ANALOG ELECTRONICS DEVICES AND CIRCUITS (Revised Edition)

Book · October 2019

2 authors:

Bishnu Charan Sarkar
University of Burdwan

Suvra Sarkar
Burdwan Raj College

ANALOG ELECTRONICS
DEVICES AND CIRCUITS
(Revised Edition)

Bishnu Charan Sarkar
Retired Professor, Physics Department
Burdwan University
Burdwan-713104

Suvra Sarkar
Associate Professor, Electronics Department
Burdwan Raj College
Burdwan-713104

Damodar Group
2019

---- ----

Analog Electronics: Devices and Circuits [Revised Edition]

By Bishnu Charan Sarkar and Suvra Sarkar

Published on: October 8, 2019 (Bijaya Dashami)

ISBN: 978-93-85775-15-4

For distribution and marketing please contact authors

Price: Rs. 500.00

Printed & Published by
Damodar Group
54/1 Kachari Road
Burdwan-713101
West Bengal, India

To the beloved memories of our parents

Late Radhakinkar Sarkar and Late Niharbala Sarkar

Late Sunil Sarkar and Late Sandhyarani Sarkar

----- -----

PREFACE TO REVISED EDITION

The revised edition of the book, "*Analog Electronics: Devices and Circuits*", is now published. As its first edition, this one is also self-financed and limited number of copies is printed. In this edition, the book is thoroughly revised correcting typographical errors and redrawing most of the figures. Also it has been abridged to cover mainly the CBCS syllabus of the UGC for Physics and Electronic Science (Honours and Generic) courses. Moreover care has been taken to include additional materials to cater the needs of M Sc (Physics) students covering some of their Electronics course. It would be useful for BE and B Tech students studying basic courses on Analog Electronics. A good number of solved problems have been added in different chapters, some of them deal with advanced topics. New chapters on op amp design and filter theory are included. As before a collected set of objective questions, short explanatory questions and model question papers are given for self study.

We express our humble gratitude to the teachers from whom we learnt every bits of the subject. We are thankful to our students, well wishers and friends who extended active support in circulating the first edition of the book and hope they would continue their support. We acknowledge the discussions we had with Dr Tanmoy Banerjee, Physics department, Burdwan University, regarding the content of the book. Affectionate encouragement from our son Dr Debdeep Sarkar to take up this tiresome exercise of revision is fondly remembered.

Thanks are due to Damodar Group, Burdwan, publishers and printers of the book. We hope that the new book would be useful for the students as a text book and for others as a reference book.

October 8, 2019 (Bijaya Dashami) Bishnu Charan Sarkar
University Teachers Co-op Housing Suvra Sarkar
Plot - II
Krishnapur Road
Burdwan 713104
October, 2019

----- -----

SOME REFERENCE BOOKS

R L. Boylested and L Nashelsky, *Electronic Devices and Circuit Theory*, Prentice Hall, India, 2009.

A S Sedra and K C Smith, *Microelectronic Circuits Theory and Applications,* Oxford Univ Press, 2010.

B G Streetman and S K Banerjee, *Solid State Electronic Devices*, Prentice-Hall, India, 2006.

T H Lee, *The design of CMOS radio frequency Integrated circuits*, Cambridge Univ Press, 2002.

P Bhattacharya, *Semiconductor Optoelectronic Devices*, Prentice Hall, India, 1999.

J Millman and A Grabel, *Microelectronics: Digital and Analog Circuits and Systems,* McGraw-Hill International Student Edition, 1979.

J D Ryder, *Electronic Fundamentals and Applications,* , Prentice Hall, India, 1976.

D Roddy and J Coolen, *Electronic Communions,* Prentice-Hall, India, 2000.

K Leaver, *Microelectronic Devices*, Allied Publishers and World Scientific, 2003.

D K Roy*, Physics of Semiconductor Devices*, Universities Press, India, 2004.

H Taub, D L Schilling, G Saha, *Principles of Communication Systems,*Tata McGraw Hill, 2008.

J D Ryder, *Network works, Lines and Fields,* Prentice-Hall, India, 2007.

I S Gonorovsky, *Radio Circuits and Signals*, Mir Publishers, Moscow, 1997.

G J Deboo and C N Burrous, *Integrated Circuits and Semiconductor Devices,* Tata McGraw-Hill, 1995.

A K Maini and V Agrawal, *Electronic Devices and Circuits,* Wiley, 2015.

R A Gayakwad, Op amps and linear Integrated Technology, PHI Learning, 2002.

J G Proakis and D G Manolakis, *Digital Signal Processing : Principles, Algorithms and Applications*, Pearson, 2014

R E Collin, *Foundations for Microwave Engineering*, McGraw-Hill International Editions, 1966.

----- -----

CONTENTS

----- -----

----- -----

----- -----

Commonly used Physical Constants

Physical constant	Value	Unit
Velocity of light in free space, c	3×10^{8}	m/s
Planck's constant, h	6.63×10^{-34} 4.14×10^{-15}	J-s eV- s
Magnitude of electronic charge, e	1.60×10^{-19}	C
Rest mass of free electron, m_0	9.11×10^{-31}	kg
Boltzmann constant, k	1.38×10^{-23} 8.62×10^{-5}	J/K eV/K
Thermal energy at 300 K	0.0259	eV
Avogadro's number, N	6.02×10^{23}	Molecules/mole
Permittivity of free space, ϵ_0	8.85×10^{-12}	F/m
Permeability of free space, μ_0	$4\pi \times 10^{-7}$	H/m

----- -----

Landmarks in Electronic Technology

Year	Event
1864	Maxwell's field equations
1886	Hertz's experiment proved Maxwell's predictions
1897	Discovery of Electron by J J Thompson
1899	Self-recovering "coherer" by J C Bose; used in Marconi's experiment
1901	Marconi's radio telegraphy experiment
1901	J C Bose got patent for solid state detector
1905	Pickard reported a crystal detector; Fleming's vacuum diode
1906	Fessenden showed audio broadcasting ; L de forest invented triode
1912	E Armstrong designed regenerative amplifier using improved triode
1922	O Losev of Russia arguably invented solid state amplifier
1927	Negative feedback amplifier by H S Black
1945-46	Electronic computer ENIAC
1939-40	High power microwave tube, RADAR
1944	Fully electronic monochrome TV
1948	Transistor invention by Shockley, Bardeen and Brattain Bell Labs
1951	Commercial discrete transistor
1954	Patent granted for frequency modulation to E Armstrong
1953-54	NTSC Color television standard
1957-60	LASER; artificial satellite (Sputnik); MOS transistor; Integrated circuit; satellite repeater,
1943	Pulse code modulation (PCM) technique
1964-65	Logic circuits on silicon chip, G Moore's prediction
1967-69	Computer networks ARPANET made operational
1970	W S Boyle and G E Smith gave the idea of CCD at Bell labs
1970	Microprocessor designed in The Intel
1980	Personal computer of IBM launched; Analog mobile communication
1983	ARPANET adopts TCP/IP; birth of Internet;
1989	WWW invented at the CERN ; Came into public domain
1991 -01	Digital mobile communication (2G, 3G, 4G…) Pentium IV
Present decade	High-speed, low-power, huge-storage technology invention continues

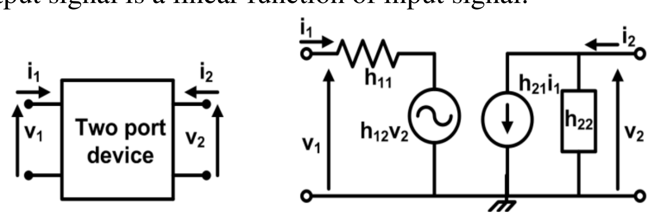
CHAPTER 8
GENERAL AMPLIFIER THEORY

Chapter outlines

Amplifiers as two port active networks; high frequency effect in amplifier model; negative resistance amplifiers; nonlinearity and distortion in amplifiers; effect of noise in amplifiers and noise figure.

8.1. Introduction

Electronic amplifiers are designed to amplify amplitude level or power level of electrical signals. Generally it is an active network comprising of input port and output port. The signal to be amplified is applied at the input port and the amplified signal is taken out from the output port. In general a linear amplifier circuit gives a magnified replica of the input signal. Note that the operation of such circuit must obey conservation of energy principle. So there must be some external source to provide additional energy obtained at output to validate "energy conservation principle". An additional source of energy, often called power supply, is used in an amplifier circuit. In our discussion here, for simplicity, we consider input and output signals as ac signals and applied power supply as a dc voltage source. However, amplification of dc voltage or current is also possible adopting special arrangements. Also in some special type of amplifiers (like, parametric amplifiers), ac power supplies are used. In amplifier circuits, output ac power is always less than or at best equal to the power of applied dc supply. Two parameters, gain and efficiency, are used to quantify the response of an amplifier. *Gain* is the ratio of output signal and input signal. *Efficiency* of an amplifier determines the ability of amplifier in converting dc energy into ac energy. To get higher efficiency, the output waveform is deliberately deformed in some amplifiers. At first, we consider linear amplifiers only where output signal is a linear function of input signal.



(a) (b)

Fig 8.1: (a) Block diagram of an amplifier as two port network (b) Equivalent circuit of the amplifier with i_1 and v_2 as independent variables

8.2. Amplifiers as two port active networks

The block diagram of a typical amplifier is shown in Fig 8.1(a). It is an active two port network (TPN), and is driven by a voltage source (VS) or current source (CS) at its input port. Looking into the circuit from output port, we can describe it as a dependent voltage source (DVS) or a dependent current source (DCS). Each of these sources may depend on input voltage or current. TPN representation of amplifier is a non-reciprocal type, i.e. response of the circuit is totally different if the output port and the input port are reversed. When this system is in dynamic condition, we consider four instantaneous electrical variables at any instant of time, two variables for input port and other two for output port. These are voltage and current obtained at respective ports. Instantaneous values of these variables are sum of their dc and ac values. DC values determine the operating condition of amplifier and these values are appropriately chosen to keep the circuit in active condition. AC values are taken small compared to respective dc values. This assumption is necessary for an ac amplifier. We discuss ac linear amplifier theory to begin with. Electrical variables of input port are denoted by v_1 and i_1 where they denote voltage and current respectively. Similarly v_2 and i_2 are variables for output port. We can take two of these four variables as independent at a time and express other two variables as linear combination of independent variables. This helps us to formulate a linear circuit model of amplifier. For example, let us choose input current i_1 and output voltage v_2 as independent variables. This choice leads to a very popular equivalent model of amplifier. We write v_1 and i_2 in terms of i_1 and v_2 as follows:

$$v_1 = h_{11}i_1 + h_{12}v_2 \qquad (8.1)$$

$$i_2 = h_{21}i_1 + h_{22}v_2 \qquad (8.2)$$

In these equations there are four parameters denoted by h_{11}, h_{12}, h_{21} and h_{22}. Note that, we use one voltage variable and one current variable as independent and parameters have different physical units. So we name these parameters as *hybrid or h-parameters*. These parameters are defined as follows:

$$h_{11} = (v_1/i_1)_{v_{2=0}} \quad (8.3a) \qquad h_{12} = (v_1/v_2)_{i_1=0} \quad (8.3b)$$

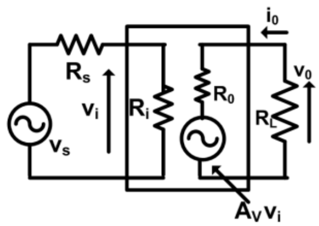
$$h_{21} = (i_2/i_1)_{v_{2=0}} \quad (8.3c) \qquad h_{22} = (i_2/v_2)_{i_1=0} \quad (8.3d)$$

Note that, zero value of ac voltage at a particular port means short circuited condition of the port; similarly zero value of ac current means open circuited condition of the port. In definitions given above, h_{11} and h_{21} are short circuit input resistance and open circuit voltage reverse feedback factor respectively. Similarly h_{12} and h_{22} are short circuit forward current gain and open circuit output admittance respectively.

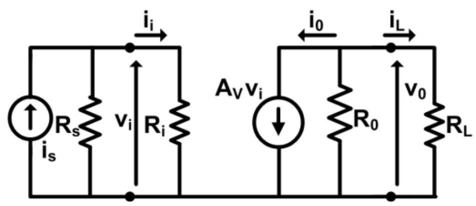
Circuit representation of (8.1) and (8.2) are given in Fig 8.1(b). It shows input port of amplifier is replaced by a DVS with input resistance in series with it. Output port is replaced by a DCS with output admittance in shunt with it. Equivalent representation of amplifiers can be made in a different way. The type of dependent source representing output port is primarily determined by output resistance of amplifiers. These equivalent dependent sources are controlled by concerned input signal sources. Again the choice of input sources is made considering input resistances of amplifier circuits. Thus we have four forms of output port, two as VSs and two as CSs. VSs are of values $A_v v_i$ or $R_m i_i$ and CSs are of values $A_i i_i$ or $G_m v_i$. Here, v_i and i_i are voltage and current at input port of the amplifier. Input port of an amplifier can be driven by a VS or a CS. If the input port offers very high resistance to applied signal source, then almost no current would flow into input port. Full source voltage would appear at input port. In that case we consider amplifier to be driven by a VS. In other extreme, if input resistance be very low, effective voltage between two terminals of input port would be almost zero and an appreciable current is injected into amplifier circuit from applied signal source. In that situation, we consider that the amplifier is driven by a CS. Ideal VS and ideal CS are characterized by their internal resistances. For ideal VS, source resistance is zero and for an ideal CS, source resistance is infinity. In practical situations, we take a small value as zero value and a very large value as infinity. Thus when we consider an amplifier as a VS, we take output resistance of amplifier as a small resistance appearing in series with the equivalent DVS. For current source representation of amplifier, output resistance is taken of large value appearing in shunt with equivalent DCS. With these considerations in mind, we discuss four classes of amplifiers.

8.3. Voltage amplifier

Fig 8.2(a) shows an amplifier considered as DVS driven by VS at input port. Here R_i and R_0 are the effective input resistance and output resistance of the amplifier respectively.



(a)



(b)

Fig 8.2: Representation of (a) voltage amplifier, (b) current amplifier

The voltage at input port is v_i and the voltage DVS (VDVS) at output port is $A_v v_i$, A_v is a parameter of the amplifier. We take R_s as source resistance of input VS v_s. We take output voltage v_0 across the load resistance R_L.

$v_i = (R_i/(R_i + R_s))v_s$ (8.4); $v_0 = -(R_L/(R_L + R_0))A_v v_i$ (8.5)

The output voltage v_0 is negative, because the output port current goes into the circuit. So v_0 is 180^0 output phase with respect to v_i. If v_s source be an ideal type then $R_s \to 0$ and $v_i = v_s$. Also for ideal VS representation of amplifier, the output port resistance $R_0 \to 0$. This makes

$$v_0 = -A_v v_i = -A_v v_s \qquad (8.6)$$

Hence, parameter A_v is – (v_0/v_s) and it is voltage gain (VG) of the amplifier. For practical circuits R_s has finite value; similarly R_0 would not be zero. However, the approximations made earlier are valid if $R_s \ll R_i$ and $R_0 \ll R_L$. Thus when R_i is large and R_0 is small, these conditions nearly satisfied and the amplifier is driven by a VS and the output port is replaced by a VDVS.

8.4. Current amplifier

The equivalent circuit of a current amplifier is shown in Fig 8.2(b). Here the input CS i_s has an internal resistance R_s. Also the current DCS (CDCS) at the output port is of magnitude $A_i i_i$ and it has output resistance R_0. In ideal case $R_i \to \infty$ and $R_0 \to \infty$. Applying KCL at the output node, we have $i_L = -i_0$. Moreover, in terms of $A_i i_i$ we write i_L and v_0 as,

$$i_L = (-A_i i_i)\,(R_0/(R_L + R_0)) \qquad (8.7)$$

$$v_0 = -(A_i i_i)\,(R_L R_0/(R_L + R_0)) \qquad (8.8)$$

In ideal case $R_0 \to \infty$ and so $i_L = (-A_i i_i)$ and $v_0 = -(R_L A_i i_i)$. These relations can also be written when $R_0 \gg R_L$. Similarly, we write input current and input voltage as $i_i = i_s(R_s/R_i + R_s))$ and v_i= $(R_s R_i/R_i + R_s))i_s$.For an ideal or nearly ideal input CS, $R_s \to \infty$ and $R_s \gg R_i$. These conditions give i_i=i_s and v_i=$R_i i_s = R_i i_i$. So we get current gain and voltage gain as,

$$(i_L/i_s) = ((-A_i i_i)/i_i) = -A_i \qquad (8.9)$$

$$(v_0/v_i) = -(R_L/R_i)A_i \qquad (8.10)$$

Negative sign in these expressions implies the phase reversal of output voltage with respect to input voltage.

8.5. Trans-conductance amplifier

Next, consider the amplifier as a DCS driven by a VS and this gives voltage DCS (VDCS). The equivalent circuit for such amplifier is given in Fig 8.3.

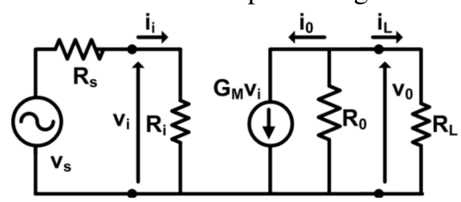


Fig 8.3: Representation of trans-conductance amplifier

The output CS is shown as $G_M v_i$. Then we write from basic circuit laws the expressions of input voltage, load current and output voltage as,

$$v_i = (R_i/(R_i + R_s))v_s \qquad (8.11)$$

$$i_L = -(R_0/(R_0 + R_L))G_M v_i \text{ (a)}; v_0 = -(R_0 R_L/(R_0 + R_L))G_M v_i \text{ (b)(8.12)}$$

For ideal situation, $R_s \to 0$ and $R_0 \to \infty$. Also in nearly ideal condition, $R_s \ll R_i$ and $R_0 \gg R_L$. These give, $v_i = v_s$; $i_L = -G_M v_i$. So we have a parameter G_M that connects output load current with input voltage of the amplifier.It has got dimension of conductance. So this amplifier is called *trans-conductance amplifier*. Moreover, the output voltage is, $v_0 = -G_M R_L v_i$. The voltage gain of trans-conductance amplifier is,

$$(v_0/v_s) = -G_M R_L \qquad (8.13)$$

This expression indicates that the gain of this amplifier is the product of the trans-conductance parameter and the load impedance.

8.6. Trans-resistance amplifier

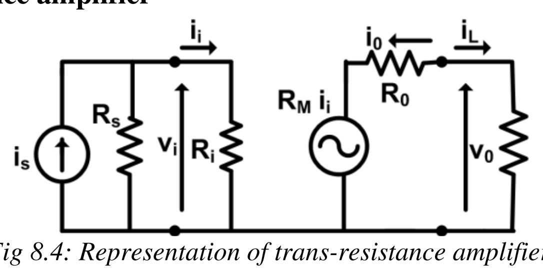


Fig 8.4: Representation of trans-resistance amplifier

Finally, we consider an amplifier which appears from output port as a DVS driven by a CS at input port. Output DVS is written as $R_M i_i$. Equivalent circuit for this amplifier is shown in Fig 8.4. Consideration of ideal type of sources is same as before i.e. $R_i \to 0$ and $R_0 \to \infty$. In practical circuit we get $R_s \gg R_i$ and $R_0 \ll R_L$. The input current and then input voltage are obtained.

$$i_i = (R_s/(R_i + R_s))i_s \quad (8.14); \quad v_i = (R_s R_i/(R_i + R_s))i_s \quad (8.15)$$

Using the conditions mentioned for this amplifier, we can get approximate relation $i_i = i_s$ and $v_i = R_i i_s = R_i i_i$. The relations for output port are, $i_L = -i_0$ and $i_0 = R_M i_i/(R_0 + R_L)$. So load current is $i_L = -R_M i_i/(R_0 + R_L)$ and output voltage is $v_0 = i_L R_L = -R_L R_M i_i/(R_0 + R_L)$. Applying the conditions of ideal source or practical source, we get $i_L = -R_M i_i/R_L$ and $v_0 = -(R_M i_i)$. Note that the parameter connecting output voltage with input current is R_M and it has got the dimension of resistance. So this amplifier is called trans-*resistance amplifier.* Voltage gain of the amplifier is $v_0/v_i = -R_M/R_i$ (8.16)
We summarize these properties in Table 8.1.

Table 8.1: Classification of Amplifiers

Sl no	Input driven by	Output port	Amplifier name
1.	Voltage signal, v_i	VDVS, v_0	Voltage, $v_0 = A_V v_i$
2.	Current signal i_i	CDCS, i_0	Current; $i_0 = A_I i_i$
3.	Voltage signal, v_i	VDVS, i_0	Trans-conductance; $i_0 = G_M v_i$
4.	Current signal, i_i	CDVS, v_0	Trans-resistance; $v_0 = R_M i_i$

The proportionality constants for four different types of amplifiers are called voltage gain (A_V), current gain (A_I), trans-conductance (G_M) and trans-resistance (R_M) respectively. Out of these, A_V and A_I are dimensionless quantities or numbers, but G_M and R_M have dimensions of conductance and resistance respectively. Amplifiers are treated as a VS or a CS when R_0 is zero or infinity respectively in ideal cases. In practical situation, relative magnitudes of R_0 and R_L determine the type of amplifier output variable, When, $R_0 << R_L$, the amplifier is considered as a VS but if $R_0 \gg R_L$, amplifier is a CS.

Table 8.2: Classification of amplifiers based on input and output resistances.

Sl no	Amplifier type	R_i and R_S	R_0 and R_L
1.	Voltage	R_i>>R_S	$R_0 \ll R_L$
2.	Current	$R_i \ll R_S$	$R_0 \gg R_L$
3.	Trans-conductance	R_i>>R_S	$R_0 \gg R_L$
4	Trans-resistance	$R_i \ll R_S$	$R_0 \ll R_L$

In Table 8.2, we have enlisted the relative magnitudes of R_i and R_0 of amplifier compared to R_0 and R_L respectively. Values of input and output resistance of an amplifier are to be obtained in dynamic condition of amplifier. Input resistance of an amplifier is defined as the ratio of input voltage measured at input port and injected current to input port. Thus, we write, $R_i = v_i/i_i$.

In an ideal amplifier, R_i is either zero or infinity. For a practical amplifier, R_i is of low or high magnitude depending on type of amplifier. Generally for BJT amplifiers, it is of low value and for MOSFET amplifiers it is of high value. in *absence of* R_L the value of R_0 can be obtained in the following way. First, R_L is removed from circuit and input excitation signal source is replaced by a short circuit.

Then, a voltage source v_x is applied at the output port. The current (i_x) going into the port is measured. In this situation the ratio of v_x and i_x is output resistance R_0 of amplifier, i.e. $R_0 = v_x/i_x$.We note that dependent voltage source considered at output port of amplifier is replaced by a short circuit when input excitation signal is zero. On the other hand, dependent current source at output port is replaced by an open circuit for zero input excitation signals. R_0 appears in series with dependent voltage source and ideally it is zero. For a dependent current source, R_0 appears in parallel to source and is infinity in ideal case. In practice, output resistance of amplifier is considered *in presence* of R_L.The effective value is denoted by R_{0E} and it is a parallel combination of R_0 and R_L.

8.7. Negative resistance amplifier

So far we have discussed amplifiers as active TPN. The devices used in these amplifiers are operated as externally controlled VS or CS when kept in proper biasing condition. There is a different class of amplifiers where active devices operate as negative resistive components under proper biasing. These are called negative resistance amplifiers (NRA). Since positive resistances consume power, it is expected that a negative resistance is capable of generating power.

Tunnel diode (TD) is one such device. Its volt current-voltage characteristic and ac equivalent circuit are shown in Fig 4.8(a) and Fig 4.10 of chapter 4. In Fig 4.10 R_S , L_S and C represent lead resistance and lead inductance and diode capacitance respectively. In simplified model we may ignore the effects of lead inductance and lead resistance at the operating frequency of the amplifier.

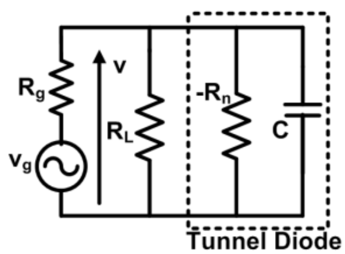


Fig 8.5: The equivalent circuit of tunnel diode based amplifier

The equivalent circuit of tunnel diode based NRA is shown in Fig 8.5. Here, an input signal source v_g of internal resistance R_g is connected with the load R_L and resistive equivalent of the TD. The diode is biased in the NDR region and at the operating point it offers an NDR taken as $-|R_n|$. We assume power gain of the amplifier as A_P and the voltage across the load as v. The power output across the load R_L is written as P_0 where $P_0 = (v^2/R_L)$ (8.17)

Thus power taken from input source P_i and power across the diode P_D are,

$$P_i = (P_0/A_P) = (v^2/A_P R_L) \qquad (8.18)$$

$$P_D = -(v^2/|R_n|) \qquad (8.19)$$

So we can write using principle of conservation of power $P_i = P_0 + P_D$

$$(v^2/A_P R_L) = (v^2/R_L) - (v^2/|R_n|) \qquad (8.20)$$

$$(1/A_P R_L) = ((|R_n| - R_L)/|R_n| R_L) \qquad (8.21)$$

Thus the power gain of the amplifier is obtained as

$$A_P = (|R_n|/(|R_n| - R_L)) \qquad (8.22)$$

This relation indicates that large power gain can be obtained at the load R_L when its magnitude is close to $|R_n|$ but less than that. From the above discussion we get that signal amplification is possible with a one port device which is properly biased and enhanced power is obtained from the source used to keep the device in proper bias condition.

8. 8. Effect of nonlinearity in amplifiers

When output voltage (v_0) of an amplifier is a nonlinear function of input voltage (v_i), the amplifier is called a nonlinear amplifier. Generally, v_0 is written as a polynomial function of v_i as given below.

$$v_0 = k_0 + k_1 v_i + k_2 {v_i}^2 + k_3 {v_i}^3 + \cdots \quad (8.23)$$

Here k_i's are constants determining the property of the amplifier. The nonlinear response of an amplifier can have different origins. It can be dc supply voltage dependent limiting type nonlinearity or circuit and device parameter dependent nonlinearity. Since v_0 of an amplifier would be within dc supply voltage level, one can have v_0 up to a level dependent on supply voltage. This nonlinearity would takes place for higher values of v_i. Again, when we use nonlinear circuit elements like diodes, transistors etc in an amplifier, the gain of the amplifier becomes dependent on the effective applied voltage level across those elements. In that case we have circuit element dependent nonlinearity. Finally, all electronic devices are inherently nonlinear in their response to external excitation. Keeping the level of excitation low, one can have linear response of the device. But as excitation level becomes high, one gets nonlinear response of the device. This results into device dependent nonlinearity of an amplifier. For simple amplifiers, nonlinearity is treated as disturbance by a circuit designer. It causes change in the waveform and output of the amplifier is not a faithful reproduction of the input signal. However, nonlinearity of an amplifier has several positive effects. Many applications of electronic circuits are not possible using linear amplifiers only. We briefly discuss some applications of nonlinear amplifiers (NLAs).

Changing of the shape of a given waveform from one type to the other is necessary in several applications and in such cases, NLAs are only solution. To get square wave or saw tooth wave, for example, from sinusoidal waveform, we use NLAs. In mathematical operations on electrical signals one often requires logarithm or antilogarithm of a given signal. Similarly, to have trigonometric functions of a given signal is necessary for signal processing applications. All these operations are done using different nonlinear amplifiers. A special group of amplifiers called operational amplifiers have been designed to perform such nonlinear operations on signals. We have discussed such applications of operational amplifiers as NLAs in a proper chapter.

Linear amplifiers are used to increase the amplitude level of a given signal. But suppose we have to multiply the frequency of a signal by a given factor. In that case NLA is only solution. Let v_0 be a quadratic function of v_i for a particular NLA i.e., we have $v_0 = K{v_i}^2$. If a signal of frequency f be applied to this amplifier we could get a signal of frequency 2f from this NLA. In this application NLA is being used as a "frequency multiplier"; besides the NLA, we have to use tuned circuit having centre frequency 2f at the output of NLA. To get multiplying factor as *n* in place of 2, we require an NLA having *n*-th degree of nonlinearity. In that case we take $v_0 =$

Kv_i^n and a tune circuit whose centre frequency is tuned at frequency nf. Frequency multipliers have many applications in signal processing. Again we consider that two sinusoidal signals of different frequencies say f_1 and f_2 are simultaneously applied to an NLA having quadratic transfer function. In that case we get a group of signals of frequencies $2f_1$, $2f_2$, (f_1+f_2), (f_1-f_2) besides a dc signal and signals having frequencies f_1 and f_2. Applying suitable frequency selective network at the output of the amplifier, we can extract different groups of signals having new frequencies. This feature of an NLA is applied in the design of frequency mixers, modulators, demodulators etc. These circuits are widely used in electronic communication systems and so importance of NLAs is easily understood.

In power amplifiers basic intension is to convert dc power of the supply voltage into useful ac power. In these circuits conversion efficiency of dc power to ac power is most important. To achieve this goal, output signal waveforms are deliberately deformed. The design principle of class B, class C, class D type of power amplifiers is very common example in this respect. Consider the case of class C amplifier where output signal is obtained during a fraction of half cycle of the input signal period. The active device used in the amplifier remains in non- conducting state during most of the signal period and in the absence of output signal the loss of dc power is minimized. This gives higher efficiency of the amplifier. Using suitable frequency selective load for the amplifier in this group of amplifiers we get full signal output. This is the principle of efficient power amplifier in simple words. We have elaborately discussed theory and technique of power amplifier in a suitable chapter. We thus observe that power amplifiers of high efficiency are special type of NLAs.

Nonlinearity of amplifiers due to inherent nonlinear response of active devices provides the basis of self-sustained oscillations in oscillator circuits. In a self-oscillator building up of oscillation starts from very small amplitude noise signals and this requires a gain element in the form of an amplifier. But the gain of the amplifier must be a function of input signal appearing at its input and for larger input the gain should decrease to provide a finite amplitude oscillation. Thus the amplifier used in an oscillator must be nonlinear type. Besides this amplitude limiting feature NLA-based oscillators shown several interesting phenomena. Frequency synchronization is one such phenomenon where an oscillator gets synchronized to an injected signal applied to it. During synchronized state, the driven oscillator follows the frequency and phase of the driving signal of very low amplitude. This physical phenomenon has been applied to design lock-in amplifiers, tracking filters, synchronous modulators and detectors etc. Synchronous communication system is developed around nonlinear oscillators and amplifiers. Using the nonlinearity of an electronic system, we can design several hardware models of several physical events of nonlinear dynamics like bifurcation and chaos. For this reason NLAs have attracted the interest of researchers of different branches of knowledge.

8.9. Noise in an amplifier and Noise Figure

In any electronic circuit, presence of noise is inevitable. This is an unwanted signal. It arises due to random fluctuations of charge carriers in circuit components due to thermal agitation. Noise in a component is expressed in terms of absolute temperature of the said component. The noise voltage is always present in an electronic circuit at nonzero temperature of operation. We know that electrons present on a conductor or in a cavity wall are always in random thermal motion. In macroscopic time scale there is no drift current in any direction due to these moving electrons. But in microscopic time scale one observes fluctuating currents in conductors with non-zero average value. This current produces a fluctuating voltage drop across any resistive component. Since this voltage is random in time domain, its frequency domain representation would have all possible frequency components of equal power. This is the characteristics of white noise spectrum.

The overall effects of different noise sources in an electronic system are generally specified by means of noise figure (NF) of the circuit. There are different ways of defining NF. In our discussion we define it for a linear TPN in the following way. For this purpose we take a standard noise source as reference. This noise source is considered to have a bandwidth (BW) B and it is kept at normal temperature T $(300\ K)$. Thus we have the available noise power from this source kTB where k is Boltzman's constant (1.381×10^{-23} joules per Kelvin). Suppose S_i and S_0 are the signal powers at the input and the output of the TPN respectively and we take N_0 as the available noise power at the output. Taking $N_i = kTB$ as the input noise power we write input signal-to-noise ratio (SNR) (S_i/N_i) and output (S_0/N_0) . Then NF in dB of the TPN is defined as "ten times of the logarithm of the ratio of input SNR to output SNR". Thus,

$$\mathrm{NF, dB\ in} = 10\log_{10}\frac{(\mathrm{S_i/N_i})}{(\mathrm{S_0/N_0})} = 10\log_{10}(\mathrm{N_0/GN_i}) \qquad (8.24)$$

We put G as the power gain of the TPN. The noise performance of an amplifier can be given in terms of NF defined above. Applying intuitive argument we write output noise of the amplifier N_0 as

$$N_0 = GN_i + N_{inh} \qquad (8.25)$$

The inherent noise of the amplifier is often expressed in terms of *noise temperature* T_n. It is the absolute temperature of a matched load at the input of the amplifier that would produce noise power N_{inh} at its output when the amplifier itself is considered to be an ideal system (i.e. it does not produce any noise itself). In that case we write, $N_{inh} = GkT_nB$. For the amplifier, we take the standard noise source mentioned earlier as the same matched load applied at the input of the real amplifier at room temperature 300 K. So, $N_i = 300kB$. Using these values for N_0 and N_i we get NF of a practical amplifier as

$$\mathrm{NF, dB} = 10\log_{10}(1 + (\mathrm{T_n}/300)) \qquad (8.26)$$

Also we use the parameter T_n i.e. noise temperature of the amplifier defined in terms of NF, dB as

$$\mathrm{T_n} = 300[10^{0.1\mathrm{NF}} - 1]\ \mathrm{Kelvin} \qquad (8.27)$$

Solved problems

SP8.1. An amplifier with gain $10\ dB$ *has noise figure* $7\ dB$*. If its input signal power and input noise power are respectively* $5.8\mu W$ *and* $1.6\mu W$ *then calculate output noise power, output signal power and output signal to noise ration in* dB*.*

Solution: We know Noise figure $NF = 10\log_{10}(\mathrm{F})$. Here noise factor $F = (SNR)_i/(SNR)_0$

Given, Input signal power $(S_i) = 5.8\mu W$, Input noise power $(N_i) = 1.6\mu W$, $NF = 7\ dB$ and for amplifier gain (G), $10\log_{10}(\mathrm{G}) = 10\ dB$. Then using given data, $F = 5.01$, $(SNR)_i = S_i/N_i = 3.625$, $(SNR)_0 = (SNR)_i/F = 0.72355$, $(SNR)_{0dB} = -1.4\ dB$. Using $F = N_0/GN_i$ One get output noise power as $N_0 = 80.16\mu W$ and output signal power as $S_0 = 57.884\mu W$

SP8.2. In a three stage cascade amplifier individual gain of 1st stage, 2nd stage and 3rd stage are respectively $7\ dB$, $10\ dB$ *and* $15\ dB$, *corresponding noise factors are* $3\ dB$, $7\ dB$ *and* $10\ dB$. *Find out the total noise factor of the cascaded amplifier.*

Solution: We know Noise figure $NF = 10\log_{10}(\mathrm{F})$. Here F is noise factor. Then for the1st stage, 2nd stage and 3rd stage the value of noise factors are $F_1 = 2$, $F_2 = 5.01, F_3 = 10$. If G_1 is the gain of 1st stage of the amplifier then $10\log_{10}G_1 = 7\ dB$, So $G_1 = 5.01$. Similarly for 2nd and 3rd stage $G_2 = 10$, $G_3 = 31.227$

According to Friiss' formula, total noise factor of the cascaded amplifier is

$$F_T = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/G_1G_2 + \ldots.$$

So using above values $F_T = 2.98036$

Important points

From the output port amplifiers can be treated as dependent voltage or current sources. The amplifier can be driven by a voltage source or current source.

There are four different types of amplifiers: voltage, current, trans-conductance and trans-resistance types.

Negative feedback has important role in the response of a generalized amplifier.

Nonlinearity in amplifiers has important role in several applications. Modulators, demodulators, frequency multipliers, power amplifiers, synchronizers etc are examples of such applications.

Exercise

Review Questions

R8.1.A trans-conductance amplifier is driven by a voltage source and it drives current to the load at the output port-Justify the statement.

R8.2.How do we model a general amplifier in the high frequency operation? What is Miller effect?

R8.3. What is gain-frequency figure of merit in an amplifier? Show that it is nearly constant for a typical amplifier and it depends on device parameters.

R8.4.What is negative resistance amplifier? Obtain an expression for power gain of a Tunnel diode based negative resistance amplifier.

R8.5. What do you mean by a nonlinear amplifier? Mention a few applications of a nonlinear amplifier.

R8.6. Show that amplitude modulators could be designed using a special class of nonlinear amplifiers.

R8.7. Define noise-figure of a typical amplifier.

Problem

1. Calculate noise temperature of an amplifier. Given its input signal to noise ratio and the output signal to noise ratio are 5.88 dB and 2.87 dB respectively.

----- -----

About the book

This book is a text-book on Analog Electronics according to the UGC CBCS syllabus on B.Sc. (Honours and Generic) in Physics and Electronic Science and a part of Electronics course of M Sc syllabus in Physics. It presents semiconductor device physics and solid state electronic circuits. Some relevant advanced topics are discussed as solved problems. Review questions and numerical problems are included in each chapter. A set of objective questions (MCQ) and model question papers are given for the benefit of the students. Chapters on integrated circuit design, filter design are included in this revised second edition of the book.

About the authors

Prof. Bishnu Charan Sarkar (Retd) had served Physics department, Burdwan University for nearly 38 years. He was Head of the Department, In-charge of Electronics section and Coordinator of M Tech in ECE (Microwave) program. He was the Dean of Science of the University. He has a long research experience and has published more than 200 technical papers in different journals and conference proceedings.. He also supervised PhD works of 15 students. He has written or edited 7 technical books and contributed 4 book chapters (Springer, Nova Publishers)

Dr. (Mrs.) Suvra Sarkar completed her B.Sc. and M.Sc. courses from the University of Burdwan securing University Gold Medals in both cases. She received her PhD degree from the same university. She was a CSIR research associate. Till date she has published more than 60 technical papers and co-authored one book chapter (Springer). Her teaching experience is more than 20 years and currently she is Associate Professor and Head of the Department of Electronics, Burdwan Raj College.