

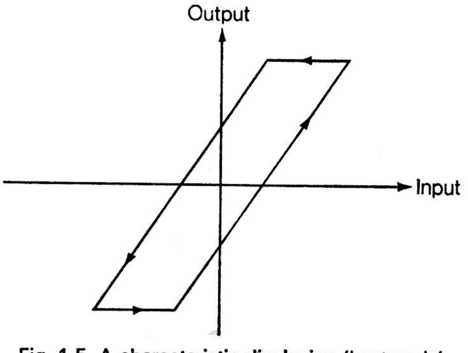

Fig. 1.5 A characteristic displaying 'hysteresis'.

outside the scope of this book, but it is not out of place to mention them here. Books for further reading on this topic are listed at the end of the book.

Equipment used in control systems ranges from small transducers with ratings of a few milliwatts to motors with ratings of several thousand horsepower, but it is possible that the performance of a small device may be similar to one many thousand times larger, if the ratio of output to input is considered. Thus, the concept of the transfer function is vital to control system engineering. Two units with identical forms of transfer functions are shown in Figs. 1.6 and 1.7, one an *R–C* circuit passing only a few milliamperes, the other a generator capable of dealing with many kilowatts.

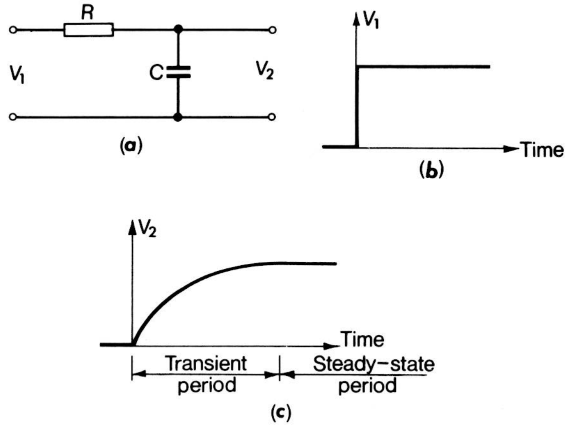

Fig. 1.6 (*a*) An electrical *R-C* circuit, showing its response in (*c*) to a step change in voltage (*b*).

The transfer function of an element is defined as the ratio of output to input, and on this basis it is possible to predict how it will perform, provided the transfer function is known. This procedure results in a quantitative analysis of the element; a similar result can be obtained more profitably in these two circuits using a simple qualitative approach.

If the voltage applied to the *R–C* circuit is increased from zero (Fig. 1.6(*b*)), the capacitor begins to charge, rapidly at first and then more slowly, until it reaches its final value (theoretically after infinite time). [In both Figs. 1.6 and 1.7, V_2 attains 99 per cent of its final value after a time corresponding to 4·6 times the time constant (product *CR* in Fig. 1.6

and ratio L/R in Fig. 1.7). In practice, a figure of 5 is commonly used.] At this time, the rate of rise of output voltage is zero and the capacitor is fully charged. If the voltage applied to the generator field, Fig. 1.7, is suddenly increased from zero, the field current rises exponentially due to the effect of inductance. The e.m.f. induced in the armature is proportional to the magnetic flux, and therefore the field current; hence the output voltage rises in the same manner as the field current, shown in Fig. 1.7(*c*).

Since the two circuits respond in a similar manner with the same form of input, it is reasonable to suppose that they have the same, or similar, transfer functions. In this case, a *step input* function was applied; a step input is defined as one which changes suddenly, theoretically in zero time, from one value to another. As the two circuits respond in like manner to one form of input, it is reasonable to suppose that they will behave in like fashions when subjected to other forms of input. For example, if a sinusoidal voltage is applied to the inputs of Figs. 1.6 and 1.7, V_2 will be sinusoidal, having an r.m.s. value less than V_1, and will lag behind it in time.

The time varying output of any system may be considered in two parts:

(*a*) The *transient* period.

(*b*) The *steady-state* period.

The transient period occurs immediately after switching on, the output changing in some manner

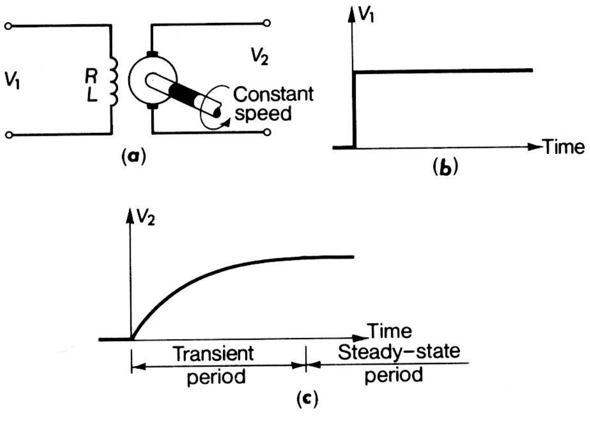

Fig. 1.7 The response of a d.c. generator (*a*) to a step change in input signal (*b*) is shown in (*c*). The networks in Figs. 1.6 and 1.7 have similar transfer functions.

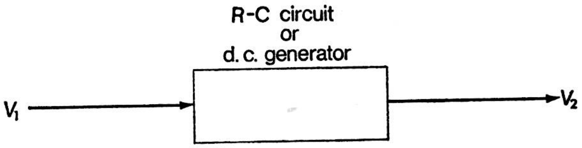

Fig. 1.8 Block diagram representation of either Figs. 1.6 or 1.7.

which is characteristic of the system; in the two cases considered above, the transient takes an exponential form. Under steady-state operating conditions the output has the same general form as the input, i.e., if the input is constant (a d.c. supply), the output is constant, if the input is sinusoidal, the output is sinusoidal. The limits of these periods are indicated in Figs. 1.6(*c*) and 1.7(*c*).

Using the block diagram notation developed in section 1.2, it is convenient to represent either the *R–C* circuit or the d.c. generator in a closed-loop system by the simple block shown in Fig. 1.8. Many other items of equipment have identical transfer functions and similar responses, and may be represented in the same fashion in a block diagram. One advantage from this similarity between circuits is that large items of equipment can readily be *simulated* in the laboratory without actually constructing them.

1.4 Types of System

Control systems may be broadly divided into two types:

(*a*) Regulators.

(*b*) Position controllers (servomechanisms).

Regulators are the most common group found in industry. Remote position controllers (r.p.c. servos), developed for military applications in the first instance, are now finding increasing application in industry (the machine tool industry in particular).

In most basic forms of regulators, e.g., speed, voltage, current, temperature, etc., a finite error exists when operating normally, i.e., under steady-state conditions. This is because power is required continuously to produce an output, thereby needing an error signal.

An example of this is illustrated in the speed regulator shown in Fig. 1.9, where 100 per cent negative feedback is applied (all the output signal