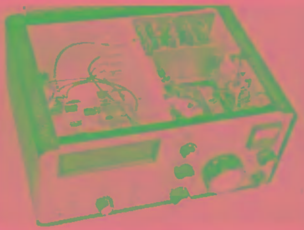
The Radio Amateur's Handbook

The Standard Manual of Amateur Radio Communication



$6.00 in the U.S.A.

1976

PUBLISHED BY THE AMERICAN RADIO RELAY LEAGUE

The Radio Amateur's Handbook

By the HEADQUARTERS STAFF

of the

AMERICAN RADIO RELAY LEAGUE

NEWINGTON, CONN., U.S.A. 06111

Editor
Robert Myers, W1FBY

Assistant Editors:
Tony Dorbuck, W1YNC
Gerald Hall, K1PLP
George Hart, W1NJM
Lewis McCoy, W1ICP
Thomas McMullen, W1SL

1976

Fifty-Third Edition

Library of Congress Catalog Card Number: 41-3345
Fifty-Third Edition

$6.00 in the U.S.A. and Possessions, $7.00 in Canada,
$8.00 elsewhere.
Clothbound edition $10.00 U.S.A., $11.00 Possessions
and Canada,
$12.00 elsewhere.

FOREWORD

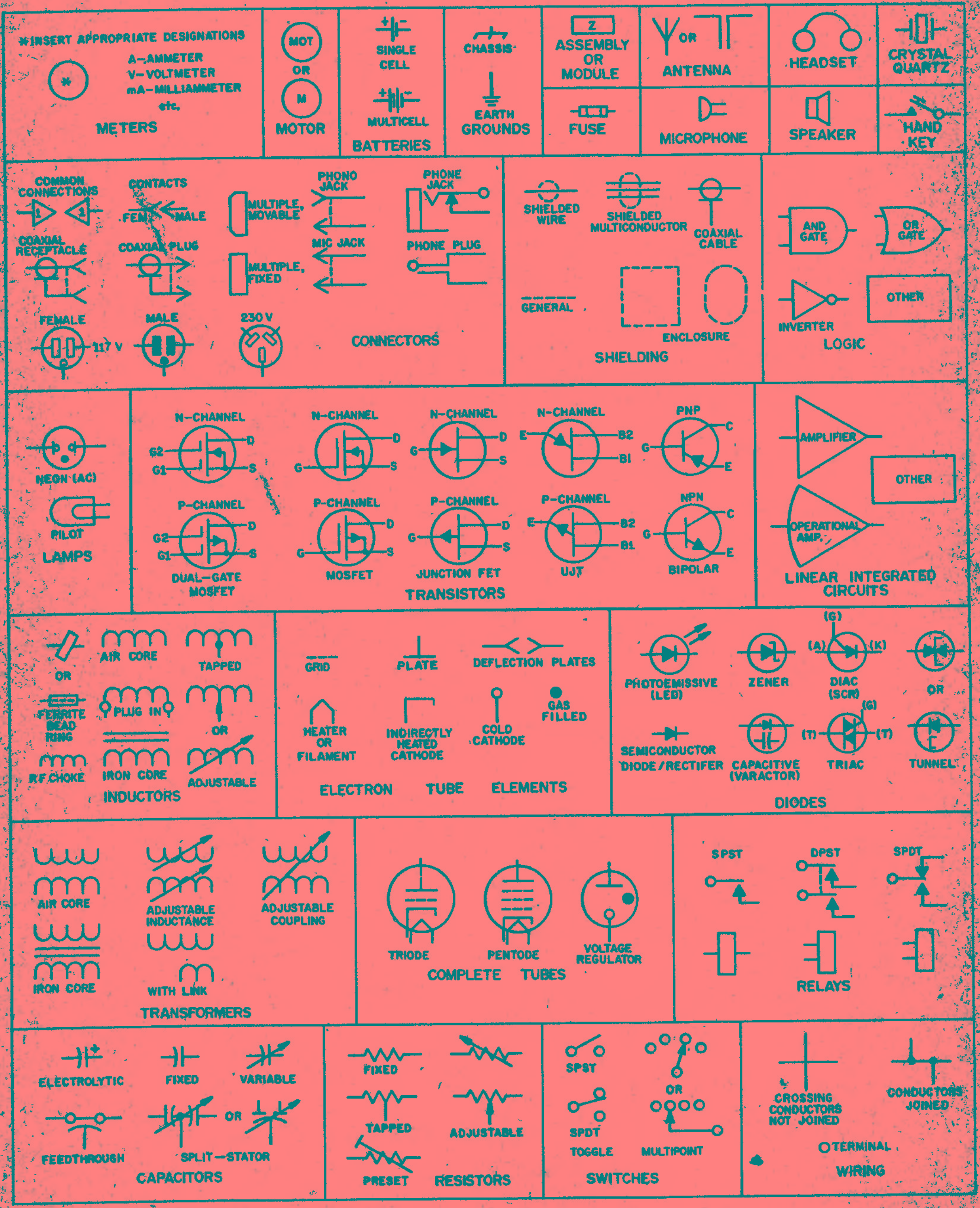
The *Radio Amateur's Handbook* has long been a staple of the radio amateur's library. Since it was first published in 1925, nearly five million copies have been distributed, putting it near the top of the all-time best seller list. It has achieved that distinguished record because it is a practical, useful manual. Its continuing purpose is to present the necessary fundamentals, as well as changing technology and applications, to serve the varied interests of the experimenter, the home builder, the DXer, the contester, and the ragchewer.

The present volume is the product of the efforts and the skills of many talented amateurs. We hope you will find it of value in the pursuit of your goals and your interests.

RICHARD L. BALDWIN, W1RU
General Manager

Newington, Conn.
November, 1975

SCHEMATIC SYMBOLS USED IN CIRCUIT DIAGRAMS



CONTENTS

The Amateur's Code

ONE

The Amateur is considerate . . .He never knowingly uses the air in such a way as to lessen the pleasure of others.

TWO

The Amateur is Loyal . . .He offers his loyalty, encouragement and support to his fellow radio amateurs, his local club and to the American Radio Relay League, through which amateur radio is represented.

THREE

The Amateur is Progressive . . .He keeps his station abreast of science. It is well built and efficient. His operating practice is above reproach.

FOUR

The Amateur is Friendly . . .Slow and patient sending when requested, friendly advice and counsel to the beginner, kindly assistance, cooperation and consideration for the interests of others; these are marks of the amateur spirit.

FIVE

The Amateur is Balanced . . .Radio is his hobby. He never allows it to interfere with any of the duties he owes to his home, his job, his school, or his community.

SIX

The Amateur is Patriotic . . . His knowledge and his station are always ready for the service of his country and his community.

– PAUL M. SEGAL

Chapter 1

Amateur Radio

Amateur radio is a scientific hobby, a means of gaining personal skill in the fascinating art of electronics and an opportunity to communicate with fellow citizens by private short-wave radio. Scattered over the globe are over 700,000 amateur radio operators who perform a service defined in international law as one of "self-training, intercommunication and technical investigations carried on by . . . duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest."

From a humble beginning at the turn of the century, amateur radio has grown to become an established institution. Today the American followers of amateur radio number over 250,000, trained communicators from whose ranks will come the professional communications specialists and executives of tomorrow – just as many of today's radio leaders were first attracted to radio by their early interest in amateur radio communication. A powerful and prosperous organization now provides a bond between amateurs and protects their interests; an internationally respected magazine is published solely for their benefit. The military services seek the cooperation of the amateur in developing communications reserves. Amateur radio supports a manufacturing industry which, by the very demands of amateurs for the latest and best equipment, is always up-to-date in its designs and production techniques – in itself a national asset. Amateurs have won the gratitude of the nation for their heroic performances in times of natural disaster; traditional amateur skills in emergency communication are also the stand-by system for the nation's civil defense. Amateur radio is, indeed, a magnificently useful institution.

Although as old as the art of radio itself, amateur radio did not always enjoy such prestige. Its first enthusiasts were private citizens of an experimental turn of mind whose imaginations went wild when Marconi first proved that messages actually could be sent by wireless. They set about learning enough about the new scientific marvel to build homemade spark transmitters. By 1912 there were numerous Government and commercial stations, and hundreds of amateurs; regulation was needed, so laws, licenses and wavelength specifications appeared. There was then no amateur organization nor spokesman. The official viewpoint toward amateurs was something like this:

"Amateurs? . . . Oh, yes . . . Well, stick 'em on 200 meters and below; they'll never get out of their backyards with that."

But as the years rolled on, amateurs found out how, and DX (distance) jumped from local to 500-mile and even occasional 1000-mile two-way contacts. Because all long-distance messages had to be relayed, relaying developed into a fine art – an ability that was to prove invaluable when the Government suddenly called hundreds of skilled amateurs into war service in 1917. Meanwhile U.S. amateurs began to wonder if there were amateurs in other countries across the seas and if, some day, we might not span the Atlantic on 200 meters.

Most important of all, this period witnessed the birth of the American Radio Relay League, the amateur radio organization whose name was to be virtually synonymous with subsequent amateur progress and short-wave development. Conceived and formed by the famous inventor, the late Hiram Percy Maxim, ARRL was formally launched in early 1914. It had just begun to exert its full force in amateur activities when the United States declared war in 1917, and by that act sounded the knell for amateur radio for the next two and a half years. There were then over 6000 amateurs. Over 4000 of them served in the armed forces during that war.

Today, few amateurs realize that World War I not only marked the close of the first phase of amateur development but came very near marking its end for all time. The fate of amateur radio was in the balance in the days immediately following the signing of the Armistice. The Government, having had a taste of supreme authority over communications in wartime, was more than half inclined to keep it. The war had not been ended a month before Congress was considering legislation that would have made it impossible for the

HIRAM PERCY MAXIM
President ARRL, 1914–1936

amateur radio of old ever to be resumed. ARRL's President Maxim rushed to Washington, pleaded, argued, and the bill was defeated. But there was still no amateur radio; the war ban continued. Repeated representations to Washington met only with silence. The League's offices had been closed for a year and a half, its records stored away. Most of the former amateurs had gone into service; many of them would never come back. Would those returning be interested in such things as amateur radio? Mr. Maxim, determined to find out, called a meeting of the old Board of Directors. The situation was discouraging: amateur radio still banned by law, former members scattered, no organization, no membership, no funds. But those few determined men financed the publication of a notice to all the former amateurs that could be located, hired Kenneth B. Warner as the League's first paid secretary, floated a bond issue among old League members to obtain money for immediate running expenses, bought the magazine *QST* to be the League's official organ, started activities, and dunned officialdom until the wartime ban was lifted and amateur radio resumed again, on October 1, 1919. There was a headlong rush by amateurs to get back on the air. Gangway for King Spark! Manufacturers were hard put to supply radio apparatus fast enough. Each night saw additional dozens of stations crashing out over the air. Interference? It was bedlam!

But it was an era of progress. Wartime needs had stimulated technical development. Vacuum tubes were being used both for receiving and transmitting. Amateurs immediately adapted the new gear to 200-meter work. Ranges promptly increased and it became possible to bridge the continent with but one intermediate relay.

TRANSATLANTICS

As DX became 1000, then 1500 and then 2000 miles, amateurs began to dream of transatlantic work. Could they get across? In December, 1921, ARRL sent abroad an expert amateur, Paul F. Godley, 2ZE, with the best receiving equipment available. Tests were run, and *thirty* American stations were heard in Europe. In 1922 another transatlantic test was carried out and 315 American calls were logged by European amateurs and one French and two British stations were heard on this side.

Everything now was centered on one objective: two-way amateur communication across the Atlantic! It must be possible – but somehow it couldn't quite be done. More power? Many already were using the legal maximum. Better receivers? They had superheterodynes. Another wavelength? What about those undisturbed wavelengths *below* 200 meters? The engineering world thought they were worthless – but they had said that about 200 meters. So, in 1922, tests between Hartford and Boston were made on 130 meters with encouraging results. Early in 1923, ARRL-sponsored tests on wavelengths down to 90 meters were successful. Reports indicated that *as the wavelength dropped the results were better.* Excitement began to spread through amateur ranks.

Finally, in November, 1923, after some months of careful preparation, two-way amateur transatlantic communication was accomplished, when Fred Schnell, 1MO (now W4CF) and the late John Reinartz, 1XAM (later K6BJ) worked for several hours with Deloy, 8AB, in France, with all three stations on 110 meters! Additional stations dropped down to 100 meters and found that they, too, could easily work two-way across the Atlantic. The exodus from the 200-meter region had started. The "short-wave" era had begun!

By 1924 dozens of commercial companies had rushed stations into the 100-meter region. Chaos threatened, until the first of a series of national and international radio conferences partitioned off various bands of frequencies for the different services. Although thought still centered around 100 meters, League officials at the first of these frequency-determining conferences, in 1924, wisely obtained amateur bands not only at 80 meters but at 40, 20, and even 5 meters.

Eighty meters proved so successful that "forty" was given a try, and QSOs with Australia, New Zealand and South Africa soon became commonplace. Then how about 20 meters? This new band revealed entirely unexpected possibilities when 1XAM worked 6TS on the West Coast, direct, at high noon. The dream of amateur radio – daylight DX! – was finally true.

PUBLIC SERVICE

Amateur radio is a grand and glorious hobby but this fact alone would hardly merit such wholehearted support as is given it by our Government at international conferences. There are other reasons. One of these is a thorough appreciation by the military and civil defense authorities of the value of the amateur as a source of skilled radio personnel in time of war. Another asset is best described as "public service."

About 4000 amateurs had contributed their skill and ability in '17-'18. After the war it was only natural that cordial relations should prevail between the Army and Navy and the amateur. These relations strengthened in the next few years and, in gradual steps, grew into cooperative activities which resulted, in 1925, in the establishment of the Naval Communications Reserve and the Army-Amateur Radio System (now the Military

A view of the ARRL laboratory.

Affiliate Radio System). In World War II thousands of amateurs in the Naval Reserve were called to active duty, where they served with distinction, while many other thousands served in the Army, Air Forces, Coast Guard, and Marine Corps. Altogether, more than 25,000 radio amateurs served in the armed forces of the United States. Other thousands were engaged in vital civilian electronic research, development and manufacturing. They also organized and manned the War Emergency Radio Service, the communications section of OCD.

The "public-service" record of the amateur is a brilliant tribute to his work. These activities can be roughly divided into two classes, expeditions and emergencies. Amateur cooperation with expeditions began in 1923 when a League member, Don Mix, 1TS, of Bristol, Conn. (from 1933 to 1968 a member of the *QST* technical staff), accompanied MacMillan to the Arctic on the schooner *Bowdoin* with an amateur station. Amateurs in Canada and the U.S. provided the home contacts. The success of this venture was so outstanding that other explorers followed suit. During subsequent years a total of perhaps two hundred voyages and expeditions were assisted by amateur radio, the several explorations of the Antarctic being perhaps the best known.

Since 1913 amateur radio has been the principal, and in many cases the only, means of outside communication in several hundred storm, flood and earthquake emergencies in this country. The earthquakes which hit Alaska in 1964, Peru in 1970 and California in 1971, the Dakota floods and the aftermath of Tropical Storm Agnes in 1972, respectively, called for the amateur's greatest emergency effort. In these disasters and many others – tornados, sleet storms, forest fires, blizzards – amateurs played a major role in the relief work and earned wide commendation for their resourcefulness in effecting communication where all other means had failed. The League's Emergency Corps, now a part of the Amateur Radio Public Service Corps (APRSC), was formalized in 1938, and a program of close cooperation with the American Red Cross was adopted. Since 1947, there has been a staff member at headquarters whose primary job is coordination of public service activities.

After World War II, it became evident that the international situation was destined to be tense and the need for some civil defense measures was apparent. In the discussions with government agencies that followed, the League got two points across: first, that amateur radio had a potential for and capability of playing a major role in this program; and second, that our participation should, this time as never before, be in our own name, as an *amateur radio service*, even if and after war should break out. These principles were included into the planning by the formulation of regulations creating a new branch of the amateur service, the Radio Amateur Civil Emergency Services, RACES. As an *amateur* service, its frequency segments are shared with the regular amateur service during peacetime. In the event of war, it is planned that regular (i.e., casual) amateur radio will cease and RACES will continue to operate under certain restrictions. In peacetime emergencies (such as natural disasters), RACES will operate closely with ARPSC.

TECHNICAL DEVELOPMENTS

The amateur is constantly in the forefront of technical progress. His incessant curiosity, his eagerness to try anything new, are two reasons. Another is that ever-growing amateur radio continually overcrowds its frequency assignments, spurring amateurs to the development and adoption of new techniques to permit the accommodation of more stations.

During World War II, thousands of skilled amateurs contributed their knowledge to the development of secret radio devices, both in Government and private laboratories. Equally as important, the prewar technical progress by amateurs provided the keystone for the development of modern military communications equipment.

From this work, amateurs have moved on to satellites of their own, launched piggyback on regular space shots at no cost to the taxpayer. Project Oscar Inc., an ARRL affiliate, designed and constructed the first four, with launch dates of December 12, 1961; June 2, 1962; March 9, 1965; and December 21, 1965. Australis-Oscar 5 was built in Australia and launched by NASA under the auspices of Radio Amateur Satellite Corporation (Amsat); it went aloft on January 23, 1970. Amsat-Oscar 6 was orbited October 15, 1972 and is expected to remain usable throughout 1973. It contains beacons operating on 435.10 and 29.45; a repeater with input from 145.9 to 146 MHz and output from 29.45 to 29.55. Ground stations using the satellite should not exceed 100 watts effective radiated power. Incidentally, Oscar stands for "Orbital Satellite Carrying Amateur Radio."

Another space-age field in which amateurs are currently working is that of long-range communication using the moon as a passive reflector. The amateur bands from 50 to 2450 MHz are being used for this work. Moonbounce communications have been carried out, for instance, between Sweden and New Zealand on 144 MHz and between California and England on both 432 and 1296 MHz.

THE AMERICAN RADIO RELAY LEAGUE

The ARRL is today not only the spokesman for amateur radio in the U.S. and Canada but it is the largest amateur organization in the world. It is strictly of, by and for amateurs, is noncommercial and has no stockholders. The members of the League are the owners of the ARRL and *QST*.

The League is pledged to promote interest in two-way amateur communication and experimentation. It is interested in the relaying of messages by amateur radio. It is concerned with the advancement of the radio art. It stands for the maintenance of fraternalism and a high standard of conduct. It represents the amateur in legislative matters.

One of the League's principal purposes is to keep amateur activities so well conducted that the amateur will continue to justify his existence. Amateur radio offers its followers countless pleasures and unending satisfaction. It also calls for the shouldering of responsibilities – the maintenance of high standards, a cooperative loyalty to the traditions of amateur radio, a dedication to its ideals and principles, so that the institution of amateur radio may continue to operate "in the public interest, convenience and necessity."

The operating territory of ARRL is divided into one Canadian and fifteen U.S. divisions. The affairs of the League are managed by a Board of Directors. One director is elected every two years by the membership of each U.S. division, and one by the Canadian membership. These directors then choose the president and three vice-presidents, who are also members of the Board. The secretary and treasurer are also appointed by the Board. The directors, as representatives of the amateurs in their divisions, meet annually to examine current amateur problems and formulate ARRL policies thereon. The directors appoint a general manager to supervise the operations of the League and its headquarters, and to carry out the policies and instructions of the Board.

ARRL owns and publishes the monthly magazine, *QST*. Acting as a bulletin of the League's organized activities, *QST* also serves as a medium for the exchange of ideas and fosters amateur spirit. Its technical articles are renowned. It has grown to be the "amateur's bible," as well as one of the foremost radio magazines in the world. Membership dues include a subscription to *QST*.

ARRL maintains a model headquarters amateur station, known as the Hiram Percy Maxim Memorial Station, in Newington, Conn. Its call is W1AW, the call held by Mr. Maxim until his death and later transferred to the League station by a special government action. Separate transmitters of maximum legal power on each amateur band have permitted the station to be heard regularly all over the world. More important, W1AW transmits on regular schedules bulletins of general interest to amateurs, conducts code practice as a training feature, and engages in two-way work on all popular bands with as many amateurs as time permits.

At the headquarters of the League in Newington, Conn., is a well-equipped laboratory to assist staff members in preparation of technical material for *QST* and the *Radio Amateur's Handbook*. Among its other activities, the League maintains a Communications Department concerned with the operating activities of League members. A large field organization is headed by a Section Communications Manager in each of the League's seventy-four sections. There are appointments for qualified members in various fields, as outlined in Chapter 24. Special activities and contests promote operating skill. A special place is reserved each month in *QST* for amateur news from every section.

AMATEUR LICENSING IN THE UNITED STATES

Pursuant to the law, the Federal Communications Commission (FCC) has issued detailed regulations for the amateur service.

A radio amateur is a duly authorized person interested in radio technique solely with a personal aim and without pecuniary interest. Amateur operator licenses are available to most permanent residents who can pass an examination on operation, apparatus, and regulations affecting amateurs, and who can demonstrate ability to send and receive code. There are five available classes of amateur license – Novice, Technician, General ("Conditional" if taken by mail), Advanced, and Amateur Extra Class. Each has different requirements, the first two being the simplest and consequently conveying limited privileges as to frequencies available. Extra Class licensees have exclusive use of the frequencies 3.5-3.525, 3.775-3.8, 7.0-7.025, 14.0-14.025, 21.0-21.025 and 21.25-21.270 MHz. Advanced and Extra have exclusive use of the frequencies 3.8-3.890, 7.15-7.225, 14.2-14.275, 21.270-21.35 and 50.0-50.1 MHz. Exams for Novice, Technician and Conditional classes are taken by mail under the supervision of a volunteer examiner. Station licenses are granted only to licensed operators. An amateur station may not be used for material compensation of any sort nor for broadcasting. Narrow bands of frequencies are allocated exclusively for use by amateur stations. Transmissions may be on any frequency within the assigned bands. All the frequencies may be used for cw telegraphy; some are available for radiotelephone, others for special forms of transmission such as teletype, facsimile amateur television or radio control. The input to the final stage of amateur stations is limited to 1000 watts (with lower limits in some cases; see the table on page 14) and on frequencies below 144 MHz must be adequately filtered direct current. Emissions must be free from spurious radiations. The licensee must provide for measurement of the transmitter frequency and establish a procedure for checking it regularly. A complete log of station operation must be maintained, with specified data. The station license also authorizes the holder to operate portable and mobile stations subject to further regulations. All radio licenses are subject to penalties for violation of regulations.

Amateur licenses are issued without regard to the applicant's age or physical condition. A fee of $9.00 (payable to the Federal Communications Commission) must accompany applications for new and renewed licenses. The fee for license modification is $4.00 (except Novices: no fee). When you are able to copy code at the required speed, have studied basic transmitter theory and are familiar with the law and amateur regulations, you are ready to give serious thought to securing the Government amateur licenses which are issued you, after examination by an FCC engineer (or by a volunteer, depending on the license class), through the FCC Licensing Unit, Gettysburg, Pa., 17325. A complete up-to-the-minute discussion of license requirements, the FCC regulations for the amateur service, and study guides for those preparing for the examinations, are to be found in *The Radio Amateur's License Manual*, available from the American Radio Relay League, Newington, Conn. 06111, for $1.00, postpaid.

AMATEUR LICENSING IN CANADA

The agency responsible for amateur radio in Canada is the Department of Communications, with its principal offices in Ottawa. Prospective amateurs, no longer restricted as to age, may take the examination for an Amateur Radio Operator Certificate at one of the regional offices of the DOC. The test is in three parts: a Morse code test at ten words per minute, a written technical exam and an oral examination. Upon passing the examination, the amateur may apply for a station license, the fee for which is $10 per year. At this point, the amateur is permitted to use cw on all authorized amateur bands (see table on page 13) and phone on those bands above 50MHz.

After six months, during which the station has been operated on cw on frequencies below 29.7 MHz, the Canadian amateur may have his certificate endorsed for phone operation in the 28.0-29.7 MHz band. The amateur may take a 15 wpm code test and more-difficult oral and written examinations for the Advanced Amateur Radio Operator Certificate, which permits phone operations on portions of all authorized amateur bands. Holders of First or Second Class or Special Radio Operator's Certificates may enjoy the privileges of Advanced class without further examinations. The maximum input power to the final stage of an amateur transmitter is limited to 1,000 watts.

Prospective amateurs living in remote areas may obtain a provisional station license after signing a statement that they can meet the technical and operating requirements. A provisional license is valid for a maximum of twelve consecutive months only; by then, a provisional licensee should have taken the regular examination.

Licenses are available to citizens of Canada, to citizens of other countries in the British Commonwealth, and to non-citizens who qualify as "landed immigrants" within the meaning of Canadian immigration law. The latter status may be enjoyed for only six years, incidentally. A U.S. citizen who obtained a Canadian license as a "landed immigrant" would have to become a Canadian citizen at the end of six years or lose his Canadian license.

Copies of the Radio Act and of the General Radio Regulations may be obtained for a nominal fee from the Queen's Printer, Ottawa, and its dealers. An extract of the amateur rules, Form AR-5-80, is available at DOC offices. Other books include: *The Canadian Amateur Radio Regulations Handbook*, $2.55 from CARF, Box 356, Kingston, K7L 4W2, Ontario; the *Ham Handbook for Beginners* and the *Ham Handbook for Advanced*, each $5.30 from ARTA Publishing Co., P.O. Box 571 Don Mills, Ont.; *Radio Amateur Licensing Handbook* $4.95, ALH Distributors, P.O. Box 27, Vancouver 1, B.C.; and *Comment Devenir Amateur*, $2.50 from Guy Cadieux, VE2BTG, 924 20th Ave. S., Ville de St. Antoine, P.Q.

RECIPROCAL OPERATING

U.S. amateurs may operate their amateur stations while visiting in Argentina, Australia, Austria, Barbados, Belgium, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Finland, France*, Germany, Guatemala, Guyana, Honduras, India, Indonesia, Ireland, Israel, Jamaica, Kuwait, Luxembourg, Monaco, Netherlands,* New Zealand, Nicaragua, Norway, Panama, Paraguay, Peru, Portugal, Sierre Leone, Sweden, Switzerland, Trinidad & Tobago, the United Kingdom*,Uruguay and Venezuela and vice versa. For the latest information, write to ARRL headquarters..

LEARNING THE CODE

In starting to learn the code, you should consider it simply another means of conveying information. The spoken word is one method, the printed page another, and typewriting and shorthand are additional examples. Learning the code is as easy – or as difficult – as learning to type.

The important thing in beginning to study code is to think of it as a language of *sound*, never as combinations of dots and dashes. It is easy to "speak" code equivalents by using "dit" and "*dah,*" so that A would be "di*dah*" (the "t" is dropped in such combinations). The sound "di" should be staccato; a code character such as "5" should sound like a machinegun burst: dididididit! Stress each "*dah*" equally; they are underlined or italicized in this text because they should be slightly accented and drawn out.

Take a few characters at a time. Learn them thoroughly in di*dah* language before going on to new ones. If someone who is familiar with code can be found to "send" to you, either by whistling or by means of a buzzer or code oscillator, enlist his cooperation. Learn the code by *listening* to it. Don't think about speed to start; the first requirement is to learn the characters to the point where you can recognize each of them without hesitation. Concentrate on any difficult letters. Learning the code is not at all hard; a simple booklet treating the subject in detail is another of the beginner publications available from the League, and is entitled, *Learning the Radiotelegraph Code*, 50 cents, postpaid.

Code-practice transmissions are sent by W1AW every evening at 0030 and 0230 GMT (0130 and 2330 May through October). Code is also sent, Monday-Friday, at 1400 GMT (1300 GMT, May through October). See Chapter 24, "Code Proficiency."

A Code-Practice Set

A simple oscillator circuit like the one shown in Fig. 1-2 may be built using a Signetics NE555

---

* Includes overseas entities.

A	didah	N	dahdit
B	dahdididit	O	dahdahdah
C	dahdidahdit	P	didahdahdit
D	dahdidit	Q	dahdahdidah
E	dit	R	didahdit
F	dididahdit	S	dididit
G	dahdahdit	T	dah
H	dididit	U	dididah
I	didit	V	didididah
J	didahdahdah	W	didahdah
K	dahdidah	X	dahdididah
L	didahdidit	Y	dahdidahdah
M	dahdah	Z	dahdahdidit
1	didahdahdahdah	6	dahdidididit
2	dididahdahdah	7	dahdahdididit
3	didididahdah	8	dahdahdahdidit
4	dididididah	9	dahdahdahdahdit
5	dididididit	0	dahdahdahdahdah

Period: didahdidahdidah. Comma: dahdahdididahdah. Question mark: dididahdahdidit. Error: didididididididit. Double dash: dahdidididah. Colon: dahdahdahdididit. Semicolon: dahdidahdidahdit. Parenthesis: dahdidahdahdidah. Fraction bar: dahdididahdit. Wait: didahdididit. End of message: didahdidahdit. Invitation to transmit: dahdidah. End of work: didididahdidah.

Fig. 1-1 — The Continental (International Morse) code.

timer and a few extra parts. The printed circuit for the oscillator is made from a 2-inch square piece of pc material but the IC could have been placed on Masonite, Formica or some other insulating material. Point-to-point wiring may be used. The circuit is housed in a homemade enclosure that provides room for a battery of almost any value between 4-1/2 and 18 volts. The speaker is attached to the front of the enclosure with caulking compound. Any speaker in the range of 4 to 50 ohms will work well and may be salvaged from a discarded transistor pocket radio.

The circuit shown costs approximately five dollars to build. R2 is made from one fixed-value resistor chosen to give a pleasant tone. The volume control could be removed altogether (placing the speaker at the negative side of C3) or be replaced with a pair of resistors equalling about 10,000 ohms. The speaker should be connected between the junction of these resistors and ground. An on-off switch should be used to disable the oscillator when it is not in use.

The audio pitch is determined by the values of R1, C2 and the setting of R2. The cost of the oscillator may be reduced somewhat by replacing R2 with a fixed value of resistance; R3 could be replaced by a fixed-value resistor. If this is done, the speaker lead must be connected to the junction of C3 and R3.

A cw code-practice oscillator along with a speaker may be mounted inside a homemade aluminum box. If desired, the battery could be mounted inside the enclosure also, thereby allowing easy portability of the unit.

When power is applied the oscillator runs continuously and the audio output is keyed on and off. This circuit gives a degree of freedom from chirps or whoop-like sounds when rapidly keyed. However, the circuit always draws about 6 mA of current when operated. If used with a small battery, such as those used in transistor portable radios, the battery could quickly be discharged, so a means of disconnecting the power should be used, such as a spst switch, as shown at S1.

If facilities are not available for etching a board, point-to-point wiring will work just as well, and perforated board stock is a suitable material to be used. If a builder does not want to solder directly to the IC leads an 8-pin IC socket can be used, making all connections to the socket.

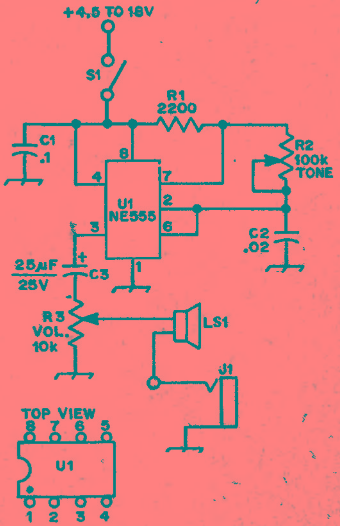


Fig. 1-2 — Schematic diagram for the code oscillator. Resistance is in ohms, k = 1000. The 0.1-μF capacitor is a disk ceramic. U1 is a Signetics NE555 IC timer.

INTRODUCTION TO RADIO THEORY

As you start your studies for an amateur license, you may wish to have the additional help available in *How to Become a Radio Amateur* ($1.00). It features an elementary description of radio theory and constructional details on a simple receiver and transmitter.

Another aid is *A Course in Radio Fundamentals* ($2.00). There are experiments, discussions, and quizzes to help you learn radio fundamentals.

A League publication, *Understanding Amateur Radio*, explains radio theory and practice in greater detail than is found in *How to Become a Radio Amateur*, but is at a more basic level than this *Handbook*. *Understanding Amateur Radio* contains 304 pages, and is priced at $2.50.

These booklets are available postpaid from ARRL, Newington, Connecticut 06111.

THE AMATEUR BANDS

Amateurs are assigned bands of frequencies at approximate harmonic intervals throughout the spectrum. Like assignments to all services, they are subject to modification to fit the changing picture of world communications needs. Modifications of rules to provide for domestic needs are also occasionally issued by FCC and DOC, and in that respect each amateur should keep himself informed by W1AW bulletins, *QST* reports, or by communication with ARRL Hq. concerning a specific point.

On this page and page 14 are summaries of the Canadian and U.S. amateur bands on which operation is permitted as of our press date. A0 and F0 mean unmodulated carriers. A1 means cw telegraphy, A2 is tone-modulated cw telegraphy, A3 is amplitude-modulated phone, A4 is facsimile, A5 is television, F1 is frequency-shift keying, F2 is frequency-modulated tone keying (Morse or teletype), F3 is fm phone, F4 is fm facsimile and F5 is fm television.

CANADIAN AMATEUR BANDS

80 meters	3.500–	3.725 MHz	A1, F1
1) 3) 4) 5)	3.725–	4.000 MHz	A1, A3, F3
40 meters	7.000–	7.150 MHz	A1, F1,
1) 3) 4) 5)	7.150–	7.300 MHz	A1, A3, F3
20 meters	14.000–	14.100 MHz	A1, F1
1) 3) 4) 5)	14.100–	14.350 MHz	A1, A3, F3
15 meters	21.000–	21.100 MHz	A1, F1
1) 3) 4) 5)	21.100–	21.450 MHz	A1, A3, F3
10 meters	28.000–	28.100 MHz	A1, F1
2) 3) 4) 5)	28.100–	29.700 MHz	A1, A3, F3
6 meters	50.000–	50.050 MHz	A1
3) 4)	50.050–	51.000 MHz	A1, A2, A3, F1 F2, F3
	51.000–	54.000 MHz	A0, A1, A2, A3 A4, F1, F2, F3, F4
2 meters	144.000–	144.100 MHz	A1
3) 4)	144.100–	148.000 MHz	A0, A1, A2, A3 A4, F1, F2, F3 F4
3) 4)	220.000–	225.000 MHz	A0, A1, A2, A3, A4, F1, F2, F3, F4
4) 6)	420.000–	450.000 MHz)	
	1215.000–	1300.000 MHz)	
	2300.000–	2450.000 MHz)	
	3300.000–	3500.000 MHz)	A0, A1, A2, A3
	5650.000–	5925.000 MHz)	A4, A5, F1, F2
	10000.000–	10500.000 MHz)	F3, F4
	21000.000–	22000.000 MHz)	

1) Phone privileges are restricted to holders of Advanced Amateur Radio Operator Certificates, and of Commercial Certificates.

2) Phone privileges are restricted as in footnote 1), and to holders of Amateur Radio Operators Certificates, whose certificates have been endorsed for operation on phone in these bands.

3) Amplitude modulation (A2, A3, A4) shall not exceed ± 3 kHz (6A3).

4) Frequency modulation (F2, F3, F4) shall not produce a carrier deviation exceeding ±3 kHz, (6F3) except that in the 52–54 MHz and 146–148 MHz bands and higher the carrier deviation shall not exceed ±15 kHz (30F3).

5) Slow Scan television (A5), permitted by special authorization, shall not exceed a bandwidth greater than that occupied by a normal single sideband voice transmission.

6) Television (A5), permitted by special authorization, shall employ a system of standard interlace and scanning with a bandwidth of not more than 4 MHz.

Operation in frequency band 1.800–2.000 MHz shall be limited to the areas as indicated in the following table and shall be limited to the indicated maximum dc power input to the anode of the final radio frequency stage of the transmitter during day and night hours respectively; for the purpose of this table "day" means the hours between sunrise and sunset, and "night" means the hours between sunset and sunrise. A1, A3 and F3 emission are permitted.

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
British Columbia	3 1)	3	3	1	0	0	0	0
Alberta	3 1)	3	3	3	1	0	0	1
Saskatchewan	3 1)	3	3	3	3	1	1	3
Manitoba	3 1)	2	2	2	2	2	2	3 1)
Ontario North of 50° N. Lat.	3	1	1	1	1	0	0	2
Ontario South of 50° N. Lat.	3 1)	2	1	0	0	0	0	1
Province of Quebec North of 52° N. Lat.	1	0	0	1	1	0	0	2
Province of Quebec South of 52° N. Lat.	3	2	1	0	0	0	0	0
New Brunswick	3	2	1	0	0	0	0	0
Nova Scotia	3	2	1	0	0	0	0	0
Prince Edward Island	3	2	1	0	0	0	0	0
Newfoundland (Island)	3	1	1	0	0	0	0	0
Newfoundland (Labrador)	2	0	0	0	0	0	0	0
Yukon Territory	3 1)	3	3	1	0	0	0	0
District of MacKenzie	3 1)	3	3	3	1	0	0	1
District of Keewatin	3	1	1	3	2	0	0	2
District of Franklin	0	0	0	0	1	0	0	1

1) The power levels 500 day – 100 night may be increased to 1000 day – 200 night when authorized by a Radio Inspector of the Department of Communications.

Frequency Band

A 1.800–1.825 MHz
B 1.825–1.850 MHz
C 1.850–1.875 MHz
D 1.875–1.900 MHz
E 1.900–1.925 MHz
F 1.925–1.950 MHz
G 1.950–1.975 MHz
H 1.975–2.000 MHz

Power Level – Watts

0 – Operation not permitted		
1 –	25 night	125 day
2 –	50 night	250 day
3 –	100 night	500 day

U.S. AND POSSESSIONS AMATEUR BANDS

	kHz	EMISSIONS
160 m.*	1800–2000	A1,A3
80 m.**	3500–4000	A1
	3500–3775	F1
	3775–3890	A5[1], F5[1]
	3775–4000	A3, F3[2]
40 m.**	7000–7300	A1
	7000–7150	F1
	7150–7225	A5[1], F5[1]
	7150–7300	A3, F3[2]
20 m.**	14000–14350	A1
	14000–14200	F1
	14200–14275	A5[1], F5[1]
	14200–14350	A3, F3[2]

	MHz	EMISSIONS
15 m.**	21.00–21.45	A1
	21.00–21.25	F1
	21.25–21.35	A5[1], F5[1]
	21.25–21.45	A3, F3[2]
10 m.	28.0–29.7	A1
	28.0–28.5	F1
	28.5–29.7	A3, A5[1], F3[2], F5[1]
	29.0–29.7	F3

NOTE: Frequencies from 3.9-4.0 MHz and 7.1-7.3 MHz are not available to amateurs on Baker, Canton, Enderbury, Guam, Howland, Jarvis, Palmyra, American Samoa, and Wake Islands.

When operating from points outside ITU Region 2 (roughly, the Western Hemisphere extended to include Hawaii), licensees of Conditional Class and higher may operate A3 and F3 from 7075-7100 kHz; Novice licensees may operate A1 from 7050-7075 kHz.

REPEATERS:

The frequency ranges (in MHz) available for repeater inputs and outputs are as follows:

52.0 – 54.0
146.0 – 148.0
222.0 – 225.0
442.0 – 450.0
any amateur frequency above 1215 MHz.

The frequency band 29.5 – 29.7 MHz may be authorized upon a special showing of need for repeater station operation in this band.

Novice licensees may use A1 emission and a maximum power input of 75 watts on the following frequencies:

3.700–3.750 MHz	21.100–21.200 MHz
7.100–7.150 MHz	28.100–28.200 MHz

	MHz	EMISSIONS
6 m.**	50.0–54.0	A1
	50.1–54.0	A2, A3, A4, A5[3], F1, F2, F3[2], F5[1]
	51.0–54.0	A0
	52.5–54.0	F3
2 m.	144-148	A1
	144.1–148	A0, A2, A3, A4, A5[3], F0, F1, F2, F3, F5[1]
	220–225	A0, A1, A2, A3, A4, A5[3], F0, F1, F2, F3, F4, F5[1]
	420–450[4] 1,215–1,300	A0, A1, A2, A3, A4, A5[3], F0, F1, F2, F3, F4, F5
	2,300–2,450 3,300–3,500 5,650–5,925 10,000–10,500[5] 24,000–24,050	A0, A1, A2, A3, A4, A5 F0, F1, F2, F3, F4, F5, pulse

The bands 220 through 10,500 MHz are shared with the Government Radio Positioning Service, which has priority.

[1] Slow-scan television no wider than a single-sideband voice signal may be used; on A5 if voice is simultaneously used, the total signal can be no wider than a standard a-m signal.

[2] Narrow-band frequency- or phase-modulation no wider than standard a-m voice signal.

[3] Slow-scan television no wider than a standard a-m voice signal.

[4] Input power must not exceed 50 watts in Fla., Ariz., and parts of Ga., Ala., Miss., N. Mex., Tex., Nev., and Ca. See the *License Manual* or write ARRL for further details.

[5] No pulse permitted in this band.

Technician licensees are permitted all amateur privileges in 50.1-54 MHz, 145-148 MHz and in the bands 220 MHz and above.

Except as otherwise specified, the maximum amateur power input is 1000 watts.

*To minimize interference to radionavigation systems sharing the 160 meter band, amateurs are required to observe frequency and power restrictions according to their geographic location. Exact limitations are contained in Section 97.61(b)(2) of the FCC Amateur Regulations. This information also appears in the ARRL *License Manual*, available for $1.00 postpaid. A chart of U.S. 160 meter limitations is available from ARRL Headquarters; send a stamped, addressed envelope and request form S-15(a).

**See page 10 for restrictions on usage of parts of these bands.

Chapter 2

Electrical Laws and Circuits

ELECTRIC AND MAGNETIC FIELDS

When something occurs at one point in space because something else happened at another point, with no visible means by which the "cause" can be related to the "effect," we say the two events are connected by a **field**. In radio work, the fields with which we are concerned are the **electric** and **magnetic**, and the combination of the two called the **electromagnetic field**.

A field has two important properties, intensity (magnitude) and direction. The field exerts a *force* on an object immersed in it; this force represents potential (ready-to-be-used) energy, so the potential of the field is a measure of the **field intensity**. The **direction** of the field is the direction in which the object on which the force is exerted will tend to move.

An electrically charged object in an electric field will be acted on by a force that will tend to move it in a direction determined by the direction of the field. Similarly, a magnet in a magnetic field will be subject to a force. Everyone has seen demonstrations of magnetic fields with pocket magnets, so intensity and direction are not hard to grasp.

A "static" field is one that neither moves nor changes in intensity. Such a field can be set up by a stationary electric charge (**electrostatic field**) or by a stationary magnet (**magnetostatic field**). But if either an electric or magnetic field is moving in space or changing in intensity, the motion or change sets up the other kind of field. That is, a changing electric field sets up a magnetic field, and a changing magnetic field generates an electric field. This interrelationship between magnetic and electric fields makes possible such things as the electromagnet and the electric motor. It also makes possible the electromagnetic waves by which radio communication is carried on, for such waves are simply traveling fields in which the energy is alternately handed back and forth between the electric and magnetic fields.

Lines of Force

Although no one knows what it is that composes the field itself, it is useful to invent a picture of it that will help in visualizing the forces and the way in which they act.

A field can be pictured as being made up of **lines of force** or **flux lines**. These are purely imaginary threads that show, by the direction in which they lie, the direction the object on which the force is exerted will move. The *number* of lines in a chosen cross section of the field is a measure of the *intensity* of the force. The number of lines per unit of area (square inch or square centimeter) is called the **flux density**.

ELECTRICITY AND THE ELECTRIC CURRENT

Everything physical is built up of atoms, particles so small that they cannot be seen even through the most powerful microscope. But the atom in turn consists of several different kinds of still smaller particles. One is the **electron**, essentially a small particle of electricity. The **quantity** or **charge** of electricity represented by the electron is, in fact, the smallest quantity of electricity that can exist. The kind of electricity associated with the electron is called **negative**.

An ordinary atom consists of a central core called the **nucleus**, around which one or more electrons circulate somewhat as the earth and other planets circulate around the sun. The nucleus has an electric charge of the kind of electricity called **positive**, the amount of its charge being just exactly equal to the sum of the negative charges on all the electrons associated with that nucleus.

The important fact about these two "opposite" kinds of electricity is that they are strongly attracted to each other. Also, there is a strong force of repulsion between two charges of the *same* kind. The positive nucleus and the negative electrons are attracted to each other, but two electrons will be repelled from each other and so will two nuclei.

In a normal atom the positive charge on the nucleus is exactly balanced by the negative charges on the electrons. However, it is possible for an atom to lose one of its electrons. When that happens the atom has a little less negative charge than it should – that is, it has a net positive charge. Such an atom is said to be **ionized**, and in this case the atom is a **positive ion**. If an atom picks up an extra electron, as it sometimes does, it has a net negative charge and is called a **negative ion**. A positive ion will attract any stray electron in the vicinity, including the extra one that may be attached to a nearby negative ion. In this way it is possible for electrons to travel from atom to atom. The movement of ions or electrons constitutes the **electric current**.

The **amplitude** of the current (its intensity or magnitude) is determined by the rate at which electric charge – an accumulation of electrons or ions of the same kind – moves past a point in a circuit. Since the charge on a single electron or ion is extremely small, the number that must move as a group to form even a tiny current is almost inconceivably large.

Conductors and Insulators

Atoms of some materials, notably metals and acids, will give up an electron readily, but atoms of other materials will not part with any of their electrons even when the electric force is extremely strong. Materials in which electrons or ions can be moved with relative ease are called conductors, while those that refuse to permit such movement are called nonconductors or insulators. The following list shows how some common materials are classified:

Conductors	*Insulators*	
Metals	Dry Air	Glass
Carbon	Wood	Rubber
Acids	Porcelain	Resins
	Textiles	

Electromotive Force

The electric force or potential (called electromotive force, and abbreviated emf) that causes current flow may be developed in several ways. The action of certain chemical solutions on dissimilar metals sets up an emf; such a combination is called a cell, and a group of cells forms an electric battery. The amount of current that such cells can carry is limited, and in the course of current flow one of the metals is eaten away. The amount of electrical energy that can be taken from a battery consequently is rather small. Where a large amount of energy is needed it is usually furnished by an electric generator, which develops its emf by a combination of magnetic and mechanical means.

Direct and Alternating Currents

In picturing current flow it is natural to think of a single, constant force causing the electrons to move. When this is so, the electrons always move in the same direction through a path or circuit made up of conductors connected together in a continuous chain. Such a current is called a direct current, abbreviated dc. It is the type of current furnished by batteries and by certain types of generators.

It is also possible to have an emf that periodically reverses. With this kind of emf the current flows first in one direction through the circuit and then in the other. Such an emf is called an alternating emf, and the current is called an alternating current (abbreviated ac). The reversals (alternations) may occur at any rate from a few per second up to several billion per second. Two reversals make a cycle; in one cycle the force acts first in one direction, then in the other, and then returns to the first direction to begin the next cycle. The number of cycles in one second is called the frequency of the alternating current.

The difference between direct current and alternating current is show in Fig. 2-1. In these graphs the horizontal axis measures time, increasing toward the right away from the vertical axis. The vertical axis represents the amplitude or strength of the current, increasing in either the up or down direction away from the horizontal axis. If the graph is *above* the horizontal axis the current is flowing in one direction through the circuit (indicated by the + sign) and if it is *below* the horizontal axis the current is flowing in the reverse direction through the circuit (indicated by the − sign). Fig. 2-1A shows that, if we close the circuit – that is, make the path for the current complete – at the time indicated by *X*, the current instantly takes the amplitude indicated by the height *A*. After that, the current continues at the same amplitude as time goes on. This is an ordinary *direct* current.

In Fig. 2-1B, the current starts flowing with the amplitude *A* at time *X*, continues at that amplitude until time *Y* and then instantly ceases. After an interval *YZ* the current again begins to flow and the same sort of start-and-stop performance is repeated. This is an *intermittent* direct current. We could get it by alternately closing and opening a switch in the circuit. It is a *direct* current because the *direction* of current flow does not change; the graph is always on the + side of the horizontal axis.

In Fig. 2-1C the current starts at zero, increases in amplitude as time goes on until it reaches the amplitude *A1* while flowing in the + direction, then decreases until it drops to zero amplitude once more. At that time (*X*) the *direction* of the current flow reverses; this is indicated by the fact that the next part of the graph is below the axis. As time goes on the amplitude increases, with the current now flowing in the − direction, until it reaches amplitude *A2*. Then the amplitude

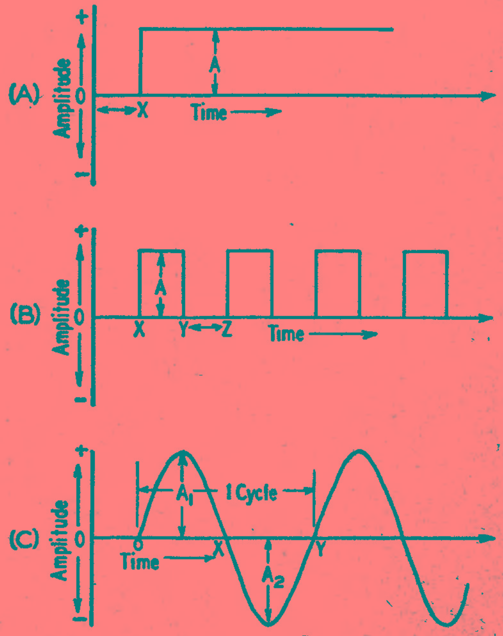


Fig. 2-1 — Three types of current flow. A — direct current; B — intermittent direct current; C — alternating current.

decreases until finally it drops to zero (*Y*) and the direction reverses once more. This is an *alternating* current.

Waveforms

The type of alternating current shown in Fig. 2-1C is known as a sine wave. The variations in many ac waves are not so smooth, nor is one half-cycle necessarily just like the preceding one in shape. However, these complex waves can be shown to be the sum of two or more sine waves of frequencies that are exact integral (whole-number) multiples of some lower frequency. The lowest frequency is called the fundamental, and the higher frequencies are called harmonics.

Fig. 2-2 shows how a fundamental and a second harmonic (twice the fundamental) might add to form a complex wave. Simply by changing the relative amplitudes of the two waves, as well as the times at which they pass through zero amplitude, an infinite number of waveshapes can be constructed from just a fundamental and second harmonic. More complex waveforms can be constructed if more harmonics are used.

Frequency multiplication, the generation of second, third and higher-order harmonics, takes place whenever a fundamental since wave is passed through a nonlinear device. The distorted output is made up of the fundamental frequency plus harmonics; a desired harmonic can be selected through the use of tuned circuits. Typical nonlinear devices used for frequency multiplication include rectifiers of any kind and amplifiers that distort an applied signal.

Electrical Units

The unit of electromotive force is called the volt. An ordinary flashlight cell generates and emf of about 1.5 volts. The emf commonly supplied for domestic lighting and power is 117 volts ac at a frequency of 60 cycles per second.

The flow of electric current is measured in amperes. One ampere is equivalent to the movement of many billions of electrons past a point in the circuit in one second. The *direct* currents used in amateur radio equipment usually are not large, and it is customary to measure such currents in milliamperes. One milliampere is equal to one one-thousandth of an ampere.

A "dc ampere" is a measure of a *steady* current, but the "ac ampere" must measure a current that is continually varying in amplitude and periodically reversing direction. To put the two on the same basis, an ac ampere is defined as the current that will cause the same heating effect as one ampere of steady direct current. For sine-wave ac, this *effective* or (rms, for *root mean square*, the mathematical derivation) value is equal to the *maximum* (or peak) amplitude (*A1* or *A2* in Fig. 2-1C) multiplied by 0.707. The instantaneous value is the value that the current (or voltage) has at any selected instant in the cycle. If all the instantaneous values in a sine wave are averaged over a *half*-cycle, the resulting figure is the average value. It is equal to 0.636 times the maximum amplitude.

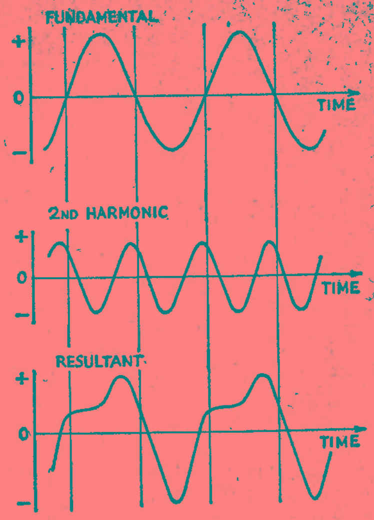


Fig. 2-2 — A complex waveform. A fundamental (top) and second harmonic (center) added together, point by point at each instant, result in the waveform shown at the bottom. When the two components have the same polarity at a selected instant, the resultant is the simple sum of the two. When they have opposite polarities, the resultant is the *difference*; if the negative-polarity component is larger, the resultant is negative at that instant.

FREQUENCY AND WAVELENGTH

Frequency Spectrum

Frequencies ranging from about 15 to 15,000 cycles per second (cps, Hertz, or Hz) are called audio frequencies, because the vibrations of air particles that our ears recognize as sounds occur at a similar rate. Audio frequencies (abbreviated af) are used to actuate loudspeakers and thus create sound waves.

Frequencies above about 15,000 cps are called radio frequencies (rf) because they are useful in radio transmission. Frequencies all the way up to and beyond 10,000,000,000 cps have been used for radio purposes. At radio frequencies it becomes convenient to use a larger unit than the cycle. Two such units are the **kilohertz**, which is equal to 1000 cycles (or hz), and is abbreviated to **kHz**, and the **megahertz**, which is equal to 1,000,000 hertz or 1000 kilohertz, and is abbreviated MHz.

The various radio frequencies are divided off into classifications. These classifications, listed below, constitute the frequency spectrum so far as it extends for radio purposes at the present time.

Frequency	*Classification*	*Abbrev*
10 to 30 kHz	Very-low frequencies	vlf
30 to 300 kHz	Low frequencies	lf
300 to 3000 kHz	Medium frequencies	mf
3 to 30 MHz	High frequencies	hf
30 to 300 MHz	Very-high frequencies	vhf
300 to 3000 MHz	Ultrahigh frequencies	uhf
3000 to 30,000 MHz	Superhigh frequencies	shf

Wavelength

Radio waves travel at the same speed as light – 300,000,000 meters or about 186,000 miles a second in space. They can be set up by a radio-frequency current flowing in a circuit, because the rapidly changing current sets up a magnetic field that changes in the same way, and the varying magnetic field in turn sets up a varying electric field. And whenever this happens, the two fields move outward at the speed of light.

Suppose an rf current has a frequency of 3,000,000 cycles per second. The field will go through complete reversals (one cycle) in 1/3,000,000 second. In that same period of time the fields – that is, the wave – will move 300,000,000/3,000,000 meters, or 100 meters. By the time the wave has moved that distance the next cycle has begun and a new wave has started out. The first wave, in other words, covers a distance of 100 meters before the beginning of the next, and so on. This distance is the wavelength.

The longer the time of one cycle – that is, the lower the frequency – the greater the distance occupied by each wave and hence the longer the wavelength. The relationship between wavelength and frequency is shown by the formula

$$\lambda = \frac{300{,}000}{f}$$

where λ = Wavelength in meters
f = Frequency in kilohertz

or

$$\lambda = \frac{300}{f}$$

where λ = Wavelength in meters
f = Frequency in megahertz

Example: The wavelength corresponding to a frequency of 3650 kilohertz is

$$\lambda = \frac{300{,}000}{3650} = 82.2 \text{ meters}$$

RESISTANCE

Given two conductors of the same size and shape, but of different materials, the amount of current that will flow when a given emf is applied will be found to vary with what is called the resistance of the material. The lower the resistance, the greater the current for a given value of emf.

Resistance is measured in ohms. A circuit has a resistance of one ohm when an applied emf of one volt causes a current of one ampere to flow. The resistivity of a material is the resistance, in ohms, of a cube of the material measuring one centimeter on each edge. One of the best conductors is copper, and it is frequently convenient, in making resistance calculations, to compare the resistance of the material under consideration with that of a copper conductor of the same size and shape. Table 2-I gives the ratio of the resistivity of various conductors to that of copper.

The longer the path through which the current flows the higher the resistance of that conductor. For direct current and low-frequency alternating currents (up to a few thousand cycles per second) the resistance is *inversely* proportional to the cross-sectional area of the path the current must travel; that is, given two conductors of the same material and having the same length, but differing in cross-sectional area, the one with the larger area will have the lower resistance.

TABLE 2-1

Relative Resistivity of Metals

Materials	*Resistivity Compared to Copper*
Aluminum (pure)	1.6
Brass	3.7–4.9
Cadmium	4.4
Chromium	1.8
Copper (hard-drawn)	1.03
Copper (annealed)	1.00
Gold	1.4
Iron (pure)	5.68
Lead	12.8
Nickel	5.1
Phosphor Bronze	2.8–5.4
Silver	0.94
Steel	7.6–12.7
Tin	6.7
Zinc	3.4

Resistance of Wires

The problem of determining the resistance of a round wire of given diameter and length – or its opposite, finding a suitable size and length of wire to supply a desired amount of resistance – can be easily solved with the help of the copper-wire table given in a later chapter. This table gives the resistance, in ohms per thousand feet, of each standard wire size.

Example: Suppose a resistance of 3.5 ohms is needed and some No. 28 wire is on hand. The wire table in Chapter 18 shows that No. 28 has a resistance of 66.17 ohms per thousand feet. Since the desired resistance is 3.5 ohms, the length of wire required will be

$$\frac{3.5}{66.17} \times 1000 = 52.89 \text{ feet.}$$

Or, suppose that the resistance of the wire in the circuit must not exceed 0.05 ohm and that the length of wire required for making the connections totals 14 feet. Then

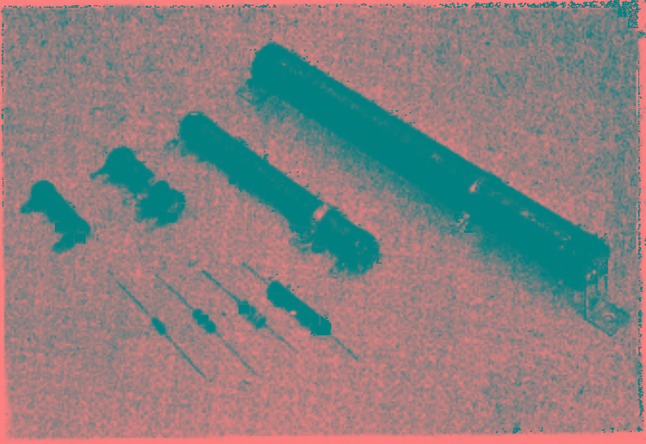
$$\frac{14}{1000} \times R = 0.05 \text{ ohm}$$

where R is the maximum allowable resistance in ohms per thousand feet. Rearranging the formula gives

$$R = \frac{0.05 \times 1000}{14} = 3.57 \text{ ohms/1000 ft.}$$

Reference to the wire table shows that No. 15 is the smallest size having a resistance less than this value.

When the wire is not copper, the resistance values given in the wire table should be multiplied by the ratios given in Table 2-I to obtain the resistance.



Types of resistors used in radio equipment. Those in the foreground with wire leads are carbon types, ranging in size from 1/2 watt at the left to 2 watts at the right. The larger resistors use resistance wire wound on ceramic tubes; sizes shown range from 5 watts to 100 watts. Three are the edjustable type, having a sliding contact on an exposed section of the resistance winding.

Example: If the wire in the first example were nickel instead of copper the length required for 3.5 ohms would be

$$\frac{3.5}{66.17 \times 5.1} \times 1000 = 10.37 \text{ feet}$$

Temperature Effects

The resistance of a conductor changes with its temperature. Although it is seldom necessary to consider temperature in making resistance calculations for amateur work, it is well to know that the resistance of practically all metallic conductors increases with increasing temperature. Carbon, however, acts in the opposite way; its resistance *decreases* when its temperature rises. The temperature effect is important when it is necessary to maintain a constant resistance under all conditions. Special materials that have little or no change in resistance over a wide temperature range are used in that case.

Resistors

A "package" of resistance made up into a single unit is called a resistor. Resistors having the same resistance value may be considerably different in size and construction. The flow of current through resistance causes the conductor to become heated; the higher the resistance and the larger the current, the greater the amount of heat developed. Resistors intended for carrying large currents must be physically large so the heat can be radiated quickly to the surrounding air. If the resistor does not get rid of the heat quickly it may reach a temperature that will cause it to melt or burn.

Skin Effect

The resistance of a conductor is not the same for alternating current as it is for direct current. When the current is alternating there are internal effects that tend to force the current to flow mostly in the outer parts of the conductor. This decreases the effective cross-sectional area of the conductor, with the result that the resistance increases.

For low audio frequencies the increase in resistance is unimportant, but at radio frequencies this skin effect is so great that practically all the current flow is confined within a few thousandths of an inch of the conductor surface. The rf resistance is consequently many times the dc resistance, and increases with increasing frequency. In the rf range a conductor of thin tubing will have just as low resistance as a solid conductor of the same diameter, because material not close to the surface carries practically no current.

Conductance

The reciprocal of resistance (that is, $1/R$) is called conductance. It is usually represented by the symbol G. A circuit having large conductance has low resistance, and vice versa. In radio work the term is used chiefly in connection with vacuum-tube characteristics. The unit of conductance is the mho. A resistance of one ohm has a conductance of one mho, a resistance of 1000 ohms has a conductance of .001 mho, and so on. A unit frequently used in connection with vacuum tubes is the micromho, or one-millionth of a mho. It is the conductance of a resistance of one megohm.

OHM'S LAW

The simplest form of electric circuit is a battery with a resistance connected to its terminals, as shown by the symbols in Fig. 2-3. A complete circuit must have an unbroken path so current can flow out of the battery, through the apparatus connected to it, and back into the battery. The circuit is broken, or open, if a connection is removed at any point. A switch is a device for making and breaking connections and thereby closing or opening the circuit, either allowing current to flow or preventing it from flowing.

The values of current, voltage and resistance in a circuit are by no means independent of each

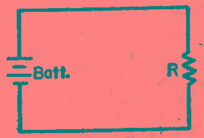


Fig. 2-3 — A simple circuit consisting of a battery and resistor.

TABLE 2-II

Conversion Factors for Fractional and Multiple Units

Change From	*To*	*Divide by*	*Multiply by*
Units	Micro-units		1,000,000
	Milli-units		1,000
	Kilo-units	1,000	
	Mega-units	1,000,000	
Micro-units	Milli-units	1,000	
	Units	1,000,000	
Milli-units	Micro-units		1,000
	Units	1,000	
Kilo-units	Units		1,000
	Mega-units	1,000	
Mega-units	Units		1,000,000
	Kilo-units		1,000

other. The relationship between them is known as Ohm's Law. It can be stated as follows: The current flowing in a circuit is directly proportional to the applied emf and inversely proportional to the resistance. Expressed as an equation, it is

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$$

The equation above gives the value of current when the voltage and resistance are known. It may be transposed so that each of the three quantities may be found when the other two are known:

$$E = IR$$

(that is, the voltage acting is equal to the current in amperes multiplied by the resistance in ohms) and

$$R = \frac{E}{I}$$

(or, the resistance of the circuit is equal to the applied voltage divided by the current).

All three forms of the equation are used almost constantly in radio work. It must be remembered that the quantities are in *volts, ohms* and *amperes*; other units cannot be used in the equations without first being converted. For example, if the current is in milliamperes it must be changed to the equivalent fraction of an ampere before the value can be substituted in the equations.

Table 2-II shows how to convert between the various units in common use. The prefixes attached to the basic-unit name indicate the nature of the unit. These prefixes are:

micro – one-millionth (abbreviated μ)
milli – one-thousandth (abbreviated *m*)
kilo – one thousand (abbreviated *k*)
mega – one million (abbreviated *M*)

For example, one microvolt is one-millionth of a volt, and one megohm is 1,000,000 ohms. There are therefore 1,000,000 microvolts in one volt, and 0.000001 megohm in one ohm.

The following examples illustrate the use of ohm's law:

The current flowing in a resistance of 20,000 ohms is 150 milliamperes. What is the voltage? Since the voltage is to be found, the equation to use is $E = IR$. The current must first be converted from milliamperes to amperes, and reference to the table shows that to do so it is necessary to divide by 1000. Therefore,

$$E = \frac{150}{1000} \times 20{,}000 = 3000 \text{ volts}$$

When a voltage of 150 is applied to a circuit the current is measured at 2.5 amperes. What is the resistance of the circuit? In this case R is the unknown, so

$$R = \frac{E}{I} = \frac{150}{2.5} = 60 \text{ ohms}$$

No conversion was necessary because the voltage and current were given in volts and amperes.

How much current will flow if 250 volts is applied to a 5000-ohm resistor? Since I is unknown

$$I = \frac{E}{R} = \frac{250}{5000} = 0.05 \text{ ampere}$$

Milliampere units would be more convenient for the current, and 0.05 amp. × 1000 = 50 milliamperes.

SERIES AND PARALLEL RESISTANCES

Very few actual electric circuits are as simple as the illustration in the preceding section. Commonly, resistances are found connected in a variety of ways. The two fundamental methods of connecting resistances are shown in Fig. 2-4. In the upper drawing, the current flows from the source of emf (in the direction shown by the arrow, let us say) down through the first resistance, *R1*, then through the second, *R2*, and then back to the source. These resistors are connected in series. The current everywhere in the circuit has the same value.

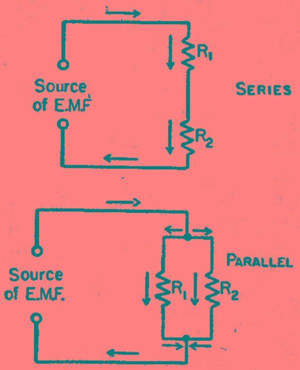


Fig. 2-4 — Resistors connected in series and in parallel.

In the lower drawing the current flows to the common connection point at the top of the two resistors and then divides, one part of it flowing through *R1* and the other through *R2*. At the lower connection point these two currents again combine; the total is the same as the current that flowed into the upper common connection. In this case the two resistors are connected in parallel.

Resistors in Series

When a circuit has a number of resistances connected in series, the total resistance of the circuit is the sum of the individual resistances. If these are numbered *R1, R2, R3*, etc., then *R* (total) = R1 + R2 + R3 + R4 + ...

where the dots indicate that as many resistors as necessary may be added.

Example: Suppose that three resistors are connected to a source of emf as shown in Fig. 2-5. The emf is 250 volts. R1 is 5000 ohms, R2 is 20,000 ohms, and R3 is 8000 ohms. The total resistance is then

$$R = R1 + R2 + R3 = 5000 + 20{,}000 + 8000$$
$$= 33{,}000 \text{ ohms}$$

The current flowing in the circuit is then

$$I = \frac{E}{R} = \frac{250}{33{,}000} = 0.00757 \text{ amp.} = 7.57 \text{ mA.}$$

(We need not carry calculations beyond three significant figures, and often two will suffice because the accuracy of measurements is seldom better than a few percent.)

Voltage Drop

Ohm's Law applies to *any part* of a circuit as well as to the whole circuit. Although the current is the same in all three of the resistances in the example, the total voltage divides among them. The voltage appearing across each resistor (the voltage drop) can be found from Ohm's Law.

Example: If the voltage across R1 (Fig. 2-5) is called E1, that across R2 is called E2, and that across R3 is called E3, then

$$E1 = IR1 = 0.00757 \times 5000 = 37.9 \text{ volts}$$
$$E2 = IR2 = 0.00757 \times 20{,}000 = 151.4 \text{ volts}$$
$$E3 = IR3 = 0.00757 \times 8000 = 60.6 \text{ volts}$$

The applied voltage must equal the sum of the individual voltage drops:

$$E = E1 + E2 + E3 = 37.9 + 151.4 + 60.6$$
$$= 249.9 \text{ volts}$$

The answer would have been more nearly exact if the current had been calculated to more decimal places, but as explained above a very high order of accuracy is not necessary.

In problems such as this considerable time and trouble can be saved, when the current is small enough to be expressed in milliamperes, if the resistance is expressed in kilohms rather than ohms. When resistance in kilohms is substituted directly in Ohm's Law the current will be milliamperes if the emf is in volts.

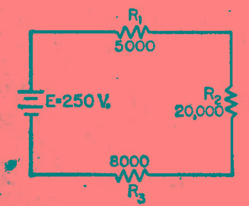


Fig. 2-5 — An example of resistors in series. The solution of the circuit is worked out in the text.

Resistors in Parallel

In a circuit with resistances in parallel, the total resistance is *less* than that of the *lowest* value of resistance present. This is because the total current is always greater than the current in any individual resistor. The formula for finding the total resistance of resistances in parallel is

$$R = \cfrac{1}{\cfrac{1}{R1} + \cfrac{1}{R2} + \cfrac{1}{R3} + \cfrac{1}{R4} + \ldots\ldots}$$

where the dots again indicate that any number of resistors can be combined by the same method. For only two resistances in parallel (a very common case) the formula becomes

$$R = \frac{R1R2}{R1 + R2}$$

Example: If a 500-ohm resistor is paralleled with one of 1200 ohms, the total resistance is

$$R = \frac{R1R2}{R1 + R2} = \frac{500 \times 1200}{500 + 1200} = \frac{600{,}000}{1700}$$
$$= 353 \text{ ohms}$$

It is probably easier to solve practical problems by a different method than the "reciprocal of reciprocals" formula. Suppose the three resistors of the previous example are connected in parallel as shown in Fig. 2-6. The same emf, 250 volts, is applied to all three of the resistors. The current in each can be found from Ohm's Law as shown below, *I1*, being the current through *R1*, *I2* the current through *R2* and *I3* the current through *R3*.

For convenience, the resistance will be expressed in kilohms so the current will be in milliamperes.

$$I1 = \frac{E}{R1} = \frac{250}{5} = 50 \text{ mA}$$

$$I2 = \frac{E}{R2} = \frac{250}{20} = 12.5 \text{ mA}$$

$$I3 = \frac{E}{R3} = \frac{250}{8} = 31.25 \text{ mA}$$

The total current is

$$I = I1 + I2 + I3 = 50 + 12.5 + 31.25$$
$$= 93.75 \text{ mA}$$

The total resistance of the circuit is therefore

$$R = \frac{E}{I} = \frac{250}{93.75} = 2.66 \text{ kilohms } (= 2660 \text{ ohms})$$

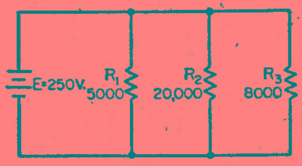


Fig. 2-6 — An example of resistors in parallel. The solution is worked out in the text.

Resistors in Series-Parallel

An actual circuit may have resistances both in parallel and in series. To illustrate, we use the same three resistances again, but now connected as in Fig. 2-7. The method of solving a circuit such as Fig. 2-7 is as follows: Consider *R2* and *R3* in parallel as through they formed a single resistor. Find their equivalent resistance. Then this resistance in series with *R1* forms a simple series circuit, as shown at the right in Fig. 2-7. An example of the arithmetic is given under the illustration.

Using the same principles, and staying within the practical limits, a value for *R2* can be computed that will provide a given voltage drop across *R3* or a given current through *R1*. Simple algebra is required.

Example: The first step is to find the equivalent resistance of R2 and R3. From the formula for two resistances in parallel,

$$\text{Req.} = \frac{R2R3}{R2 + R3} = \frac{20 \times 8}{20 + 8} = \frac{160}{28}$$
$$= 5.71 \text{ kilohms}$$

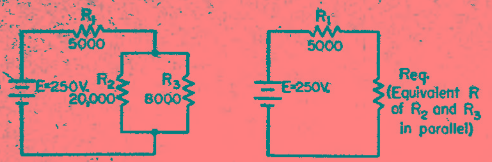


Fig. 2-7 — An exemple of resistors in series-parallel. The equivalent circuit is at the right. The solution is worked out in the text.

The total resistance in the circuit is then

$$R = R1 + Req. = 5 + 5.71 \text{ kilohms}$$
$$= 10.71 \text{ kilohms}$$

The current is

$$I = \frac{E}{R} = \frac{250}{10.71} = 23.3 \text{ mA}$$

The voltage drops across R1 and Req are

$$E1 = IR1 = 23.3 \times 5 = 117 \text{ volts}$$
$$E2 = IReq = 23.3 \times 5.71 = 133 \text{ volts}$$

with sufficient accuracy. These total 250 volts, thus checking the calculations so far, because the sum of the voltage drops must equal the applied voltage. Since E2 appears across both R2 and R3,

$$I2 = \frac{E2}{R2} = \frac{133}{20} = 6.65 \text{ mA}$$

$$I3 = \frac{E2}{R3} = \frac{133}{8} = 16.6 \text{ mA}$$

where I2 = Current through R2
I3 = Current through R3

The total is 23.25 mA, which checks closely enough with 23.3 mA, the current through the whole circuit.

POWER AND ENERGY

Power — the rate of doing work — is equal to voltage multiplied by current. The unit of electrical power, called the watt, is equal to one volt multiplied by one ampere. The equation for power therefore is

$P = EI$ where P = Power in watts
E = Emf in volts
I = Current in amperes

Common fractional and multiple units for power are the milliwatt, one one-thousandth of a watt, and the kilowatt, or one thousand watts.

Example: The plate voltage on a transmitting vacuum tube is 2000 volts and the plate current is 350 milliamperes. (The current must be changed to amperes before substitution in the formula, and so is 0.35 amp.) Then

$$P = EI = 2000 \times 0.35 = 700 \text{ watts}$$

By substituting the Ohm's Law equivalent for E and I, the following formulas are obtained for power:

$$P = \frac{E^2}{R} \qquad P = I^2R$$

These formulas are useful in power calculations when the resistance and either the current or voltage (but not both) are known.

Example: How much power will be used up in a 4000-ohm resistor if the voltage applied to it is 200 volts? From the equation

$$P = \frac{E^2}{R} = \frac{(200)^2}{4000} = \frac{40{,}000}{4000} = 10 \text{ watts}$$

Or, suppose a current of 20 milliamperes flows through a 300-ohm resistor. Then

$$P = I^2R = (0.02)^2 \times 300 = 0.0004 \times 300$$
$$= 0.12 \text{ watt}$$

Note that the current was changed from milliamperes to amperes before substitution in the formula.

Electrical power in a resistance is turned into heat. The greater the power the more rapidly the heat is generated. Resistors for radio work are made in many sizes, the smallest being rated to "dissipate" (or carry safely) about 1/8 watt. The largest resistors commonly used in amateur equipment will dissipate about 100 watts.

Generalized Definition of Resistance

Electrical power is not always turned into heat. The power used in running a motor, for example, is converted to mechanical motion. The power supplied to a radio transmitter is largely converted into radio waves. Power applied to a loudspeaker is changed into sound waves. But in every case of this kind the power is completely "used up" — it cannot be recovered. Also, for proper operation of the device the power must be supplied at a definite ratio of voltage to current. Both these features are characteristics of resistance, so it can be said that any device that dissipates power has a definite value of "resistance." This concept of resistance as something that absorbs power at a definite voltage/current ratio is very useful, since it permits substituting a simple resistance for the load or power-consuming part of the device receiving power, often with considerable simplification of calculations. Of course, every electrical device has some resistance of its own in the more narrow sense, so a part of the power supplied to it is dissipated in that resistance and hence appears as heat even though the major part of the power may be converted to another form.

Efficiency

In devices such as motors and vacuum tubes, the object is to obtain power in some other form than heat. Therefore power used in heating is considered to be a loss, because it is not the *useful* power. The efficiency of a device is the useful power output (in its converted form) divided by the power input to the device. In a vacuum-tube transmitter, for example, the object is to convert power from a dc source into ac power at some radio frequency. The ratio of the rf power output to the dc input is the efficiency of the tube. That is,

$$Eff. = \frac{P_o}{P_i}$$

where $Eff.$ = Efficiency (as a decimal)
P_o = Power output (watts)
P_i = Power input (watts)

Example: If the dc input to the tube is 100 watts, and the rf power output is 60 watts, the efficiency is

$$Eff. = \frac{P_o}{P_i} = \frac{60}{100} = 0.6$$

Efficiency is usually expressed as a percentage; that is, it tells what percent of the input power will be available as useful output. The efficiency in the above example is 60 percent.

Energy

In residences, the power company's bill is for electrical energy, not for power. What you pay for is the *work* that electricity does for you, not the *rate* at which that work is done. Electrical work is equal to power multiplied by time; the common unit is the watt-hour, which means that a power of one watt has been used for one hour. That is,

$W = PT$ where W = Energy in watt-hours
P = Power in watts
T = Time in hours

Other energy units are the kilowatt-hour and the watt-second. These units should be self-explanatory.

Energy units are seldom used in amateur practice, but it is obvious that a small amount of power used for a long time can eventually result in a "power" bill that is just as large as though a large amount of power had been used for a very short time.

CAPACITANCE

Suppose two flat metal plates are placed close to each other (but not touching) and are connected to a battery through a switch, as shown in Fig. 2-8. At the instant the switch is closed, electrons will be attracted from the upper plate to the positive terminal of the battery, and the same number will be repelled into the lower plate from the negative battery terminal. Enough electrons move into one plate and out of the other to make the emf between them the same as the emf of the battery.

If the switch is opened after the plates have been charged in this way, the top plate is left with a deficiency of electrons and the bottom plate with an excess. The plates remain charged despite the fact that the battery no longer is connected. However, if a wire is touched between the two plates (short-circuiting them) the excess electrons on the bottom plate will flow through the wire to the upper plate, thus restoring electrical neutrality. The plates have then been discharged.

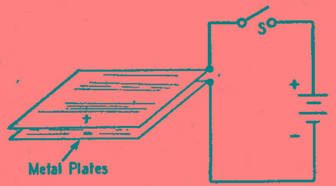


Fig. 2-8 — A simple capacitor.

The two plates constitute an electrical capacitor; a capacitor possesses the property of storing electricity. (The energy actually is stored in the electric field between the plates.) During the time the electrons are moving – that is, while the capacitor is being charged or discharged – a current is flowing in the circuit even though the circuit is "broken" by the gap between the capacitor plates. However, the current flows only during the time of charge and discharge, and this time is usually very short. There can be no continuous flow of direct current "through" a capacitor, but an alternating current can pass through easily if the frequency is high enough.

The charge or quantity of electricity that can be placed on a capacitor is proportional to the applied voltage and to the capacitance of the capacitor. The larger the plate area and the smaller the spacing between the plate the greater the capacitance. The capacitance also depends upon the kind of insulating material between the plates; it is smallest with air insulation, but substitution of other insulating materials for air may increase the capacitance many times. The ratio of the capacitance with some material other than air between the plates, to the capacitance of the same capacitor with air insulation, is called the dielectric constant of that particular insulating material. The material itself is called a dielectric. The dielectric constants of a number of materials commonly used as dielectrics in capacitors are given in Table 2-III. If a sheet of polystyrene is substituted for air between the plates of a capacitor, for example, the capacitance will be increased 2.6 times.

Units

The fundamental unit of capacitance is the farad, but this unit is much too large for practical work. Capacitance is usually measured in microfarads (abbreviated μF) or picofarads (pF). The microfarad is one-millionth of a farad, and the picofarad (formerly micromicrofarad) is one-millionth of a microfarad. Capacitors nearly always have more than two plates, the alternate plates being connected together to form two sets as shown in Fig. 2-9. This makes it possible to attain a fairly large capacitance in a small space, since several plates of smaller individual area can be

TABLE 2-III

Dielectric Constants and Breakdown Voltages

Material	*Dielectric Constant**	*Puncture Voltage***
Air	1.0	
Alsimag 196	5.7	240
Bakelite	4.4–5.4	300
Bakelite, mica-filled	4.7	325–375
Cellulose acetate	3.3–3.9	250–600
Fiber	5–7.5	150–180
Formica	4.6–4.9	450
Glass, window	7.6–8	200–250
Glass, Pyrex	4.8	335
Mica, ruby	5.4	3800–5600
Mycalex	7.4	250
Paper, Royalgrey	3.0	200
Plexiglass	2.8	990
Polyethylene	2.3	1200
Polystyrene	2.6	500–700
Porcelain	5.1–5.9	40–100
Quartz, fuxed	3.8	1000
Steatite, low-loss	5.8	150–315
Teflon	2.1	1000–2000

* At 1 MHz ** In volts per mil (0.001 inch)

Fig. 2-9 – A multiple-plate capacitor. Alternate plates are connected together.

stacked to form the equivalent of a single large plate of the same total area. Also, all plates, except the two on the ends, are exposed to plates of the other group on *both sides*, and so are twice as effective in increasing the capacitance.

The formula for calculating capacitance is:

$$C = 0.224 \frac{KA}{d} (n - 1)$$

where C = Capacitance in pF.
K = Dielectric constant of material between plates
A = Area of one side of *one* plate in square inches
d = Separation of plate surfaces in inches
n = Number of plates

If the plates in one group do not have the same area as the plates in the other, use the area of the *smaller* plates.

Capacitors in Radio

The types of capacitors used in radio work differ considerably in physical size, construction, and capacitance. Some representative types are shown in the photograph. In variable capacitors (almost always constructed with air for the dielectric) one set of plates is made movable with respect to the other set so that the capacitance can be varied. Fixed capacitors – that is, assemblies having a single, non-adjustable value of capacitance – also can be made with metal plates and with air as the dielectric, but usually are constructed from plates of metal foil with a thin solid or liquid dielectric sandwiched in between, so that a relatively large capacitance can be secured in a small unit. The solid dielectrics commonly used are mica, paper and special ceramics. An example of a liquid dielectric is mineral oil. The electrolytic capacitor uses aluminum-foil plates, with a semiliquid conducting chemical compound between them; the actual dielectric is a very thin film of insulating material that forms on one set of plates through electrochemical action when a dc voltage is applied to the capacitor. The capacitance obtained with a given plate area in an electrolytic capacitor is very large, compared with capacitors having other dielectrics, because the film is so thin – much less than any thickness that is practicable with a solid dielectric.

The use of electrolytic and oil-filled capacitors is confined to power-supply filtering and audio bypass applications. Mica and ceramic capacitors are used throughout the frequency range from audio to several hundred megacycles.

Voltage Breakdown

When a high voltage is applied to the plates of a capacitor, a considerable force is exerted on the electrons and nuclei of the dielectric. Because the dielectric is an insulator the electrons do not become detached from atoms the way they do in conductors. However, if the force is great enough the dielectric will "break down"; usually it will puncture and may char (if it is solid) and permit current to flow. The breakdown voltage depends upon the kind and thickness of the dielectric, as shown in Table 2-III. It is not directly proportional to the thickness; that is, doubling the thickness does not quite double the breakdown voltage. If the dielectric is air or any other gas, breakdown is evidenced by a spark or arc between the plates, but if the voltage is removed the arc ceases and the capacitor is ready for use again. Breakdown will occur at a lower voltage between pointed or sharp-edged surfaces than between rounded and polished surfaces; consequently, the breakdown voltage between metal plates of given spacing in air can be increased by buffing the edges of the plates.

Since the dielectric must be thick to withstand high voltages, and since the thicker the dielectric the smaller the capacitance for a given plate area, a high-voltage capacitor must have more plate area than a low-voltage one of the same capacitance. High-voltage high-capacitance capacitors are physically large.

Fixed and variable capacitors. The large unit at the left is a transmitting-type variable capacitor for rf tank circuits. To its right are other air-dielectric variables of different sizes ranging from the midget "air padder" to the medium-power tank capacitor at the top center. The cased capacitors in the top row are for power-supply filters, the cylindrical-can unit being an electrolytic and the rectangular one a paper-dielectric capacitor. Various types of mica, ceramic, and paper-dielectric capacitors are in the foreground.

CAPACITORS IN SERIES AND PARALLEL

The terms "parallel" and "series" when used with reference to capacitors have the same circuit meaning as with resistances. When a number of capacitors are connected in parallel, as in Fig. 2-10, the total capacitance of the group is equal to the sum of the individual capacitances, so

$$C\text{ (total)} = C1 + C2 + C3 + C4 + \ldots\ldots\ldots\ldots\ldots$$

However, if two or more capacitors are connected in series, as in the second drawing, the total capacitance is less than that of the smallest capacitor in the group. The rule for finding the capacitance of a number of series-connected capacitors is the same as that for finding the resistance of a number of *parallel*-connected resistors. That is,

$$C\text{ (total)} = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \frac{1}{C4} + \ldots\ldots\ldots\ldots}$$

and, for only two capacitors in series,

$$C\text{ (total)} = \frac{C1C2}{C1 + C2}$$

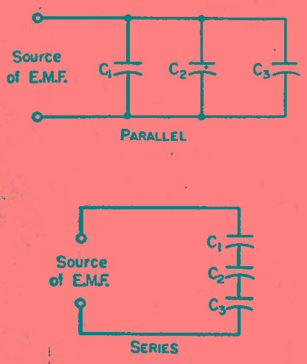


Fig. 2-10 — Capacitors in parallel and in series.

The same units must be used throughout; that is, all capacitances must be expressed in either μF or pF; both kinds of units cannot be used in the same equation.

Capacitors are connected in parallel to obtain a larger total capacitance than is available in one unit. The largest voltage that can be applied safely to a group of capacitors in parallel is the voltage that can be applied safely to the one having the *lowest* voltage rating.

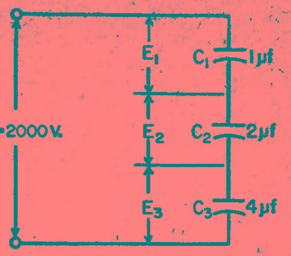


Fig. 2-11 — An example of capacitors connected in series. The solution to this arrangement is worked out in the text.

When capacitors are connected in series, the applied voltage is divided up among them, the situation is much the same as when resistors are in series and there is a voltage drop across each. However, the voltage that appears across each capacitor of a group connected in series is in *inverse* proportion to its capacitance, as compared with the capacitance of the whole group.

Example: Three capacitors having capacitances of 1, 2 and 4 μF, respectively, are connected in series as shown in Fig. 2-11. The total capacitance is

$$C = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}} = \frac{1}{\frac{1}{1} + \frac{1}{2} + \frac{1}{4}} = \frac{1}{\frac{7}{4}} = \frac{4}{7}$$

$$= 0.571\ \mu F$$

The voltage across each capacitor is proportional to the *total* capacitance divided by the capacitance of the capacitor in question, so the voltage across C1 is

$$E1 = \frac{0.571}{1} \times 2000 = 1142 \text{ volts}$$

Similarly, the voltages across C2 and C3 are

$$E2 = \frac{0.571}{2} \times 2000 = 571 \text{ volts}$$

$$E3 = \frac{0.571}{4} \times 2000 = 286 \text{ volts}$$

totaling approximately 2000 volts, the applied voltage.

Capacitors are frequently connected in series to enable the group to withstand a larger voltage (at the expense of decreased total capacitance) than any individual capacitor is rated to stand. However, as shown by the previous example, the applied voltages does not divide equally among the capacitors (except when all the capacitances are the same) so care must be taken to see that the voltage rating of no capacitor in the group is exceeded.

INDUCTANCE

It is possible to show that the flow of current through a conductor is accompanied by magnetic effects; a compass needle brought near the conductor, for example, will be deflected from its normal north-south position. The current, in other words, sets up a magnetic field.

The transfer of energy to the magnetic field represents work done by the source of emf. Power is required for doing work, and since power is equal to current multiplied by voltage, there must be a voltage drop in the circuit during the time in which energy is being stored in the field. This voltage "drop" (which has nothing to do with the voltage drop in any resistance in the circuit) is the result of an opposing voltage "induced" in the circuit while the field is building up to its final value. When the field becomes constant the induced emf or back emf disappears, since no further energy is being stored.

Since the induced emf opposes the emf of the source, it tends to prevent the current from rising rapidly when the circuit is closed. The amplitude of the induced emf is proportional to the rate at which the current is changing and to a constant associated with the circuit itself, called the inductance of the circuit.

Inductance depends on the physical characteristics of the conductor. If the conductor is formed into a coil, for example, its inductance is increased. A coil of many turns will have more inductance than one of few turns, if both coils are otherwise physically similar. Also, if a coil is placed on an iron core its inductance will be greater than it was without the magnetic core.

The polarity of an induced emf is always such as to oppose any change in the current in the circuit. This means that when the current in the circuit is increasing, work is being done against the induced emf by storing energy in the magnetic field. If the current in the circuit tends to decrease, the stored energy of the field returns to the circuit, and thus adds to the energy being supplied by the source of emf. This tends to keep the current flowing even though the applied emf may be decreasing or be removed entirely.

The unit of inductance is the henry. Values of inductance used in radio equipment vary over a wide range. Inductance of several henrys is required in power-supply circuits (see chapter on Power Supplies) and to obtain such values of inductance it is necessary to use coils of many turns wound on iron cores. In radio-frequency circuits, the inductance values used will be measured in millihenrys (a mH, one one-thousandth of a henry) at low frequencies, and in microhenrys (µH, one one-millionth of a henry) at medium frequencies and higher. Although coils for radio frequencies may be wound on special iron cores (ordinary iron is not suitable) most rf coils made and used by amateurs are of the "air-core" type; that is, wound on an insulating support consisting of nonmagnetic material.

Every conductor has inductance, even though the conductor is not formed into a coil. The inductance of a short length of straight wire is small, but it may not be negligible because if the current through it changes its intensity rapidly enough the induced voltage may be appreciable. This will be the case in even a few inches of wire when an alternating current having a frequency of the order of 100 MHz. or higher is flowing. However, at much lower frequencies the inductance of the same wire could be ignored because the induced voltage would be negligibly small.

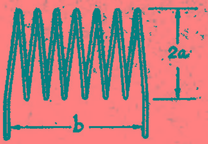


Fig. 2-12 – Coil dimensions used in the inductance formula. The wire diameter does not enter into the formula.

Calculating Inductance

The approximate inductance of single-layer air-core coils may be calculated from the simplified formula

$$L\ (\mu\text{H}) = \frac{a^2 n^2}{9a + 10b}$$

where L = Inductance in microhenrys
a = Coil radius in inches
b = Coil length in inches
n = Number of turns

The notation is explained in Fig. 2-12. This formula is a close approximation for coils having a length equal to or greater than $0.8a$

Example: Assume a coil having 48 turns wound 32 turns per inch and a diameter of 3/4 inch. Thus $a = 0.75 \div 2 = 0.375$, $b = 48 \div 32 = 1.5$, and $n = 48$. Substituting,

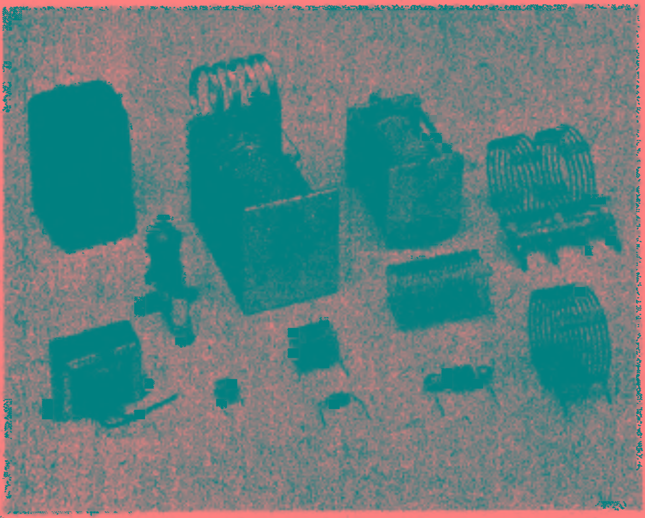
$$L = \frac{.375 \times .375 \times 48 \times 48}{(9 \times .375) \div (10 \times 1.5)} = 17.6\ \mu\text{H}$$

To calculate the number of turns of a single-layer coil for a required value of inductance,

$$n = \sqrt{\frac{L\,(9a + 10b)}{a^2}}$$

Example: Suppose an inductance of 10 µH is required. The form on which the coil is to be wound has a diameter of one inch and is long enough to accommodate a coil of 1 1/4 inches. Then $a = 0.5$, $b = 1.25$, and $L = 10$. Substituting,

$$n = \sqrt{\frac{10\,(4.5 \div 12.5)}{.5 \times .5}} = \sqrt{680} = 26.1 \text{ turns}$$



Inductors for power end radio frequencies. The two iron-core coils at the left ere "chokes" for power-supply filters. The mounted air-core coils at the top center are adjustable inductors for transmitting tank circuits. The "pie-wound" coils at the left and in the foreground are radio-frequency choke coils. The remaining coils are typical of inductors used in rf tuned circuits, the larger sizes being used principally for transmitters.

A 26-turn coil would be close enough in practical work. Since the coil will be 1.25 inches long, the number of turns per inch will be 26.1 ÷ 1.25 =20.8. Consulting the wire table, we find that No. 17 enameled wire (or anything smaller) can be used. The proper inductance is obtained by winding the required number of turns on the form and then adjusting the spacing between the turns to make a uniformly-spaced coil 1.25 inches long.

Inductance Charts

Most inductance formulas lose accuracy when applied to small coils (such as are used in vhf work and in low-pass filters built for reducing harmonic interference to television) because the conductor thickness is no longer negligible in comparison with the size of the coil. Fig. 2-13 shows the measured inductance of vhf coils, and may be used as a basis for circuit design. Two curves are given: curve A is for coils wound to an inside diameter of 1/2 inch; curve B is for coils of 3/4-inch inside diameter. In both curves the wire size is No. 12, winding pitch 8 turns to the inch (1/8 inch center-to-center turn spacing). The inductance values given include leads 1/2 inch long.

The charts of Figs. 2-14 and 2-15 are useful for rapid determination of the inductance of coils of the type commonly used in radio-frequency circuits in the range 3-30 MHz. They are of sufficient accuracy for most practical work. Given the coil length in inches, the curves show the multiplying factor to be applied to the inductance value given in the table below the curve for a coil of the same diameter and number of turns per inch.

Example: A coil 1 inch in diameter is 1 1/4 inches long and has 20 turns. Therefore it has 16 turns per inch, and from the table under Fig. 2-15 it is found that the reference inductance for a coil of this diameter and number of turns per inch is 16.8 μH. From curve B in the figure the multiplying factor is 0.35, so the inductance is

$$16.8 \times 0.35 = 5.9\ \mu H$$

The charts also can be used for finding suitable dimensions for a coil having a required value of inductance.

Example: A coil having an inductance of 12 μH is required. It is to be wound on a form having a diameter of 1 inch, the length available for the winding being not more than 1 1/4 inches. From Fig. 2-15, the multiplying factor for a 1-inch diameter coil (curve B) having the maximum possible length of 1 1/4 inches is 0.35. Hence the number of turns per inch must be chosen for a reference inductance of at least 12/0.35, or 34 μH. From the Table under Fig. 2-15 it is seen that 16 turns per inch (reference inductance 16.8 μH) is too small. Using 32 turns per inch, the multiplying factor is 12/68, or 0.177, and from curve B this corresponds to a coil length of 3/4 inch. There will be 24 turns in this length, since the winding "pitch" is 32 turns per inch.

Machine-wound coils with the diameters and turns per inch given in the tables are available in many radio stores, under the trade names of "B&W Miniductor" and "Illumitronic Air Dux."

IRON-CORE COILS

Permeability

Suppose that the coil in Fig. 2-16 is wound on an iron core having a cross-sectional area of 2 square inches. When a certain current is sent through the coil it is found that there are 80,000 lines of force in the core. Since the area is 2 square inches, the flux density is 40,000 lines per square inch. Now suppose that the iron core is removed and the same current is maintained in the coil, and that the flux density without the iron core is found to be 50 lines per square inch. The ratio of the flux density with the given core material to the flux density (with the same coil and same current) with an air core is called the **permeability** of the material. In this case the permeability of the iron is 40,000/50 = 800. The inductance of the coil is increased 800 times by inserting the iron core since, other things being equal, the inductance will be proportional to the magnetic flux through the coil.

The permeability of a magnetic material varies with the flux density. At low flux densities (or with an air core) increasing the current through the coil will cause a proportionate increase in flux, but at very high flux densities, increasing the current may cause no appreciable change in the flux. When this is so, the iron is said to be saturated. Saturation causes a rapid decrease in permeability, because it decreases the ratio of flux lines to those obtainable with the same current and an air core. Obviously, the inductance of an iron-core inductor is highly dependent upon the current flowing in the coil. In an air-core coil, the inductance is independent of current because air does not saturate.

Iron core coils such as the one sketched in Fig. 2-16 are used chiefly in power-supply equipment. They usually have direct current flowing through the winding, and the variation in inductance with current is usually undesirable. It may be overcome by keeping the flux density below the saturation point of the iron. This is done by opening the core so that there is a small "air gap," as indicated by the dashed lines. The magnetic "resistance" introduced by such a gap is so large – even though the gap is only a small fraction of an inch – compared with that of the iron that the gap, rather than the iron, controls the flux density. This reduces the inductance, but makes it practically constant regardless of the value of the current.

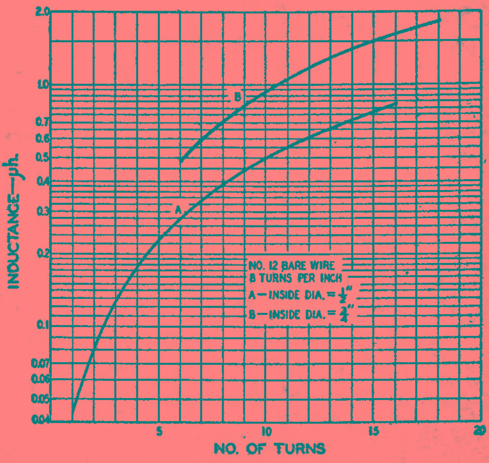


Fig. 2-13 – Measured inductance of coils wound with No. 12 bare wire, 8 turns to the inch. The values include half-inch leads.

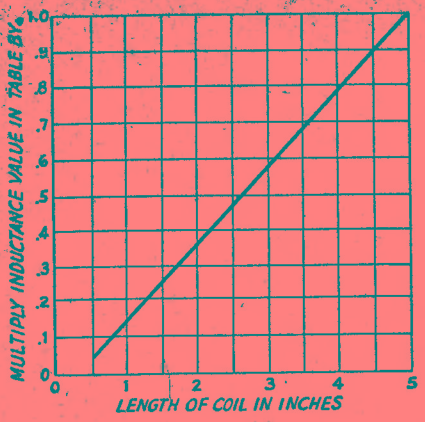


Fig. 2-14 – Factor to be applied to the inductance of coils listed in the table below, for coil lengths up to 5 inches.

Eddy Currents and Hysteresis

When alternating current flows through a coil wound on an iron core an emf will be induced, as previously explained, and since iron is a conductor a current will flow in the core. Such currents (called eddy currents) represent a waste of power because they flow through the resistance of the iron and thus cause heating. Eddy-current losses can be reduced by laminating the core; that is, by cutting it into thin strips. These strips or laminations must be insulated from each other by painting them with some insulating material such as varnish or shellac.

There is also another type of energy loss: the iron tends to resist any change in its magnetic state, so a rapidly-changing current such as ac is forced continually to supply energy to the iron to overcome this "inertia." Losses of this sort are called hysteresis losses.

Eddy-current and hysteresis losses in iron increase rapidly as the frequency of the alternating current is increased. For this reason, ordinary iron cores can be used only at power and audio frequencies – up to, say, 15,000 cycles. Even so, a very good grade of iron or steel is necessary if the core is to perform well at the higher audio frequencies. Iron cores of this type are completely useless at radio frequencies.

Coil dia, Inches	*No. of tpi*	*Inductance in μH*
1 1/4	4	2.75
	6	6.3
	8	11.2
	10	17.5
	16	42.5
1 1/2	4	3.9
	6	8.8
	8	15.6
	10	24.5
	16	63
1 3/4	4	5.2
	6	11.8
	8	21
	10	33
	16	85
2	4	6.6
	6	15
	8	26.5
	10	42
	16	108
2 1/2	4	10.2
	6	23
	8	41
	10	64
3	4	14
	6	31.5
	8	56
	10	89

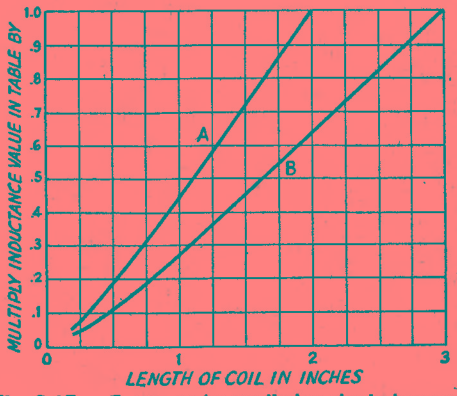


Fig. 2-15 – Factor to be applied to the inductance of coils listed in the table below, as a function of coil length. Use curve A for coils marked *A*, and curve B for coils marked *B*.

Coil dia, Inches	*No. of tpi*	*Inductance in μH*
1/2 (A)	4	0.18
	6	0.40
	8	0.72
	10	1.12
	16	2.9
	32	12
5/8 (A)	4	0.28
	6	0.62
	8	1.1
	10	1.7
	16	4.4
	32	18
3/4 (B)	4	0.6
	6	1.35
	8	2.4
	10	3.8
	16	9.9
	32	40
1 (B)	4	1.0
	6	2.3
	8	4.2
	10	6.6
	16	16.9
	32	68

For radio-frequency work, the losses in iron cores can be reduced to a satisfactory figure by grinding the iron into a powder and then mixing it with a "binder" of insulating material in such a way that the individual iron particles are insulated from each other. By this means cores can be made that will function satisfactorily even through the vhf range – that is, at frequencies up to perhaps 100 MHz. Because a large part of the magnetic path is through a nonmagnetic material, the permeability of the iron is low compared with the values

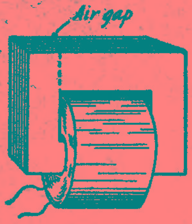


Fig. 2-16 — Typical construction of an iron-core inductor. The small air gap prevents magnetic saturation of the iron and thus maintains the inductance et high currents.

obtained at power-supply frequencies. The core is usually in the form of a "slug" or cylinder which fits inside the insulating form on which the coil is wound. Despite the fact that, with this construction, the major portion of the magnetic path for the flux is in air, the slug is quite effective in increasing the coil inductance. By pushing the slug in and out of the coil the inductance can be varied over a considerable range.

INDUCTANCES IN SERIES AND PARALLEL

When two or more inductors are connected in series (Fig. 2-17, left) the total inductance is equal to the sum of the individual inductances, *provided the coils are sufficiently separated so that no coil is in the magnetic field of another.*

That is,

$$L_{total} = L1 + L2 + L3 + L4 + \dots\dots\dots\dots$$

If inductors are connected in parallel (Fig. 2-17, right) — and the coils are separated sufficiently, the total inductance is given by

$$L_{total} = \cfrac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \frac{1}{L4} + \dots\dots}$$

and for two inductances in parallel,

$$L = \frac{L1L2}{L1 + L2}$$

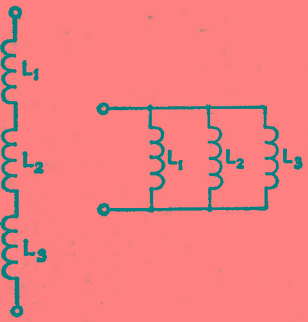


Fig. 2-17 — Inductances in series and parallel.

Thus the rules for combining inductances in series and parallel are the same for resistances, *if* the coils are far enough apart so that each is unaffected by another's magnetic field. When this is not so the formulas given above cannot be used.

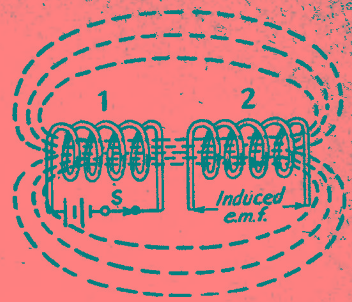


Fig. 2-18 — Mutual inductance. When the switch, *S*, is closed current flows through coil No. 1, setting up a magnetic field that induces an emf in the turns of coil No. 2.

MUTUAL INDUCTANCE

If two coils are arranged with their axes on the same line, as shown in Fig. 2-18, a current sent through Coil 1 will cause a magnetic field which "cuts" Coil 2. Consequently, an emf will be induced in Coil 2 whenever the field strength is changing. This induced emf is similar to the emf of self-induction, but since it appears in the *second* coil because of current flowing in the *first*, it is a "mutual" effect and results from the **mutual** inductance between the two coils.

If all the flux set up by one coil cuts all the turns of the other coil the mutual inductance has its maximum possible value. If only a small part of the flux set up by one coil cuts the turns of the other the mutual inductance is relatively small. Two coils having mutual inductance are said to be **coupled.**

The ratio of actual mutual inductance to the maximum possible value that could theoretically be obtained with two given coils is called the **coefficient of coupling** between the coils. It is frequently expressed as a percentage. Coils that have nearly the maximum possible (coefficient = 1 or 100%) mutual inductance are said to be **closely,** or **tightly,** coupled, but if the mutual inductance is relatively small the coils are said to be **loosely** coupled. The degree of coupling depends upon the physical spacing between the coils and how they are placed with respect to each other. Maximum coupling exists when they have a common axis and are as close together as possible (one wound over the other). The coupling is least when the coils are far apart or are placed so their axes are at right angles.

The maximum possible coefficient of coupling is closely approached only when the two coils are wound on a closed iron core. The coefficient with air-core coils may run as high as 0.6 or 0.7 if one coil is wound over the other, but will be much less if the two coils are separated.

TIME CONSTANT

Capacitance and Resistance

Connecting a source of emf to a capacitor causes the capacitor to become charged to the full emf practically instantaneously, if there is no resistance in the circuit. However, if the circuit contains resistance, as in Fig. 2-19A, the resistance limits the current flow and an appreciable length of time is required for the emf between the capacitor

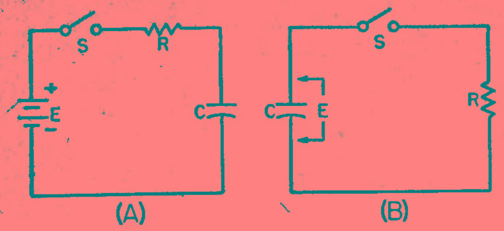


Fig. 2-19 — Illustrating the time constant of an *RC* circuit.

plates to build up to the same value as the emf of the source. During this "building-up" period the current gradually decreases from its initial value, because the increasing emf stored on the capacitor offers increasing opposition to the steady emf of the source.

Theoretically, the charging process is never really finished, but eventually the charging current drops to a value that is smaller than anything that can be measured. The time constant of such a circuit is the length of time, in seconds, required for the voltage across the capacitor to reach 63 per cent of the applied emf (this figure is chosen for mathematical reasons). The voltage across the capacitor rises with time as shown by Fig. 2-20.

The formula for time constant is

$$T = RC$$

where T = Time constant in seconds
C = Capacitance in farads
R = Resistance in ohms

Example: The time constant of a 2-μF capacitor and a 250,000-ohm (0.25 megohm) resistor is

$$T = RC = 0.25 \times 2 = 0.5 \text{ second}$$

If the applied emf is 1000 volts, the voltage between the capacitor plates will be 630 volts at the end of 1/2 second.

If C is in microfarads and R in megohms, the time constant also is in seconds. These units usually are more convenient.

If a charged capacitor is *discharged* through a resistor, as indicated in Fig. 2-19B, the same time constant applies. If there were no resistance, the capacitor would discharge instantly when S was closed. However, since R limits the current flow the capacitor voltage cannot instantly go to zero, but it will decrease just as rapidly as the capacitor can rid itself of its charge through R. When the capacitor is discharging through a resistance, the time constant (calculated in the same way as above) is the time, in seconds, that it takes for the capacitor to *lose* 63 percent of its voltage; that is, for the voltage to drop to 37 percent of its initial value.

Example: If the capacitor of the example above is charged to 1000 volts, it will discharge to 370 volts in 1/2 second through the 250,000-ohm resistor.

Inductance and Resistance

A comparable situation exists when resistance and inductance are in series. In Fig. 2-21, first consider L to have no resistance and also assume that R is zero. Then closing S would tend to send a current through the circuit. However, the instantaneous transition from no current to a finite value, however small, represents a very rapid *change* in current, and a *back emf* is developed by the self-inductance of L that is practically equal and opposite to the applied emf. The result is that the initial current is very small.

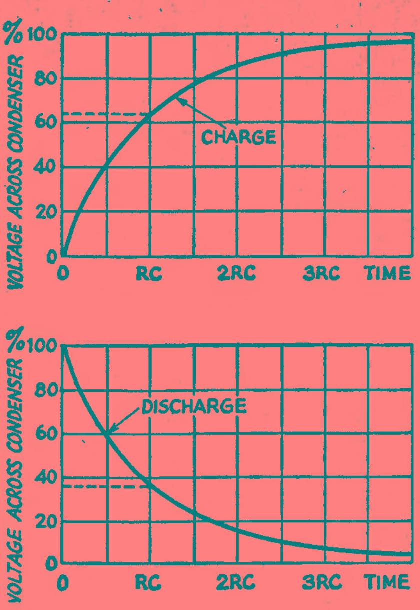


Fig. 2-20 — How the voltage across a capacitor rises, with time, when charged through a resistor. The lower curve shows the way in which the voltage decreases across the capacitor terminals on discharging through the same resistor.

The back emf depends upon the *change* in current and would cease to offer opposition if the current did not continue to increase. With no resistance in the circuit (which would lead to an infinitely large current, by Ohm's Law) the current would increase forever, always growing just fast enough to keep the emf of self-induction equal to the applied emf.

When resistance is in series, Ohm's Law sets a limit to the value that the current can reach. The back emf generated in L has only to equal the *difference* between E and the drop across R, because that difference is the voltage actually applied to L. This difference becomes smaller as the current approaches the final Ohm's Law value. Theoretically, the back emf never quite disappears and so the current never quite reaches the Ohm's Law value, but practically the differences becomes unmeasurable after a time. The time constant of an

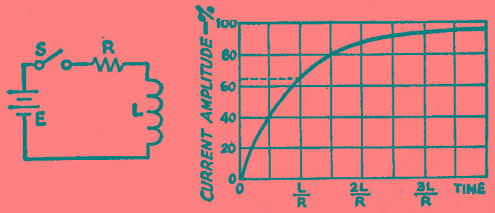


Fig. 2-21 — Time constant of an *LR* circuit.

inductive circuit is the time in seconds required for the current to reach 63 percent of its final value. The formula is

$$T = \frac{L}{R}$$

where T = Time constant in seconds
L = Inductance in Henrys
R = Resistance in ohms

The resistance of the wire in a coil acts as if it were in series with the inductance.

> Example: A coil having an inductance of 20 henrys and a resistance of 100 ohms has a time constant of
>
> $$T = \frac{L}{R} = \frac{20}{100} = 0.2 \text{ second}$$
>
> if there is no other resistance in the circuit. If a dc emf of 10 volts is applied to such a coil, the final current, by Ohm's Law, is
>
> $$I = \frac{E}{R} = \frac{10}{100} = 0.1 \text{ amp. or } 100 \text{ mA}$$
>
> The current would rise from zero to 63 milliamperes in 0.2 second after closing the switch.

An inductor cannot be "discharged" in the same way as a capacitor, because the magnetic field disappears as soon as current flow ceases. Opening S does not leave the inductor "charged." The energy stored in the magnetic field instantly returns to the circuit when S is opened. The rapid disappearance of the field causes a very large voltage to be induced in the coil – ordinarily many times larger than the voltage applied, because the induced voltage is proportional to the *speed* with which the field changes. The common result of opening the switch in a circuit such as the one shown is that a spark or arc forms at the switch contacts at the instant of opening. If the inductance is large and the current in the circuit is high, a great deal of energy is released in a very short period of time. It is not at all unusual for the switch contacts to burn or melt under such circumstances. The spark or arc at the opened switch can be reduced or suppressed by connecting a suitable capacitor and resistor in series across the contacts.

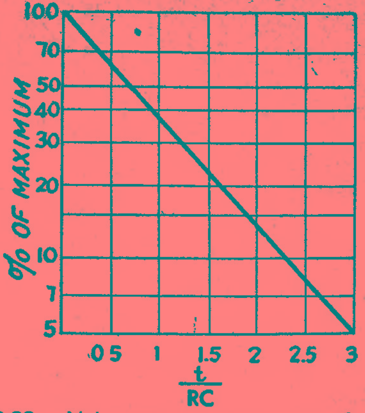


Fig. 2-22 – Voltage across capacitor terminals in a discharging *RC* circuit, in terms of the initial charged voltage. To obtain time in seconds, multiply the factor *t/RC* by the time constant of the circuit.

Time constants play an important part in numerous devices, such as electronic keys, timing and control circuits, and shaping of keying characteristics by vacuum tubes. The time constants of circuits are also important in such applications as automatic gain control and noise limiters. In nearly all such applications a resistance-capacitance (*RC*) time constant is involved, and it is usually necessary to know the voltage across the capacitor at some time interval larger or smaller than the actual time constant of the circuit as given by the formula above. Fig. 2-22 can be used for the solution of such problems, since the curve gives the voltage across the capacitor, in terms of percentage of the initial charge, for percentages between 5 and 100, at any time after discharge begins.

> Example: A 0.01-μF capacitor is charged to 150 volts and then allowed to discharge through a 0.1-megohm resistor. How long will it take the voltage to fall to 10 volts? In percentage, 10/150 = 6.7%. From the chart, the factor corresponding to 6.7% is 2.7. The time constant of the circuit is equal to $RC = 0.1 \times .01 = .001$. The time is therefore $2.7 \times 0.001 = .0027$ second, or 2.7 milliseconds.

ALTERNATING CURRENTS

PHASE

The term phase essentially means "time," or the *time interval* between the instant when one thing occurs and the instant when a second related thing takes place. The later event is said to *lag* the earlier, while the one that occurs first is said to *lead*. In ac circuits the current amplitude changes continuously, so the concept of phase or time becomes important. Phase can be measured in the ordinary time units, such as the second, but there is a more convenient method: Since each ac cycle occupies exactly the same amount of time as every other cycle of the same frequency, we can use the cycle itself as the time unit. Using the cycle as the time unit makes the specification or measurement of phase independent of the frequency of the current, so long as only one frequency is under consideration at a time. When two or more frequencies are to be considered, as in the case where harmonics are present, the phase measurements are made with respect to the lowest, or fundamental, frequency.

The time interval or "phase difference" under consideration usually will be less than one cycle. Phase difference could be measured in decimal parts of a cycle, but it is more convenient to divide the cycle into 360 parts or degrees. A phase degree is therefore 1/360 of a cycle. The reason for this choice is that with sine-wave alternating current the value of the current at any instant is proportional to the sine of the angle that corresponds to the number of degrees – that is, length of time – from the instant the cycle began. There is no actual "angle" associated with an alternating current. Fig. 2-23 should help make this method of measurement clear.