Automatic Control Systems and Applications in Digital Electronics

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Abstract
In our day to day life, all our tools and machines require control of work, otherwise it will be very difficult for us in finishing our daily tasks. Hence, automatic control systems are made to guide, instruct and regulate our tools and machines. Common controlling systems includes some electronic and computer supported systems with defined input, output and processing units.

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INTRODUCTION

Automatic control system analyze, design, and optimize systems that are integrated through coordination of mechanical, electrical, chemical, metallurgical and electronic elements. It deals with diverse range of dynamic systems which include interfacing by technological interferences. It also deals with the principle of control theory for designing desired and controlled behaving systems. The controlled variations are measured with a speed specified value with desired results. Hence, the price of energy, power and processing is reduced. And these systems do not require any manual control.

AUTOMATIC CONTROL AND SYSTEMS

Control system focuses on analysis and design of systems to improve the speed of response, accuracy and stability of system. The two methods of control system include classical methods and modern methods (Figure 1). The mathematical model of system is set up as first step followed by analysis, designing and testing. Necessary conditions for the stability are checked and finally optimization follows.

In classical method, mathematical modeling is usually done in time domain, frequency domain or complex s domain. Step response of a system is mathematically modeled in time domain differential analysis to find its settling time, % overshoot, etc. Laplace transforms are most commonly used in frequency domain to find the open loop gain, phase margin, band width etc. of system. Concept of transfer function, sampling of data, poles and zeros, system delays all come under the classical control engineering stream.

Fig. 1: *Configuration of a Control System.*

Modern control engineering deals with multiple input multiple output (MIMO) systems, State space approach, eigen values and vectors etc. Instead of transforming complex ordinary differential equations, modern approach converts higher order equations to first order differential equations and solved by vector method.

Historical Review of Control Engineering

The application of automatic control system is believed to be in use even from the ancient civilizations. Several types of water clocks were designed and implemented to measure the time accurately from the third century BC, by Greeks and Arabs. But the first automatic system is considered as the Watts Flyball Governor in 1788, which started the industrial revolution[1]. The mathematical modeling of Governor was analyzed by Maxwell in 1868. In 19th century, Leonhard Euler, Pierre Simon Laplace and Joseph Fourier developed different methods for mathematical modeling. The second system is considered as Al Butz's Damper Flapper-thermostat in 1885. He started the company now named as Honeywell.

The beginning of 20th century is known as the golden age of control engineering. During this time classical control methods were developed at the Bell Laboratory by Hendrik Wade Bode and Harry Nyquist. Automatic controllers for steering ships were developed by Minorsky, Russian American mathematician. He also introduced the concept of integral and derivative control in 1920s. Meanwhile the concept of stability was put forward by Nyquist and followed by Evans. The transforms were applied in control system by Oliver Heaviside. Modern control methods were developed after 1950s by Rudolf Kalman, to overcome the limitation of classical methods. PLC's were introduced in 1975.

Types of Control Engineering

Control engineering has its own categorization depending on the different methodologies used, which are as follows:

Classical Control Engineering

The systems are usually represented by using ordinary differential equations. In classical control engineering, these equations are transformed and analyzed in transformed domain. Laplace transform, Fourier transform and z transform are examples. This method is commonly used in single input single output systems[2].

Modern Control Engineering

In modern control engineering higher order differential equations are converted to first order differential equations. These equations are solved very similar to vector method. By doing so, many complications dealt in solving higher order differential equations are solved. These are applied in multiple input multiple output systems where analysis in frequency domain is not possible. Nonlinearities with multiple variables are solved by modern methodology. State space vectors, eigen values and eigen vectors belong to this category. State variables describe the input, output and system variables.

Robust Control Engineering

In robust control methodology, the changes in performance of system with change in parameters are measured for optimization. This aids in widening the stability and performance, also in finding alternate solutions. Hence, in robust control the environment, internal in accuracies, noises and disturbances are considered to reduce the fault in system.

Optimal Control Engineering

In optimal control engineering, the problem is formulated as mathematical model of process, physical constraints and performance constraints, to minimize the cost function. Thus, optimal control engineering is the most feasible solution for designing a system with minimum cost.

Adaptive Control Engineering

In adaptive control engineering, the controllers employed are adaptive controllers; in which parameters are made adaptive by some mechanism. The block diagram of Figure 2 is given below showing an adaptive control system.

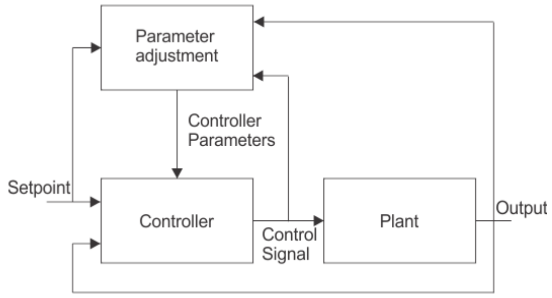

Fig. 2: *Configuration of an Adaptive Control System.*

In this kind of controllers an additional loop for parameter adjustment is present in addition to the normal feedback of process.

Nonlinear Control Engineering

Nonlinear control engineering focuses on the non-linearity's which cannot be represented by using linear ordinary differential equations. This system will exhibit multiple isolated equilibrium points, limit cycles, bifurcations with finite escape time. The main limitation is that it requires laborious mathematical analysis. In this analysis the system is divided into linear part and nonlinear part.

Game Theory

In game theory, each system will have to reduce its cost function against the disturbances/noises. Hence, it is a study of conflict and cooperation. The disturbances will try to maximize the cost function. This theory is related to robust and optimal control engineering.

THEORY OF SEMICONDUCTOR AND DIGITAL ELECTRONICS

The materials can be classified on the basis of energy gap between their valence band and conduction band. The valence band is the band consisting of free valence electron and the conduction band is empty band. Conduction takes place when an electron jumps from valence band to conduction band and the gap between these two bands is energy gap. Wider the gap between the bands, higher the energy it requires to shift the electron to conduction band[3].

In case of conductors, this energy gap is absent or in other words conduction band and valence band overlap each other. Thus electron requires minimum energy to jump from valence band, e.g. silver, copper and aluminum. In insulators, this gap is very large. Therefore, it requires large amount of energy to shift an electron from valence to conduction band. Semiconductors have energy gap in between conductors and insulators (~1 eV) and thus require energy more than conductors but less than insulators. They don't conduct electricity at low temperature but as temperature increases conductivity increases e.g. silicon and germanium. This is the most basic theory of semiconductor. The materials that are neither conductor nor insulator with energy gap of about 1 eV (electron volt) are called semiconductors. Most common type of materials that are used as semiconductors, are germanium (Ge) and silicon (Si) because of their

property to withstand high temperature. For Si and Ge energy gap is given as:
1. Eg=1.21–3.6X10–4T eV (for Si)
2. Eg=0.785–2.23X10–4T eV (for Ge)
Where, T=absolute temperature in °K
Assuming room temperature to be 300°K, Eg=0.72 eV for Ge and 1.1 eV for Si.

At room temperature resistivity of semiconductor is in between insulators and conductors[4]. Semiconductors show negative temperature coefficient of resistivity i.e. its resistance decreases with increase in temperature.

Both Si and Ge are elements of IV group i.e. both elements have four valence electrons. Both form covalent bond with neighboring atom. At absolute zero temperature both behave as insulator i.e. the valence band is full while conduction band is empty but as temperature is raised more and more covalent bonds break and electrons are set free and jump to conduction band (Figure 3).

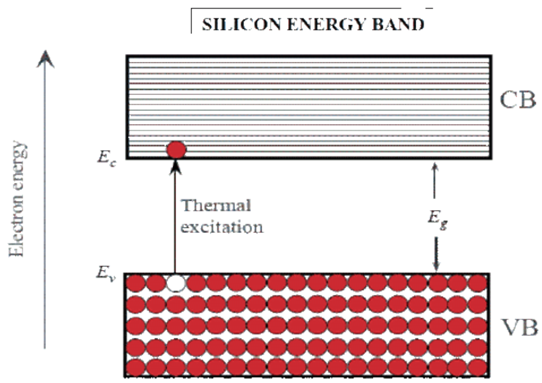

Fig. 3: *Energy Band Diagram of a Semiconductor.*

CB is the conduction band and VB is the valence band. At 0°K, the VB is full with all the valence electrons.

Intrinsic Semiconductors

As per theory of semiconductor, semiconductor in its pure form is called as intrinsic semiconductor. In pure semiconductor number of electrons (n) is equal to number of holes (p) and thus conductivity is very low as valence electrons are covalent bonded. In this case we write n=p=ni, where ni is called the intrinsic concentration (Figure 4). It can be shown that ni can be written as:
ni=n0T3/2 exp(–VG/2VT) Where, n0 is a constant, T is the absolute temperature, VG is the semiconductor band gap voltage, and VT is the thermal voltage.
The thermal voltage is related to the temperature by VT=kT/q
Where, k is the Boltzmann constant (k=1.381×10−23 J/K).

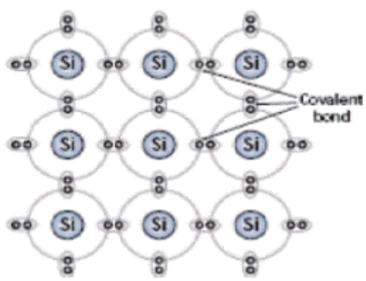

Fig. 4: *Intrinsic Semiconductors.*

In intrinsic semiconductors conductivity (σ) is determined by both electrons (σe) and holes (σh) and depends on the carrier density. σe=neμeσh=peh Conductivity, σ=σe+σh=neμe+peμh=Ne(μe+μh) Where n, p=numbers of electrons and holes respectively. μh, μe=mobility of free holes and electrons respectively N=n=pe=charge on carrier.

Extrinsic Semiconductors

As per theory of semiconductor, impure semiconductors are called extrinsic semiconductors. Extrinsic semiconductor is formed by adding a small amount of impurity[5]. Depending on the type of impurity added we have two types of semiconductors: N-type and P-type semiconductors. In 100 million parts of semiconductor one part of impurity is added.

N-Type Semiconductor

In this type of semiconductor majority carriers are electrons and minority carriers are holes. N-type semiconductor is formed by adding pentavalent (five valence electrons) impurity in pure semiconductor crystal, e.g. P, As, Sb.

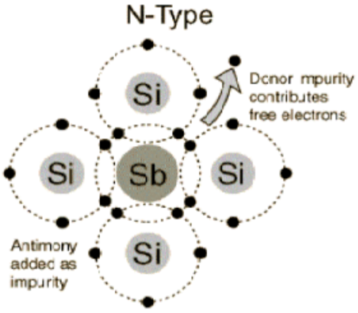

Fig. 5: *N-type Extrinsic Semiconductors.*

Four of the five valence electron of pentavalent impurity forms covalent bond with Si atom and the remaining electron is free to move anywhere within the crystal. Pentavalent impurity donates electron to Si that's why N-type impurity atoms are known as donor atoms (Figure 5). This enhances the conductivity of pure Si. Majority carriers are electrons therefore conductivity is due to these electrons only and is given by, σ=neμe.

P-Type Semiconductors

In this type of semiconductor majority carriers are holes and minority carriers are electrons. P-type semiconductor is formed by adding trivalent (three valence electrons) impurity in pure semiconductor crystal, e.g. B, Al, Ba.

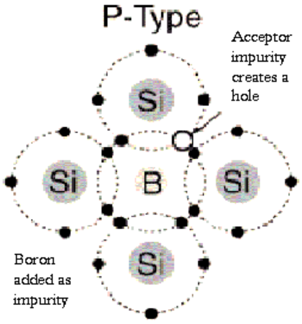

Fig. 6: *P-Type Extrinsic Semiconductors.*

Three of the four valence electron of tetravalent impurity forms covalent bond with Si atom. This leaves an empty space which is referred to as hole. When temperature is raised; electron from another covalent bond jumps to fill this empty space. This leaves a hole behind. In this way conduction takes place. P-type impurity accepts electron and is called acceptor atom (Figure 6). Majority carriers are holes and therefore conductivity is due to these holes only and is given by, $\sigma = ne\mu h$.

Digital Electronics

We know there are two types of signals, one is analog or continuous signal and the second one is digital or discrete signal. So the science or field of research in the area of engineering is termed as analog and digital electronics respectively[6]. Now coming to the area of digital electronics, it is essential to understand wide range of applications from industrial electronics to the fields of communication, from micro embedded systems to military equipment. The main and perhaps the most revolutionary advantage of digital electronics, is the decrease in size and the improvement in technology.

We have chosen to discuss various topics of digital electronics from the very fundamentals of this subject such as number systems, logic circuits going deep into those topics, like discussing various types of number systems, which we should use and how, inter relation among those number systems to the somewhat tougher concepts of digital electronics like TTL, PMOS- NMOS logic, flip flops etc. to get an idea about the whole subject.

All the topics of the related articles have been amply presented by diagrams, designs, tables and examples to make every topic understandable as much as possible. The topics are written in such a manner that if one goes through them he will grasp the very basic idea at first attempt and further reading will enhance the technical knowledge. Now let us inform you what we have included in the topics of digital electronics, as we have already discussed we have started from the very basic topics of digital electronics like number system. Then we have discussed the extension of number system like various types of number system, interrelation among different types of number systems making oneself absolutely comfortable with the fundamentals of number system[7]. Then we have enlightened the very important field of digital electronics i.e. binary arithmetic and Boolean algebra. And we have discussed about them in elaborated manner and from binary addition, binary subtraction, binary multiplication and binary division to the basics of Boolean algebra. After that we have written topics about various types of codes such as ASCII code, Gray Code, Hamming code which has made the input output format very easy. Then various types of logic gates (AND gate, OR gate, NOT gate, NAND gate, NOR gate, EX-OR gate) have been discussed in an elaborated manner with diagrams, explanations and truth tables to make each one of them very easy to understand. These may be classified as the fundamentals of digital electronics without which the subject cannot be understood at all. So after discussing about them we have gone deep into the subject. Topics like TTL, logic families, various MOS gates, Flip Flops (J-K, D, T etc.) have been discussed.

The sole purpose of introducing this subject in our electrical engineering website is because now days all the engineering streams are interrelated and the knowledge of digital electronics is very much essential for an electrical engineer and we have tried our best to make oneself familiar with the subject technically as much as possible.

THYRISTOR APPLICATION TYPES CONSTRUCTION PRINCIPLE OF THYRISTOR

A thyristor is normally four layer three-terminal device. Four layers are formed by alternating n-type and p-type semiconductor materials. Consequently there are three p-n junctions formed in the device. It is a bi-stable device. The three terminals of this device are called anode (A), cathode (K) and gate (G), respectively. The gate (G) terminal is control terminal of the device. That means, the current flowing through the device is controlled by electrical signal applied to the gate (G) terminal. The anode (A) and cathode (K) are the power terminals of the device handle the large applied voltage and conduct the major current through the thyristor. For example, when the device is connected in series with load circuit, the load current will flow through the device from anode (A) to cathode (K) but this load current will be controlled by the gate (G) signal applied to the device externally. A tyristor is on-off switch which is used to control output power of an electrical circuit by switching on and off the load circuit periodically in a preset interval. The main difference of thyristors with other digital and electronics switches is that, a thyristor can handle large current and can withstand large voltage, whereas other digital and electronic switches handle only tiny current and tiny voltage[8].

When positive potential applied to the anode with respect to the cathode, ideally no current will flow through the device and this condition is called forward blocking state but when appropriate gate signal is applied, a large forward anode current starts flowing, with a small anode-cathode potential drop and the device becomes in forward-conduction state. Although after removing the gate signal, the device will remain in its forward-conduction mode until the polarity of the load reverses. Some thyristors are also controllable in switching from forward-conduction back to a forward-blocking state[9].

Applications of Thyristor

As we already said that a thyristor is designed to handle large current and voltage, it is used mainly in electrical power circuit with system voltage more than 1 kV or currents more than 100 A. The main advantage of using thyristors as power control device is that as the power is controlled by periodic on-off switching operation hence (ideally) there is no internal power loss in the device for controlling power in output circuit. Thyristors are commonly used in some alternating power circuits to control alternating output power of the circuit to optimize internal power loss at the expense of switching speed.

In this case thyristors are turned from forward-blocking into forward-conducting state at some predetermined phase angle of the input sinusoidal anode-cathode voltage waveform. Thyristors are also very popularly used in inverter for converting direct power to alternating power of specified frequency. These are also used in converter to convert an alternating power into alternating power of different amplitude and frequency. This is the most common application of thyristor[10].

Types of Thyristors

There are four major types of thyristors: (i) Silicon Controlled Rectifier (SCR); (ii) Gate Turn-off Thyristor (GTO) and Integrated Gate Commutated Thyristor (IGCT); (iii) MOS-Controlled Thyristor (MCT) (iv) Static Induction Thyristor (SITh).

Basic Construction of Thyristor

A high resistive, n-base region, presents in every thyristor. As it is seen in the figure, this n-base region is associated with junction, J2. This must support the large applied forward voltages that occur when the switch is in its off- or forward-blocking state (non-conducting). This n-base region is typically doped with impurity phosphorous atoms at a concentration of 1013 to 1014 per cube centimeter. This region is typically made 10 to 100 micrometer thick to support large voltages. High-voltage thyristors are generally made by diffusing aluminum or gallium into both surfaces to create p-doped regions forming deep junctions with the n-base. The doping profile of the p-regions ranges from about 1015 to 1017 per cube centimeter. These p-regions can be up to tens of micrometer thick.

The cathode region (typically only a few micrometers thick) is formed by using phosphorous atoms at a doping density of 1017 to 1018 cube centimeter. For higher forward-blocking voltage rating of thyristor, the n-base region is made thicker. But thicker n- based high-resistive region slows down on off operation of the device. This is because of more stored charge during conduction. A device rated for forward blocking voltage of 1 kV will operate much more slowly than the thyristor rated for 100 V.

Thicker high-resistive region also causes larger forward voltage drop during conduction. Impurity atoms, such as platinum or gold, or electron irradiation are used to create charge-carrier recombination sites in the thyristor. The large number of recombination sites reduces the mean carrier lifetime (average time that an electron or hole moves through the Si before recombining with its opposite charge-carrier type). A reduced carrier lifetime shortens the switching times (in particular the turn-off or recovery time) at the expense of increasing the forward-conduction drop. There are other effects associated with the relative thickness and layout of the various regions that make up modern thyristors, but the major tradeoff between forward-blocking voltage rating and switching times and between forward-blocking voltage rating and forward-voltage drop during conduction should be kept in mind. (In signal-level electronics an analogous trade off appears as a lowering of amplification (gain) to achieve higher operating frequencies, and is often referred to as the gain-bandwidth product.)

Basic Operating Principle of Thyristor

Although there are different types of thyristors but basic operating principle of all thyristors is more or less same. The Figure 7 below represents a conceptual view of a typical thyristor. There are three p-n junctions J1, J2 and J3. There are also three terminals anode (A), cathode (K) and gate (G) as levelled in the figure. When the anode (A) is in higher potential with respect to the cathode, the junctions J1 and J3 are forward biased and J2 is reverse biased and the thyristor is in the forward blocking mode[11]. A thyristor can be considered as back to back connected two bipolar transistors. A p-n-p-n structure of thyristor can be represented by the p-n-p and n-p-n transistors, as shown in the figure.

Here in this device, the collector current of one transistor is used as base current of other transistor. When the device is in forward blocking mode if a hole current is injected through the gate (G) terminal, the device is triggered on.

When potential is applied in reverse direction, the thyristor behaves as a reverse biased diode. That means it blocks current to flow in revere direction. Considering ICO to be the leakage current of each transistor in cut-off condition, the anode current can be expressed in terms of gate current in Figure 7.

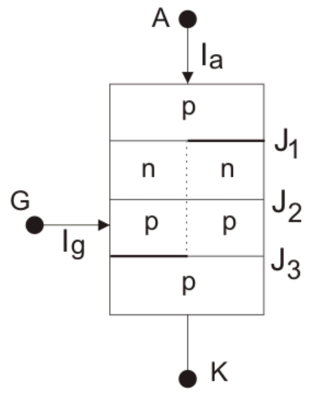

Fig. 7: *Operating of a Thyristor*.

Where α is the common base current gain of the transistor (α=IC/IE). The anode current becomes arbitrarily large as ($\alpha 1+\alpha 2$) approaches unity. As the anode-cathode voltage increases, the depletion region expands and reduces the neutral base width of the n1 and p2 regions. This causes a corresponding increase in α of the two transistors. If a positive gate current of sufficient magnitude is applied to the thyristor, a significant amount of electrons will be injected across the forward-biased junction, J3, into the base of the n1p2n2 transistor. The resulting collector current provides base current to the p1n1p2 transistor. The combination of the positive feedback connection of the npn and pnp BJTs and the current-dependent base transport factors eventually turn the thyristor on by regenerative action. Among the power semiconductor devices known, the thyristor shows the lowest forward voltage drop at large current densities. The large current flow between the anode and cathode maintains both transistors in saturation region, and gate control is lost once the thyristor latches on[12].

Transient Operation of Thyristor

A thyristor is not turned on as soon as the gate current is injected, there is one minimum time delay required for regenerative action. After this time delay, the anode current starts rising rapidly to on-state value. The rate of rising of anode current can only be limited by external current elements. The gate signal can only turn on the thyristor but it cannot turn off the device. It is turned off naturally when the anode current tends to flow in reverse direction during the reverse cycle of the alternating current. A thyristor exhibits turn-off reverse recovery characteristics just like a diode. Excess charge is removed once the current crosses zero and attains a negative value at a rate determined by external circuit elements. The reverse recovery peak is reached when either junction J1 or J3 becomes reverse biased. The reverse recovery current starts decaying, and the anode-cathode voltage rapidly attains its off-state value. Because of the finite time required for spreading or collecting the charge plasma during turn-on or turn-off stage, the maximum dI/dt and dV/dt that may be imposed across the device are limited in magnitude[13]. Further, device manufacturers specify a circuit-commutated recovery time, for the thyristor, which represents the minimum time for which the thyristor must remain in its reverse blocking mode before forward voltage is reapplied.

CONCLUSION

In designing a control system, one should consider factors such as its modes of input, process and output. Sometimes, a single control system may contain a number of systems, such as electrical driving systems, electronic control systems, mechanical systems, computer control programs, etc.

They are all known as sub-systems. Before designing the system, one must first study the relations between each sub-system and how they can be coordinated.

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