Elementary Electricity and Electronics component by component

Mannie Horowitz

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Elementary Electricity and Electronics

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FIRST EDITION

SECOND PRINTING

Printed in the United States of America

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Library of Congress Cataloging in Publication Data

Horowitz, Mannie.
Elementary electricity and electronics—component by component.

Includes index.
1. Electronics. I. Title.
TK7816.H73 1986 621.381 86-5961
ISBN 0-8306-0853-2
ISBN 0-8306-2753-7 (pbk.)

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Contents

	Introduction	**vii**
1	**Origins of Electricity** The Atom—Static Electricity—Current Electricity	1
2	**Relationship Between Current and Voltage** Resistors—Ohm's Law—Measuring Electricity	19
3	**Characteristics of Resistor Circuits** Series Circuits—Parallel Circuits—Circuit Analysis Series—Parallel Circuits—Power and Energy	39
4	**Alternating Current** Graphs and Things—Comparison of AC with DC—Transformers	77
5	**Passive Components in AC Circuits** Inductors—Capacitors—Filters—Resonance	112
6	**Diodes** Semiconductor Materials—Junction Diode Structure—Diode Rectifiers—Voltage Ratings, Power Ratings, etc.—Diodes in Series—Special Diodes	155
7	**Power Supplies** Full-Wave Supply—Bridge Rectifiers—Positive/Negative Supplies—Voltage Doublers, Triplers, etc.—Voltage Regulators—Meters to Measure Voltages	180

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

8 Bipolar Junction Transistors 211

The Junction Transistor—Current Gain or Loss—Circuits with Transistors—Coupled Stages—Darlington Pairs—Noise—Filters—Bias Circuits—Power Amplifiers

9 Field-Effect Transistors 252

Junction FETs—IGFETs and MOSFETs—Characteristics of FETs—FET Circuits—Bias Circuits—Dual-Gate FETs—Power FETs—Transistor Circuits

10 Feedback 274

Gain with Feedback—Positive Feedback—Voltage Regulators—Feedback Amplifiers—Operational Amplifiers—Radios

11 SCRs and Other Devices 308

Silicon Controlled Rectifier—Diacs—Triacs—Unijunction Transistor—The PUT—Electronic Flashtubes—Applications

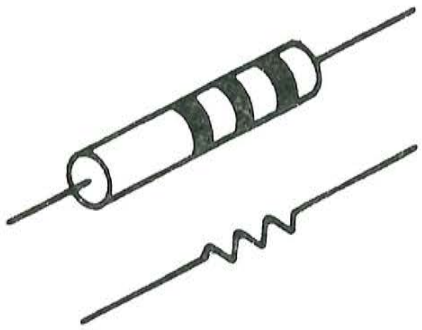
12 Digital Electronics 329

Number Systems—Logic Gates—AND Gates—OR Gates—NOT Gates—NAND and NOR Gates—XOR Gates and XNOR Gates—Symbols and Notations—Circuits with Gates—Flip-Flops—Digital Techniques

Index 350

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Chapter 3



Characteristics of Resistor Circuits

Voltmeter circuits were described as consisting of two resistors—the resistance of the meter movement and the resistance of a discrete component—both connected in a series circuit. This is one of many practical applications where two or more resistors or components with resistance are connected in series.

Another practical circuit arrangement consists of several resistors connected in *parallel*. Here, two or more resistors or other electric components are connected across one another. As in a series circuit, parallel circuits are designed into many different types of equipment.

Both arrangements may be present at the same time in an individual circuit. Either or both arrangement may have been deliberately designed into some of these circuits. In other circuits, these configurations may be present although the designer did not intentionally create this array.

SERIES CIRCUITS

Two series circuits are in Fig. 3-1. In Fig. 3-1A, a battery is in series with a single resistor, R_1. In Fig. 3-1B, a battery, resistor R_1 and resistor R_2 are all connected in series. When components are connected in series, the same current must flow through all components, because there is only one path for the current.

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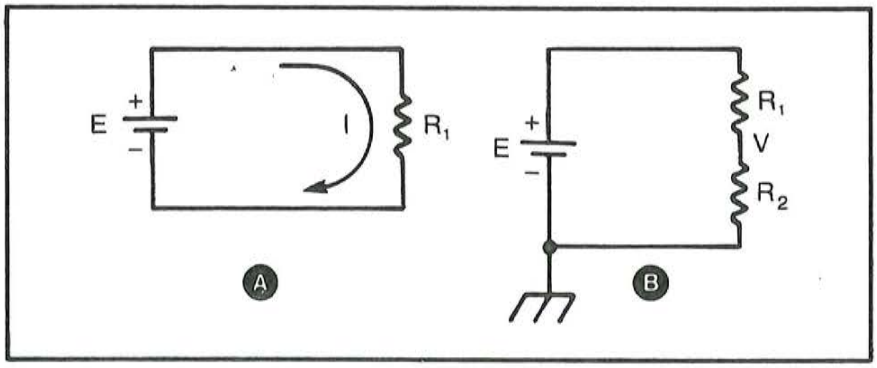


Fig. 3-1. Two circuits with components connected in series.

Equivalent Resistance

An important fact to remember is that when two or more resistors are connected in series, the equivalent resistance presented by the combination of the components is the sum of their individual resistances. If R_1 in Fig. 3-1B is 10 ohms and R_2 is 5 ohms, the total resistance supplied by the combination is $R_1 + R_2 = 15$ ohms. So if E is 1.5 volt, the current in the circuit, using Ohm's law, is 1.5 volt/15 ohms = 0.1 ampere. In A, with only R_1 in the circuit, the current would be 1.5 volt/10 ohms = 0.15 ampere.

Because the same quantity of current flows through both resistors in Fig. 3-1B, and because both components differ in resistance, a different portion of the applied 1.5 volt is across each resistor. Using Equation 2-3, the voltage across R_1 is 0.1 A × 10 ohm = 1 volt. In a similar fashion, it can be seen that the voltage across R_2 is 0.1 A × 5 ohm = 0.5 volt. Because both resistors are connected in a series circuit across the battery, the total voltage across the two resistors must be equal to that of the battery. This can be seen here when the 1 volt across the 10-ohm resistor is added to the 0.5 volt across the 5-ohm resistor. The total voltage across the two resistors is 1.5 volt.

Voltage is usually measured with respect to one point in a circuit. It is quite frequently the negative terminal of the battery or other power supply. This point in the circuit is usually referred to as the *common* or *ground.* Symbols used to indicate ground are shown in Fig. 3-2. These symbols may serve the dual function of also indicating that this point is connected to the chassis or two common land (common area) on a printed circuit board.

Voltage Divider

Utilizing the numbers determined above, assume 1.5 volt is at

EX-1043
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the plus (+) terminal of the battery with respect to its negative terminal and ground. In Fig. 3-1B, this is the same as the voltage at the upper terminal of R_1 with respect to ground. But the voltage at the junction of the two resistors and across R_2 with respect to the common ground is +0.5 volt. Using this circuit, we can therefore establish a method of supplying a terminal with a voltage that is lower with respect to ground or the negative battery terminal than is available at the positive battery terminal.

The two resistors in Fig. 3-1B form what is known as a *voltage divider*. If the resistors are selected properly, a specific voltage less than that of the supply will be at their junction. The voltage V at the junction is related to the supply voltage E by the equation

$$V = \left(\frac{R_2}{R_1 + R_2}\right) E \qquad \textbf{Eq.(3-1)}$$

Several examples will help to indicate how the voltage at the junction varies with the resistors in the circuit. Assume E is 1.5 volt.

In the first example, let's use the resistors we mentioned above where $R_1 = 10$ ohms and $R_2 = 5$ ohms. Substituting these numbers into the equation,

$$V = \left(\frac{5}{10 + 5}\right) 1.5 = 0.5 \text{ volt}$$

This is the same number of volts that was determined by using Ohm's law.

As a second example, assume R_1 and R_2 are interchanged so that $R_1 = 5$ ohms and $R_2 = 10$ ohms. Now

$$V = \left(\frac{10}{5 + 10}\right) 1.5 = 1 \text{ volt}$$

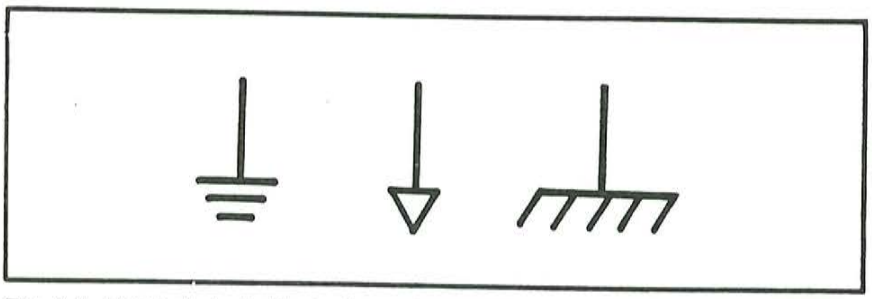


Fig. 3-2. Symbols to indicate the reference or ground point of a circuit.

EX-1043
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If both resistors are the same, let us say 10 ohms,

$$V = \left(\frac{10}{10 + 10}\right) 1.5 = 0.75 \text{ volt}$$

Now the voltage at the junction is one-half of the voltage provided by the supply.

Let's look at all this in another way. Assume that the supply is fixed at 10 volts and that R_2 must be 20 ohms. What must R_1 be if there is 2/10 or 0.2 volt at the output?

Using Equation 3-1, $V = [20/(R_1 + 20)]\, 10 = 0.2$ volt. Multiply the 20 in the numerator (top number of the fraction) by 10 to get 200 while the denominator (bottom number in the fraction) remains at $R_1 + 20$. You now have the simplified equation $200/(R_1 + 20) = 0.2$. Proceeding through the steps to determine R_1, start by multiplying both sides of the equation by $R_1 + 20$.

$$(R_1 + 20)\,(0.2) = \left(\frac{200}{R_1 + 20}\right)(R_1 + 20)$$

so

$$(R_1 + 20)\,(0.2) = 200$$

so that $0.2R_1 + 4 = 200$. Solving for R_1, we find it to be equal to $(200 - 4)/0.2 = 980$ ohms.

Multirange Voltmeter

Circuits that consist of more than two resistors connected in series are quite common. One such arrangement is shown in Fig. 3-3 where there are two resistors and the resistance of a meter movement in one series circuit. A switch has been added to the circuit to short R_2 when it is closed or set in the ON position. Assume a 1 mA meter movement is being used with a coil resistance, R_M, of 200 ohms, and its scale calibrated from 0 to 5.

This is essentially the voltmeter circuit in Fig. 2-7 with the addition of a second resistor, R_2, and a switch. Assume you want to measure up to 5 volts on one range. All that need be done to establish this range is to set the switch to ON to short R_2 and make the sum $R_1 + R_M$ equal to 5000 ohms because it is equal to (5 volts/1 mA). Because $R_M = 200$ ohms, R_1 must be 5000 ohms − 200 ohms = 4800 ohms.

EX-1043
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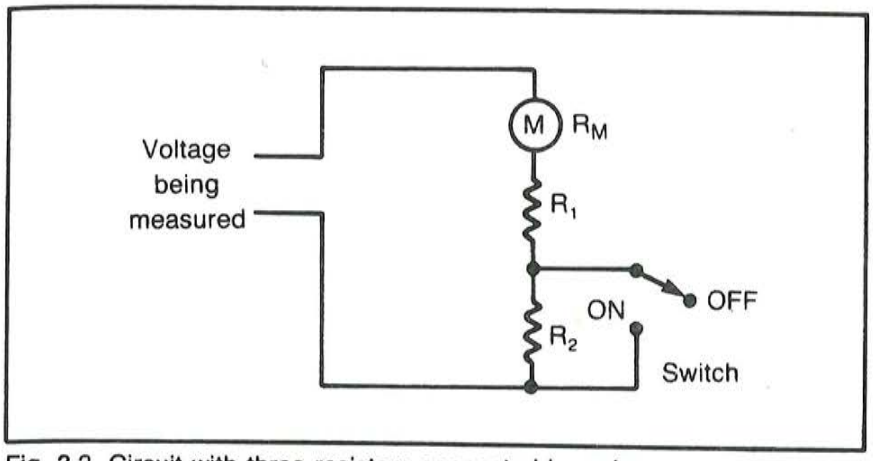


Fig. 3-3. Circuit with three resistors connected in series.

But now let us carry this a little further to a meter capable of measuring up to 50 volts. Anything above 5 volts at the input to the circuit as described, would cause more than 1 mA to flow through the meter. This would deflect the pointer off the scale and above its highest 5 volt marking. The new goal is to have the pointer deflect to 5 when 50 volts is applied to the circuit. In this way, the numbers on the meter face used for the 5-volt range can be multiplied by 10 to determine the newly applied unknown voltage. If the current is to be 1 mA when 50 volts is across the meter circuit, the total circuit resistance as determined by Equation 2-2 must be

$$\frac{50 \text{ volts}}{10^{-3} \text{ A}} = 50 \times 10^3$$
$$= 50{,}000 \text{ ohms.}$$

This can be achieved by setting the switch in the circuit in Fig. 3-3 to OFF so that R_2 is now in the circuit and connected in series with R_M and R_1. The total circuit resistance is now $R_M + R_1 + R_2$. Because $R_M + R_1$ is 5000 ohms, R_2 must be 50,000 – 5000 = 45,000 ohms.

You now have a voltmeter with two ranges—5 volts and 50-volts. When the switch is closed (set to ON, 5 volts must be applied to the circuit for the pointer to deflect to 5 or full scale. When the switch is open (set to OFF), 50 volts must be applied to the circuit for the pointer to deflect to 5. The two ranges are useful. If only the 50-volt range were available, 5 volts or less would cause the pointer to deflect to the lower 1/10 , or below 10% full scale. Readings of low voltages could not be made with the same preci-

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sion on the lower portion of the scale as when the pointer is deflected to near full scale. This larger deflection capability for the low voltages, is possible only when these low voltages can deflect the pointer to indicate a reading near full scale.

Should you want a voltmeter with facilities for full scale deflection when either 50 volts, 5 volts, or 0.5 volt is applied across the test leads, the circuit in Fig. 3-4 can be used. Here, four resistors are connected in series, namely R_1, R_2, R_3 and (meter resistance) R_M. Unlike the two position switch drawn in Fig. 3-3, a three-position switch is used in this circuit. In position #1 of the switch shown in the drawing, the moving arm or wiper of the switch is connected to its terminal #1. This shorts resistors R_1 and R_2, leaving only R_3 in the circuit along with R_M. In the second switch position, the wiper is connected to terminal #2 of the switch, shorting only R_2. As for the third switch position, the wiper is connected to terminal #3. Because this terminal is not connected to any point in the circuit, no resistors are shorted when the switch is put into this setting.

In switch position #1, with only R_3 and R_M in the circuit, 1 mA must flow when 0.5 volt is applied. Therefore $R_3 + R_M$ must be equal to 0.5 volt/10^{-3}ampere = 500 ohms. Because R_M was previously indicated as being equal to 200 ohms, R_3 = 500 ohms – 200 ohms = 300 ohms. For the 5-volt range when the wiper makes contact with terminal #2 of the switch, you know from the previous discussion that the total circuit resistance must be 5000 ohms. Because there is 500 ohms already in the circuit, R_1 should be 5000 ohms – 500 – ohms = 4500 ohms. As for R_2, it should be

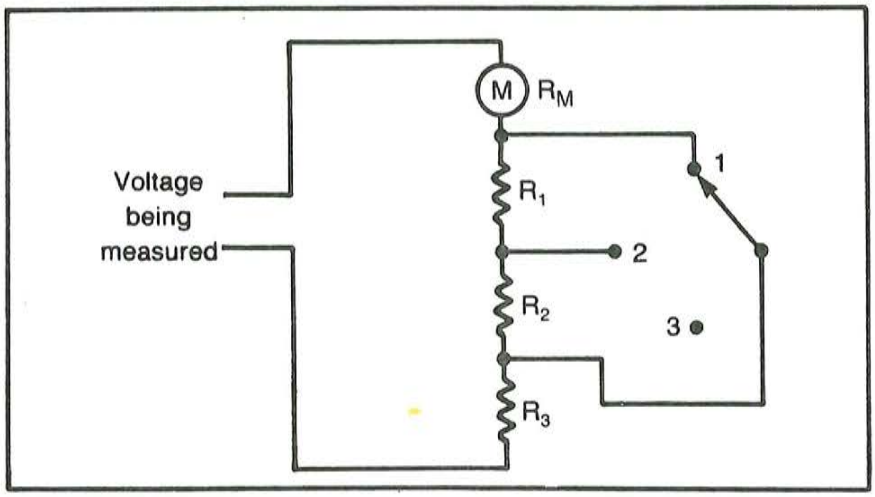


Fig. 3-4. Three-range voltmeter.

EX-1043
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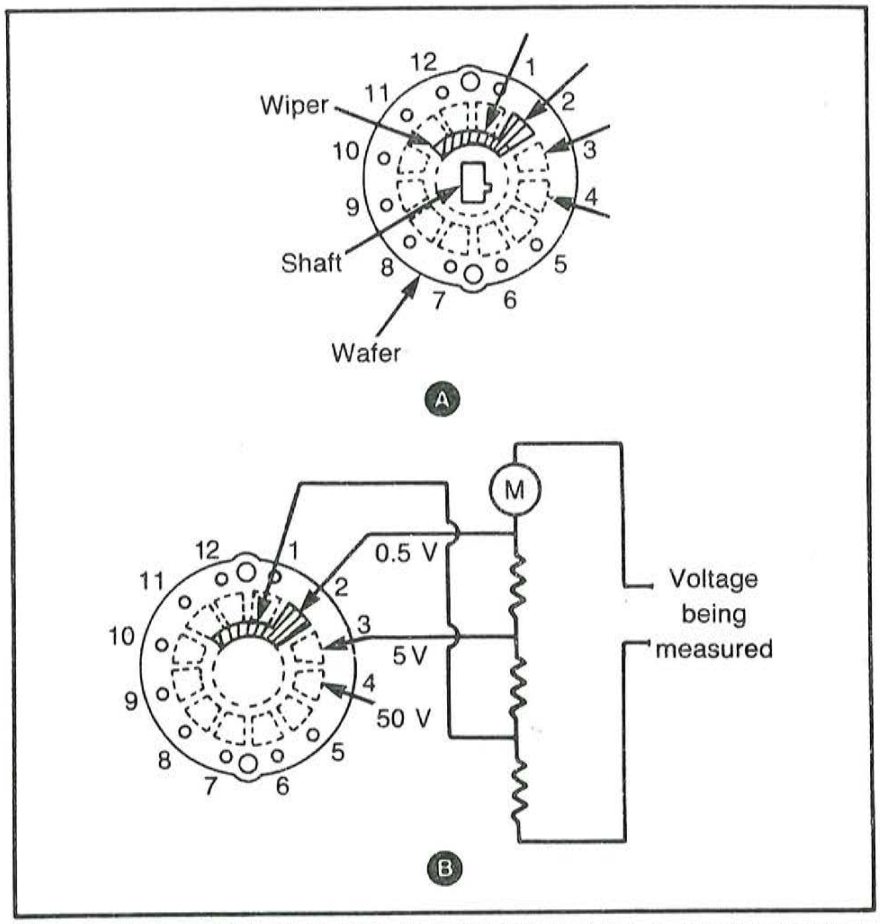


Fig. 3-5. Rotary switch. A. Designation of parts on wafer. B. Three-range voltmeter using a rotary switch to select ranges.

made equal to 45,000 ohms as before, so that $R_1 + R_2 + R_3 + R_M = 4500 + 45{,}000 + 300 + 200 = 50{,}000$ ohms, the circuit resistance required for a 50-volt range when a 1 mA meter movement is being used.

The schematic representation of the switch drawn in Fig. 3-4, can represent any one of the many different types of switches used in electronic and electric equipment. In voltmeters, the rotary-type switch in Fig. 3-5A is commonly used. It is readily available at electronic parts distributors. The mechanism consists of a shaft perpendicular to the wafer. Terminals that make contact with the wiper are mounted on the wafer. A knob is usually affixed to the shaft. The knob is used to rotate the shaft. It must be rotated to set the wiper in its different positions. Wiper contacts with the terminals, complete the circuit between the appropriate terminals on the wafer. These switch elements are shown in the drawing.

EX-1043
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Terminal #1 is the common or stator terminal. It is always connected to the wiper. As the wiper is rotated, it completes the circuit between terminal #1 and one of the other terminals. In the position shown, terminal #1 is connected to terminal #2. After the wiper is rotated 30° or one position further in a clockwise direction, terminal #1 gets connected to terminal #3. By rotating the wafer into its third position, terminal #1 gets connected to terminal #4. Only these three positions is necessary for the three-range voltmeter circuit described here. But there is actually sufficient room to accommodate twelve terminals on this wafer. In each position, terminal #1 would be connected to one of the other terminals, so that it is connected, in turn, to terminals #2 through #12. The terminal to which it is connected depends upon how much the wiper has been rotated from the setting shown in the figure.

The circuit in Fig. 3-4 is repeated in Fig. 3-5B. But this time a practical rotating switch is used. Different voltage ranges are selected by the different positions on the switch.

Many of the practical voltmeters on the market have different circuit arrangements. In all of these no more than one resistor is in series with the meter movement in any switch setting. A different resistor is switched into the circuit in each of the ranges. A schematic showing this is shown in Fig. 3-6.

In position 1, the 200-ohm meter movement is in series with a 300-ohm resistor for a total resistance of 500 ohms. This combination establishes the 0.5 volt range for the voltmeter. Similarly, in position #2, the 4800-ohm resistor is switched into the circuit so that it is in series with the 200-ohm meter. In this way, the total circuit resistance of 5000 ohms is achieved to establish the 5-volt

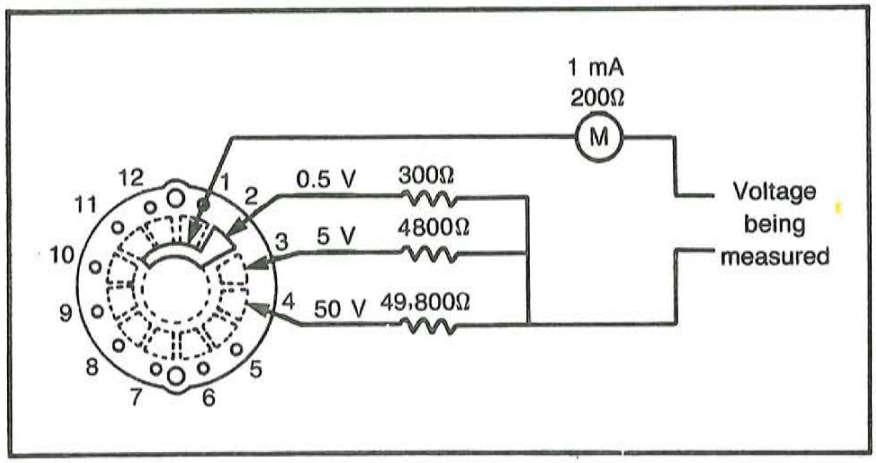


Fig. 3-6. Conventional voltmeter circuit.

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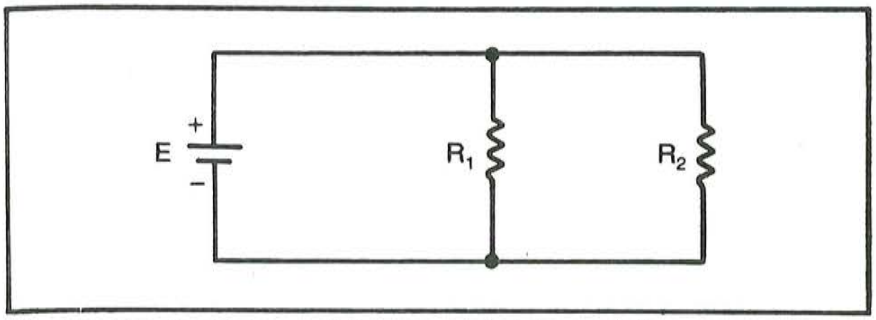


Fig. 3-7. Circuit with two resistors connected in parallel.

range. A total of 50,000 ohms, 200 ohms + 49,800 ohms is present for the 50-volt range in the third setting of the switch.

PARALLEL CIRCUITS

A circuit with two resistors connected in parallel, is in Fig. 3-7. The same voltage is across each of the resistors because both resistors are connected directly across the battery. Considering this and Equation 2-1, the current I_1 through R_1 is E/R_1 and the current I_2 through R_2 is E/R_2. The total current supplied by the battery is the current flowing through both resistors or $E/R1 + E/R_2$.

Using numbers, if E is set equal to 1.5 volt, R_1 = 1.5 ohms and R_2 = 3 ohms, the total current flowing through the circuit is 1.5 volt/1.5 ohm + 1.5 volt/3 ohms = 1 A + 0.5 A = 1.5 A. If there were one resistor, R_P, instead of two resistors, it would draw the same amount of current from the battery as is demanded by the two resistors, if R_P were made equal to 1.5 volt/1.5 amps = 1 ohm. This 1 ohm is the *equivalent resistance* of a 1.5-ohm and a 3-ohm resistor connected in parallel. The equivalent resistance of any two resistors connected in parallel can be determined by Equation 3-2

$$R_P = \frac{R_1 R_2}{R_1 + R_2} \qquad \textbf{Eq. 3-2}$$

Try it with the numbers just used where R_1 = 1.5 ohms and R_2 = 3 ohms.

$$R_P = \frac{(1.5)\,(3)}{1.5 + 3} = \frac{4.5}{4.5} = 1 \text{ ohm}$$

As an example, determine how much current a 9-volt battery must

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be capable of supplying, if two resistors, R_1 = 9 ohms and R_2 = 4.5 ohms, are connected as shown in the parallel circuit in Fig. 3-7.

One method that can be used in determining the current is to calculate the current flowing through each individual resistor with the voltage applied and then add the two currents. Using this method the current through R_1 is 9 volt/9 ohm = 1 A. The current through R_2 is 9 volt/4.5 ohms = 2 A. The total battery current is then 1 A + 2 A = 3 A.

The alternate method of determining the current starts by calculating the equivalent resistance of the parallel combination. Here, it is (9 ohms) (4.5 ohms)/(9 ohms + 4.5 ohms) = 3 ohms. The current supplied by the battery to this resistance is 9 volts/3 ohms = 3 amperes. This is the same solution as when the resistors were considered individually. But the equivalent resistance method is more practical when the requirements and characteristics of different types of circuits must be determined.

Three Resistors in Parallel

It is quite simple to handle a circuit when three resistors are connected in parallel as in Fig. 3-8A. Because all three resistors are across the voltage source, E, the voltages across all of the resistors are identical. As a general rule, it should be noted that the

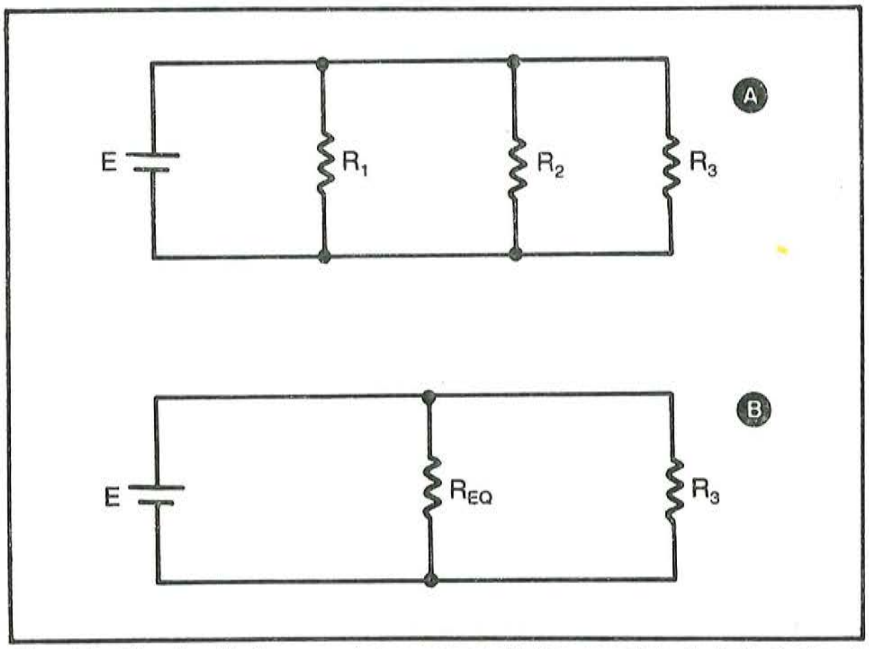


Fig. 3-8. Circuit with three resistors connected in parallel. A. Actual circuit. B. Circuit with the equivalent resistance of the R1 = R2 combination.

EX-1043
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voltages across all resistors connected in parallel are always identical. Consequently, the total current supplied by the battery to the combination is $E/R_1 + E/R_2 + E/R_3$.

One method of determining the equivalent resistance of the three resistors connected in parallel is to consider combinations of only two of these resistors at a time. Start with R_1 and R_2. The equivalent resistance, R_{EQ} of these two resistors connected in parallel is $R_1 R_2 + R_2/(R1)$. This equivalent resistance is in parallel with R_3, as shown in Fig. 3-8B. You now effectively have two resistors left in the circuit. The parallel resistance, R_{P7} of this new combination is $R_{EQ} R_3/(R_{EQ} + R_3)$. If E is divided by R_P, the quotient is the current the battery is supplying to the resistor combination. This current is identical to that calculated when considering the sum of the currents flowing through the resistors individually.

Four or More Resistors in Parallel

The method just described for determining the equivalent resistance of three resistors connected in parallel can become very tedious if more than three resistors are in the circuit. Considering the circuit in Fig. 3-9A with five resistors in parallel, the first idea would be to keep combining two resistors at a time until the solution will finally yield only one equivalent resistance for the overall circuit. This lengthy sequence is shown in Fig. 3-9B. All steps are indicated in turn, with the equivalent circuits and appropriate formulas. The combining sequence continues until there is but one resistance, R_P, left in the circuit. R_P represents the equivalent resistance of the five-resistor combination. It is the actual resistance seen by E, the supply voltage. The number of steps in the sequence depends upon the number of resistors connected in parallel. Equation 3-3 could have been used to determine the equivalent resistance in one shot:

$$\frac{1}{R_P} + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} \text{ etc.} \quad \textbf{[Eq. 3-3]}$$

This formula says to calculate the quotient of one divided by each of the resistors in the parallel circuit. Then add all the numbers (each number is referred to as the reciprocal of each resistance or as the *conductance* of each resistance) that are involved. Divide this sum into 1. After going through this process, you end up with the

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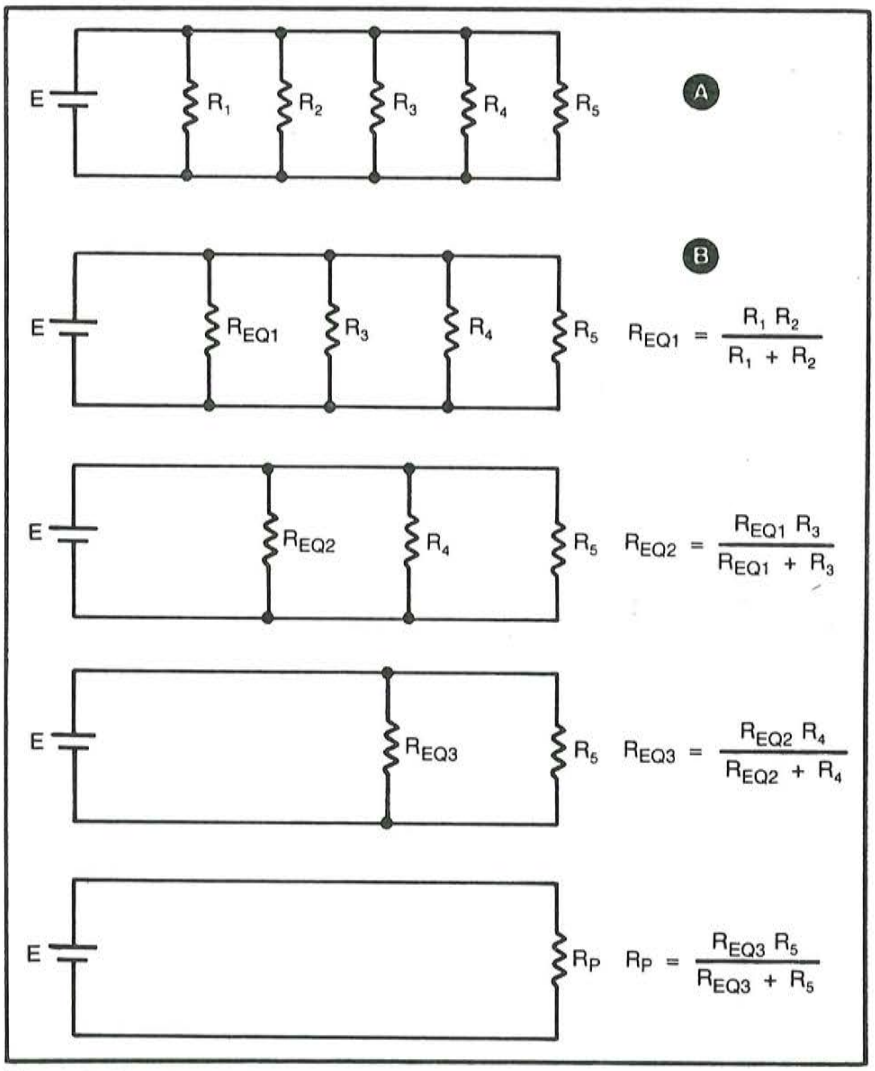


Fig. 3-9. Circuit with five resistors connected in parallel. A. Actual circuit. B. Sequence of calculations used to determine the equivalent resistance of the group of five resistors.

equivalent resistance of this combination. This is the same result that was achieved by using the procedure illustrated in Fig. 3-9B.

You now have a choice of two methods to use in determining the parallel resistance, R_P. You can take your pick. Either method supplies you with the same answer. But note that whatever R_P is, it is always less than the smallest resistance in the parallel circuit.

Current in Parallel Circuits

In an any parallel circuit, different quantities of current flow through different sections of the wire connecting the resistors. This

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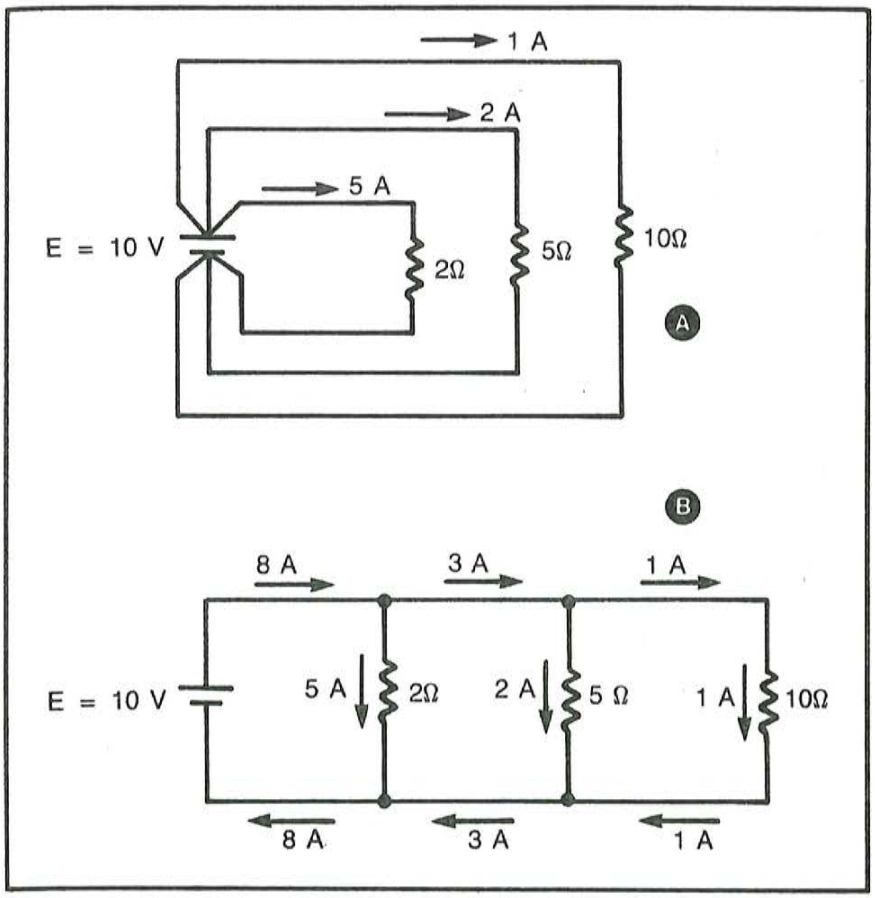


Fig. 3-10. Actual current in the leads from the battery to the resistors. A. All leads are connected directly to the battery terminals. B. Only one resistor is connected directly to the battery, while the second resistor is connected to the first resistor and the third resistor is connected to the second resistor.

can be demonstrated using the circuit in Fig. 3-10A where a power supply and three resistors are connected in parallel. Here leads from all resistors are connected directly to the battery. The total current flows only through the battery terminals. Current for each resistor flows only through the leads connected to that particular component. The total current supplied by the battery to the parallel resistor circuit, is the sum of the currents flowing through all resistor leads.

In Fig. 3-10B, the 1 A current for the 10-ohm resistor, flows through all wires. But only 1 A flows through the 10-ohm resistor and through the wires connected exclusively to that resistor.

The wires between the 2-ohm and 5-ohm resistors conduct the current for both the 5-ohm and 10-ohm resistors. Because only 2 A flows through the 5-ohm resistor and 1 A flows through the

EX-1043
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10-ohm resistor, the sections of wires marked 3 A must conduct this current to both resistors.

Leads between the battery and the resistor bank must conduct current to all resistors. Because the total current is 8 A, this current must flow through the two leads between the battery and the balance of the circuit.

The wires in Fig. 3-10A do not perform this type of dual conduction function. Each wire conducts current to only one of the resistors. But all wires are not perfect conductors. Because wire is usually made of copper, each wire has some slight resistance. These resistances are in series with the physical resistor so that the voltage across each resistor is slightly less than the voltage supplied at the terminals of the battery. The voltage across a resistor is equal to the battery voltage less the voltage lost in the resistance of the leads. If all leads are the same length, more voltage is lost across wires carrying the larger current than across those carrying smaller quantities of current. This is obvious from Ohm's law where $E = IR$.

Current-Measuring Instruments

The milliammeter shown in the current-measuring circuit in Fig. 2-6 is limited to one current range. Just as in the case of the voltmeter, it is also very desirable for current meters to have more than only one range. A milliammeter with 1 mA and 10 mA ranges is shown in Fig. 3-11. E and R_S determine the quantity of current in the circuit.

When the switch is set to OFF R_1 is not in the circuit. Only the meter movement is in series with resistor R_S. All current flows through the movement. The pointer deflects to full scale when 1 mA is flowing.

Should R_S and E be of such magnitude that 10 mA flows through the circuit, the meter pointer will deflect off-scale and above its uppermost marking. In order to make the pointer deflect to exactly full scale when 10 mA is in the circuit, 9 of the 10 mA must be diverted from the meter movement. Then, only 1 mA is left to flow through the movement. To achieve this a shunting resistor must be connected across the meter movement as a path for the 9 mA. In Fig. 3-11, this is accomplished by setting the switch to the ON position. Now R_1 is in the circuit and shunts the 1 mA movement.

It is very easy to determine what resistor R_1 must be to do its job properly. For a full-scale deflection, the voltage across the meter

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

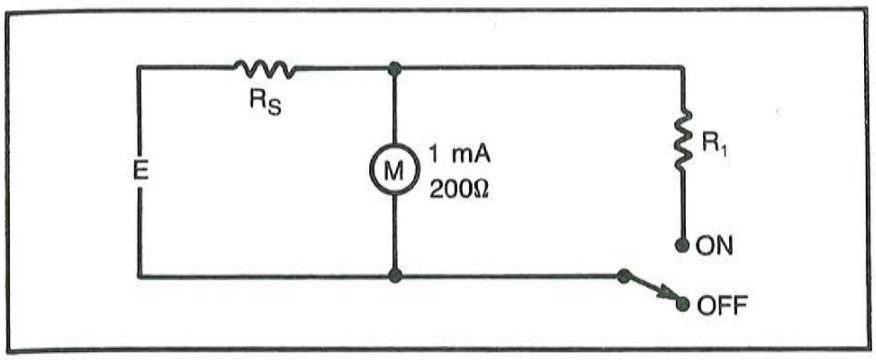


Fig. 3-11. Two-range milliameter.

movement is 1 mA × 200 ohms = 0.2 volt. Because R_1 is across the movement, 0.2 volt must be across the resistor when 10 mA is supplied to the circuit. Since 9 mA of this 10 mA flows through the resistor, R_1 must be equal to (0.2 volt)/(9 mA) ≈ 22.2 ohms. (The symbol ≈ means "*approximately equal to.*")

This idea can be expanded to a three or more range current-measuring instrument. A practical three-range circuit using a rotary switch is shown in Fig. 3-12. The ranges are 1 mA, 10 mA, and 100 mA. The resistor for use on the 100 mA range can be calculated by employing the same procedure used when setting up the 10-mA range. Now 99 mA of the 100 mA available to the instrument on this range must flow through the shunting resistor while 1 mA flows through the meter movement. The shunting resistor is 0.2 volt/99 mA ≈ 2.02 ohms.

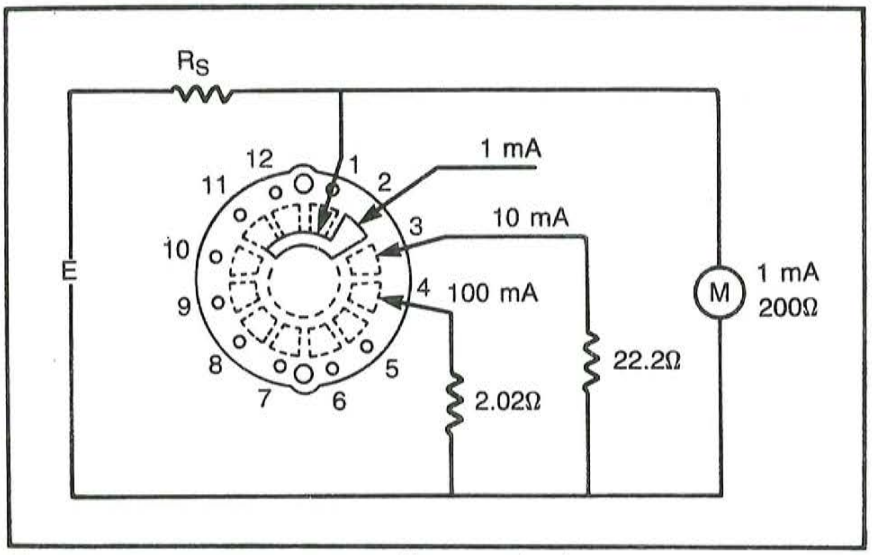


Fig. 3-12. Practical three-range milliameter circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Current Divider

When two resistors are connected in parallel as in a milliammeter circuit the total current divides between the two resistors. For the 10 mA range, the current in R_s of Fig. 3-11 is divided between the meter movement and R_1. Circuit current is also divided between resistors R_1 and R_2 in Fig. 3-7. The portion of the total current, I_T that flows in R_1 is $[R_2/(R_1 + R_2)]\, I_T$, while the portion of I_T flowing through R_2 is $[R_1/(R_1 + R_2)]\, I_T$. Note that in order to determine the portion of the total current that flows in R_1, R_2 is divided by a number equal to the sum, R_T, of the two resistors in the circuit. The portion of the current that flows in R_2 is equal to R_1 divided by R_T.

As numerical examples, I will use the circuits in Fig. 3-13. In Fig. 3-13A, R_T = 10 ohms + 5 ohms = 15 ohms. The portion of the total current that flows in the 10-ohm resistor is 5 ohms/15 ohms = 1/3, while 10/15 = 2/3 of the total current flows in the 5 ohm resistor. More current flows through the smaller resistor than through the larger resistor. This is to be expected because the voltage, E, across the two resistors is identical and I = E/10 for the 10-ohm resistor and I = E/5 for the 5-ohm resistor.

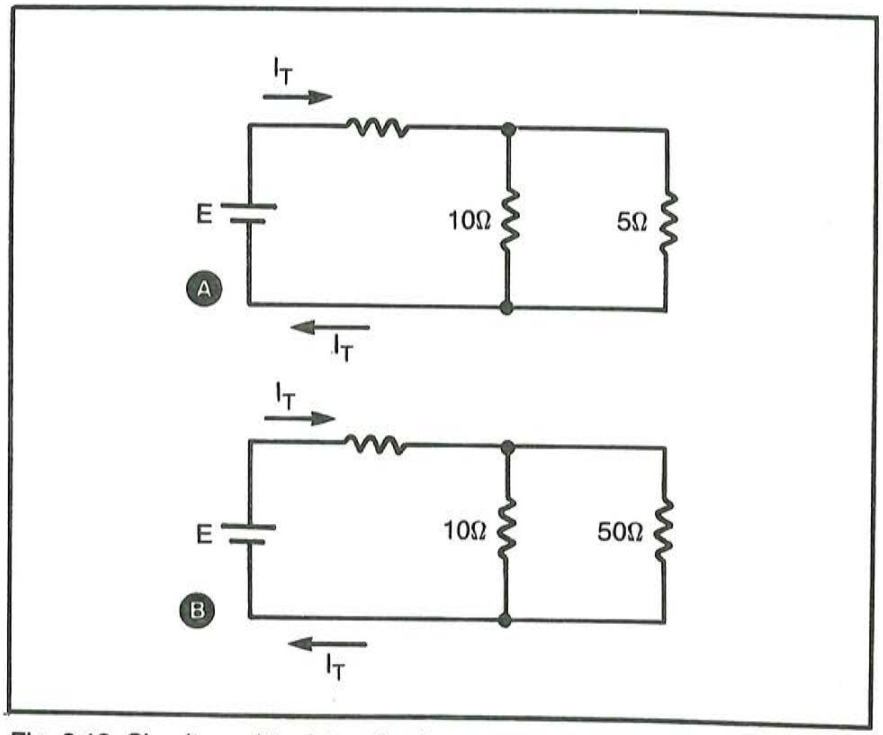


Fig. 3-13. Circuit used to determine how current is divided between parallel-connected resistors.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

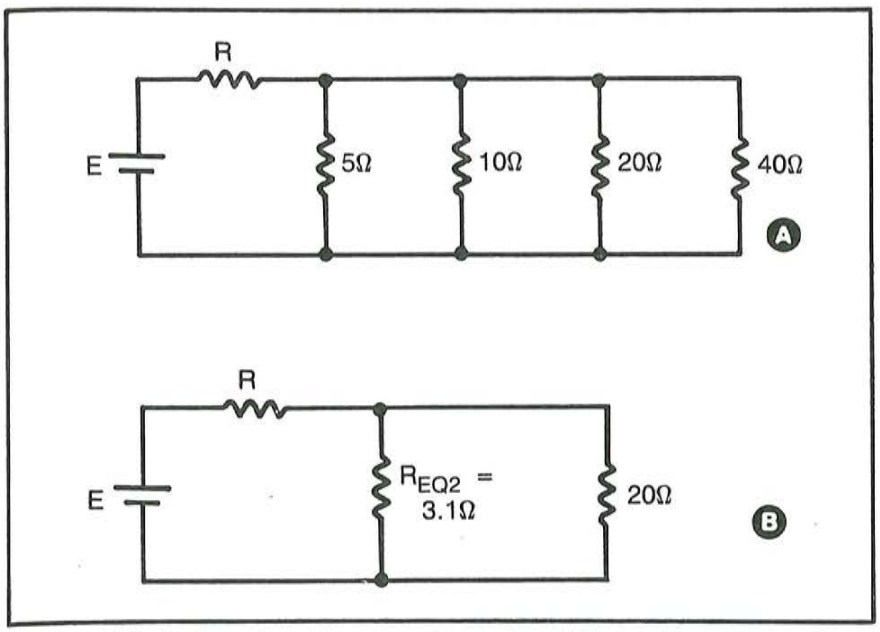


Fig. 3-14. Method used to determine the portion of the total current that flows through the 20-ohm resistor. A. Actual circuit. B. Final equivalent circuit.

Identical logic can be used for the circuit in Fig. 3-13B. Now R_T = 10 ohm + 50 ohm = 60 ohms. The portion of the total current in the 10-ohm resistor is 50/60 or 5/6 of I_T, and in the 50-ohm resistor is 10/60 or 1/6 of I_T. As always, the larger portion of current in the parallel circuit flows through the component with the lower resistance.

If more than two resistors are in a parallel circuit, other methods are available for determining the portion of the total current flowing in one of the resistors, R_x. The proper procedure is to first determine the equivalent resistance of all resistors in the parallel circuit, without involving R_x. Then use this calculated resistance as if it were a single resistor in parallel with R_x. For example, determine the portion of the total circuit current flowing through R_x in Fig. 3-14. Here, assume that the 20-ohm resistor is R_x. The equivalent resistance of the parallel circuit consisting of the 5-ohm and 10-ohm resistors is $(5 \times 10)/(5 + 10) = 3.33$ ohms. This resistance, R_{EQ1}, in parallel with the remaining 40-ohm resistor, results in a total parallel resistance of $(3.33 \times 40)/(3.33 + 40) \approx 3.1$ ohms. This is R_{EQ2}. The portion of the total current in the 20-ohm resistor is $3.1/(20 + 3.1) \approx 13/100$. So if the total current from the battery is 500 mA, $(13/100) \times 500 = 65$ mA flows into the 20-ohm resistor.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

SERIES-PARALLEL CIRCUITS

The circuit in Fig. 3-11 can be used when 10 mA is required from the supply to achieve a full-scale deflection of the meter pointer. It is essentially a parallel combination of resistors in series with another resistor, R_S. This series-parallel combination is not an unusual arrangement.

If E is equal to 1.5 volt, what must R_S be for 10 mA to flow through the circuit? You know that the voltage across the meter movement and R_1 is 0.2. Consequently, 1.5 volt – 0.2 volt = 1.3 volt, remains for R_S. 10 mA will flow only if R_S is made equal to 1.3 volt/10 mA = 130 ohms.

In Fig. 3-11, you see one very elementary example of this type of relatively complex circuit. It can be found in many different forms in electrical and electronic equipment.

CIRCUIT ANALYSIS

It is frequently very enlightening to apply different theorems and rules to circuits. Through use of these methods, it is possible to analyze circuits which may, at first, appear too complex to comprehend. These processes are very useful, the mathematics and electrical concepts are simple, and the steps should become common knowledge to anyone engaged in electrical work or applying electrical concepts as a hobby.

Kirchhoff's Rules for Networks

Two Kirchhoff rules exist. They have been described or intimated in our discussions. They can be stated as follows.

1. The sum of all voltage drops in any circuit with a closed path is equal to the sum of all the voltages in that path.
2. The sum of all currents entering a particular point in a circuit is equal to the sum of all currents leaving that point.

The *voltage rule* was discussed with respect to the series circuits and expanded through use of the circuit in Fig. 3-1B. The sum of the voltages across R_1 and R_2 must be equal to the supply voltage, E. A method of analyzing a similar circuit using two batteries and two resistors in the loop can be illustrated with the help of Figs. 3-15A and 3-15B.

Analysis starts by arbitrarily selecting a direction for the current to flow through the circuit. In Fig. 3-15A, I chose a clockwise

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

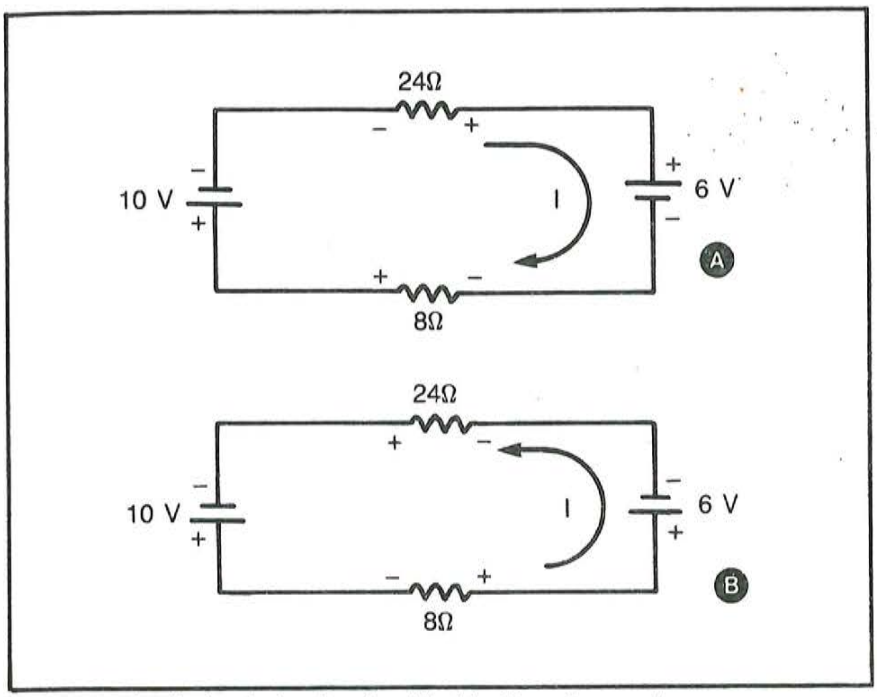


Fig. 3-15. Analysis of circuit using Kirchhoff's voltage rule.

direction. Results would be the same if a counter-clockwise direction were chosen.

When current flows through a resistor, one end becomes positive and the second end becomes negative. In Fig. 3-1A, current from E flowed through R_1. There was a voltage developed across the resistor because the current, I, flows through it. According to Equation 2-3, this voltage is IR_1. Because there is a voltage across the resistor, one end is positive and the second end is negative. Electron current flows from the negative to the positive terminal of the battery through R_1. The bottom terminal of R_1 is negative, and the top terminal is positive. This relative polarity is also true because the battery is connected with its negative terminal at the bottom end of R_1.

This fact that one terminal of each resistor must be positive or + and the second end must be negative or – is noted at the resistors in Fig. 3-15A. The end of the resistor first approached by the current is assigned a – and the second end is assigned a +. The direction of the current and polarity of the resistors will be corrected, if necessary, after the circuit has been fully analyzed.

Now you can apply three rules to determine various facts about the circuit. You want to know the current flowing in the circuit, the voltage across the resistors, and the actual polarity at the ter-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

minals of each resistor. These rules are:

1. When current flows through a battery, the battery voltage is considered positive when the arrow indicating the current is shown as entering into the positive terminal of the battery. This current flows through the battery, and originates from the negative terminal. Battery voltage is considered negative if the reverse is true and the current enters the battery in the negative terminal and flows through it to exit from the positive terminal.

2. Current enters one terminal of a resistor and exits from its second terminal. The terminal through which the current enters is considered negative. The second terminal is considered positive. This polarity is marked at the resistors in Fig. 3-15A. Just as in the case of the battery, the voltage across the resistor with the polarity shown is negative, because the current enters it through a negatively marked terminal.

3. The sum of all voltages in the circuit must add to zero. This was also true for the circuit in Fig. 3-1A where the voltage supplied by the battery and the voltage across the resistor was identical. Because of this relationship and the opposing polarities, the sum of the two voltages adds to zero.

Apply the three rules to Fig. 3-15. In this analysis, you can assume that the current can start flowing at any point in the circuit. Suppose that it starts to flow through the 24-ohm resistor. The voltage across the resistor is $-24 \times I$. Continuing in this direction of current flow, the voltage supplied by the 6-volt battery is $+6$ volts, voltage across the 8-ohm resistor is $-8 \times I$, and the voltage supplied by the 10 volt battery is $+10$ volts. Applying the third rule, the sum of all voltages in the loop is zero or

$$-24I + 6 - 8I + 10 = 0$$

Solving for I, you will find that $-32I = -16$ and that $I = 1/2$ ampere.

In Fig. 3-15B, the polarity of the 6-volt battery and the direction of current flow are reversed. Here, the voltage across the 24-ohm resistor is $-24I$, and the voltage across the 10-volt battery is -10 because the current enters it through the negative terminal. The voltage across the 8-ohm resistor is $-8I$, and the voltage across the 6-volt battery is $+6$. Combining these bits of information, the equation for the loop becomes

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

$$-24I - 10 - 8I + 6 = 0$$

or $-32I = +4$. Now, I is equal to $-4/32 = -1/8$ ampere. I obviously chose the wrong direction for I because the solution shows the current to be negative. The real electron current actually flows in the opposite direction. The polarity of the voltages across the two resistors are therefore opposite to those shown in the drawing.

A more involved circuit is shown in Fig. 3-16. The aim here is to find the voltage across the 24-ohm resistor.

Current I_1 flows in the left loop and I_2 flows in the right loop. Polarity of voltages across all resistors due to both currents are as shown. Note that the polarity of the voltage across the 24-ohm resistor, is in one direction due to I_1 and in the opposite direction due to I_2. Both polarities are noted at the respective sides of the resistor. The voltage across the resistor is due to the difference of the two voltages caused by the presence of both I_1 and I_2. It is effectively $24\ I_1 - 24\ I_2$ because the polarities oppose each other. The relative magnitudes of I_1 and I_2 determine the direction of the actual current flowing through the resistor.

Summing the voltages in the left loop,

$$+48 - 8I_1 - 24I_1 + 24I_2 = 0$$

because the voltage developed across the 24-ohm resistor due to I_2 affects I_1. This voltage is added to the other voltages in the equation because the polarity of the voltage across the resistor due to I_2 is opposite to the polarity of the voltage due to I_1. In a similar fashion, the voltages in the right-hand loop are

$$+72 - 24I_2 - 12I_2 + 24I_1 = 0$$

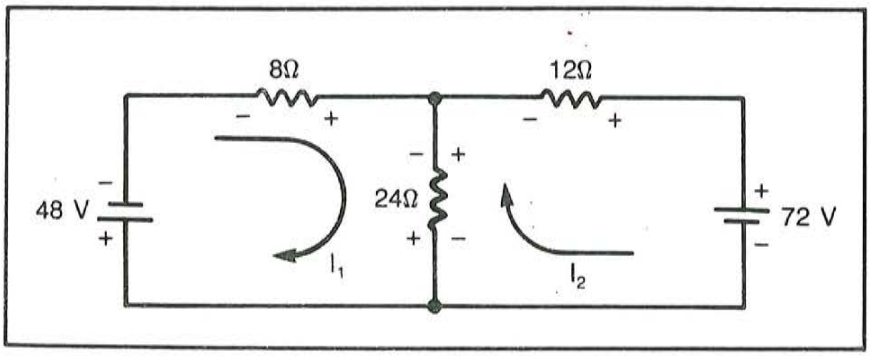


Fig. 3-16. Voltage across the 24-ohm resistor determined in circuit with two currents using Kirchhoff's rule.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Simplifying the two equations,

$$32I_1 - 24I_2 = 48$$
$$-24I_1 + 36I_2 = 72$$

Two equations arranged as shown, with the same two variables in both, are known as *simultaneous equations.* Two equations are necessary in order to find the magnitudes of two unknown currents. You can determine what one of these unknowns is by applying methods to eliminate the second unknown. The two equations are combined into one equation with one unknown. To do this, the numbers multiplied by the same variable in both equations must be made identical. The equations are then either added or subtracted from each other, as required, to eliminate one of the variables.

When the multipliers of a particular variable are equal in both equations, the difference (or sum) of the two equations will result in a zero factor where this variable was. To accomplish this for the equations shown, multiply the upper equation by 3 and the lower equation by 2. The resulting equations are

$$96I_1 - 72I_2 = 144$$
$$-48I_1 + 72I_2 = 144$$

Adding the individual terms leaves us with

$$48I_1 - 0I_2 = 288$$

so that $I_1 = 288/48 = 6$ amperes. Once you know I_1, it is substituted into either one of the original equations to determine I_2. Using the second equation,

$$-24\ (6) + 36I_2 = 72$$

so that $36I_2 = 72 + 144$ and $I_2 = 216/36 = 6$ amperes.

Using this information, the voltage across the 8-ohm resistor is $8I_1 = 8\ \Omega \times 6\ A = 48$ volts. The voltage across the 12-ohm resistor is $12I_2 = 12\ \Omega \times 6\ A = 72$ volts. The voltage across the 24-ohm resistor is $24\ (I_2 - I_1) = 24\ (6 - 6) = 0$ volt. In the left loop the supply is 48 volts. With 0 volt across the 24-ohm resistor, the entire 48 volts is across the 8-ohm resistor. As for the right loop, the entire voltage from the 72-volt supply is across the 12-ohm resistor because 0 volt is across the 24-ohm resistor.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

This procedure can be applied with equal success to a circuit where I_1 and I_2 are not equal. Consider the components shown in Fig. 3-17. What are the voltages across the various resistors? Polarities due to both currents are marked at all resistors. Note that polarities of voltages developed across the 10,000-ohm resistor due to I_1 and I_2 are identical, so that voltages developed by these two currents add. The equations are

$$\begin{aligned} 100 - 2000I_1 - 10{,}000I_1 - 1000I_1 - 10{,}000I_2 &= 0 \\ 200 - 10{,}000I_2 - 4000I_2 - 10{,}000I_1 &= 0 \end{aligned}$$

Simplifying the equations,

$$\begin{aligned} 13{,}000I_1 + 10{,}000I_2 &= 100 \\ 10{,}000I_1 + 14{,}000I_2 &= 200 \end{aligned}$$

Multiplying the top equation by 14 and the bottom equation by 10 yields

$$\begin{aligned} 182{,}000I_1 + 140{,}000I_2 &= 1400 \\ 100{,}000I_1 + 140{,}000I_2 &= 2000 \end{aligned}$$

Subtracting the bottom equation from the top one results in the relationship $82{,}000I_1 = -600$ so that $I_1 = -7.3 \times 10^{-3}$ A, a negative current. Substituting this into the first original equation,

$$13{,}000\,(-7.3 - 10^{-3}) + 10{,}000I_2 = 100$$

we find that $10{,}000I_2 = 100 + 94.9$, so that $I_2 = +19.5 \times 10^{-3}$ A.

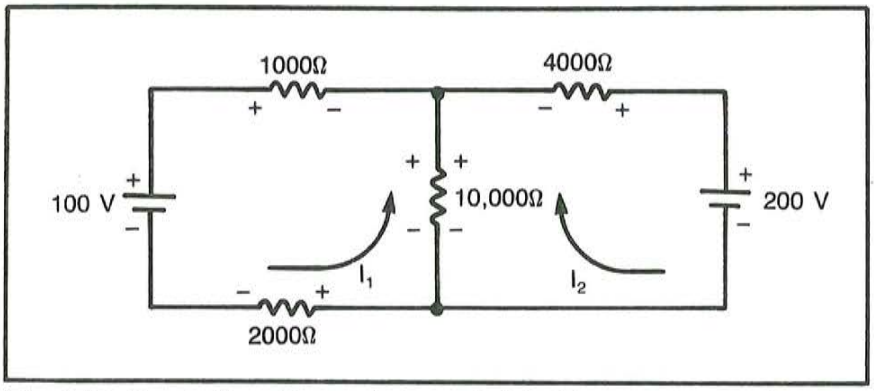


Fig. 3-17. Kirchhoff's voltage rule is applied in this second example.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Using this information, the voltage across the 1000-ohm resistor is $(-7.3 \times 10^{-3})(1000) = -7.3$, voltage across the 2000-ohm resistor is $(-7.3 \times 10^{-3})(2000) = -14.6$, voltage across the 4000-ohm resistor is $(19.5 \times 10^{-3})(4000) = 78$, and the voltage across the 10,000 ohm resistor is $(-7.3 \times 10^{-3})(10{,}000) + (19.5 \times 10^{-3})(10{,}000) = -73 + 195 = +122$ volts.

When determining the voltages across the 1000-ohm and 2000-ohm resistors, you found the voltages to be negative. Voltage across the 1000-ohm resistor is -7.3 and across the 2000-ohm resistor is -14.6. The fact that the voltages showed up in the equations as being negative, indicates that the actual polarity of voltages across these resistors are opposite to those shown in the drawing. But when added to all other voltages in the left loop, the sum must equal the 100 volts supplied. The sum of the two negative voltages in that loop is $-14.6 - 7.3 = -21.9$ or about -22 volts. The voltage across the 10,000 - ohm resistor is $+122$ volts. The total voltage in the loop is $+122 - 22 = 100$ volts. This is identical to the voltage supplied by the voltage source in this loop.

As for the loop at the right half of the drawing, when the 122 volts across the 10,000-ohm resistor is added to the $+78$ volts across the 4000-ohm resistor, the total is 200 volts. This is identical to the voltage supplied by the voltage source in that loop.

Note that the polarity of the voltages across the resistors in the left loop are the reverse of those shown. This is due to the relative magnitudes of the voltages and currents in the two loops.

As a final example, let us reverse the 200-volt battery and determine just what the various voltages and currents are in the circuit. This is shown in Fig. 3-18. The equations are

$$\begin{aligned} 13{,}000I_1 - 10{,}000I_2 &= 100 \\ -10{,}000I_1 + 14{,}000I_2 &= 200 \end{aligned}$$

Multiplying the top equation by 14 and the bottom by 10 yields

$$\begin{aligned} 182{,}000I_1 - 140{,}000I_2 &= 1400 \\ -100{,}000I_1 + 140{,}000I_2 &= 2000 \end{aligned}$$

Adding the two equations yields

$$82{,}000I_1 = 3400$$

so that $I_1 = 41.5 \times 10^{-3}$ A. Substituting this information into the first equation,

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

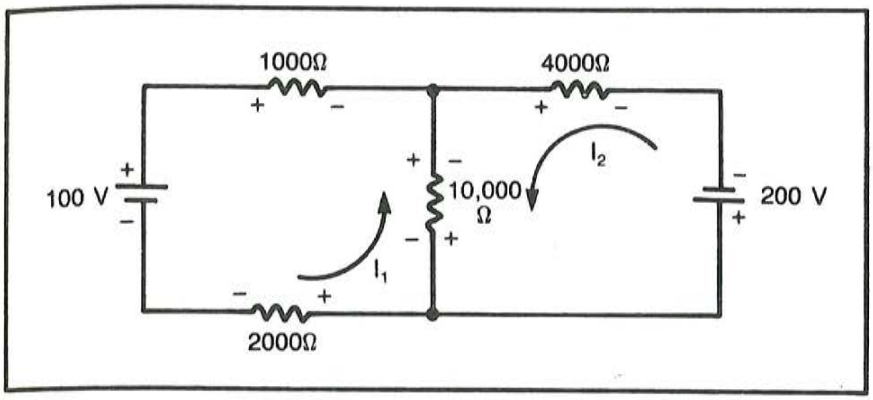


Fig. 3-18. Circuit identical to the one in Fig. 3-17, but with the connections to the 200-volt supply reversed.

$$539.5 - 10{,}000I_2 = 100$$

indicates that

$$I_2 = 43.9 \times 10^{-3} \text{ A.}$$

Using Equation 2-3 and the values determined for I_1 and I_2, I find that the voltage across the 1000-ohm resistor is 41.5, across the 2000-ohm resistor 83, across the 4000-ohm resistor 175.6, and across the 10,000-ohm resistor it is $(43.9 \times 10^{-3})(10{,}000) - (41.5 \times 10^{-3})(10{,}000) = 24$ volts. The polarity of the voltages across the two ends of the 10,000-ohm resistor is primarily due to the direction of I_2. This is because the voltage developed in that resistor when I_2 flows is greater than the voltage developed by the I_1 current.

Now add all voltages in the circuit. In the left loop, the total voltage is $41.5 + 83 - 24 = 100.5$. This is close to the 100 volts provided by the voltage source in that loop. In the right loop, voltages add to $175.6 + 24 = 199.6$. The difference between the calculated 199.6 volts and the actual 200 volts supplied, as well as the difference between the calculated 100.5 volts and the actual 100 volts supplied, is due to calculation tolerances. These differences can be ignored. If more significant figures were considered in the calculations, the errors would not exist.

Kirchhoff's current rule can be described using Fig. 3-17. Current I_1 flows from the 100-volt supply. Current I_2 flows from the 200-volt supply. Both currents are at one junction in the circuit, along with the current flowing in the lead connected to the 10,000-ohm resistor. According to Kirchhoff's rule, all current entering a junction must flow out of it. Since I_1 and I_2 entered the junction, $I_1 + I_2$ must flow out of it. The only place for this cur-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

rent to flow is through the 10,000-ohm resistor. Because $I_2 = 19.5 \times 10^{-3}$ A and $I_1 = -7.3 \times 10^{-3}$ A (both were calculated above), the total current that flows out from the junction is $19.5 \times 10^{-3} - 7.3 \times 10^{-3} = 12.2 \times 10^{-3}$ A. This current flows through the 10,000-ohm resistor. Because of this current, the voltage across the resistor is (12.2×10^{-3}) (10,000) = 122 volts. This is the same voltage calculated earlier when I applied Kirchhoff's voltage rule. It just confirms that all current entering any junction is equal to the sum of the currents flowing out of that junction.

Thevenin's Theorem

Circuit analysis can be made less complex by establishing simplified equivalent circuits for complex arrangements. Determining one equivalent resistance for a group of parallel or series-connected resistors is an example of a simplified representation of a group of resistors. Now suppose you have a complex circuit with resistors and a power supply. How would you proceed to determine the voltage and current flowing through one of the resistors? Thevenin's theorem can be applied here.

All elements in the circuit are considered when applying the Thevenin theorem, other than the load. Using methods described here, the load is removed from the circuit. Components under consideration are combined to form a circuit consisting of a voltage in series with a resistance. When the load is once again connected to this circuit, it sees this simple arrangement. Because of this simplicity, it becomes a trivial matter to calculate the load current and voltage.

Three steps are required to determine the Thevenin equivalent of any circuit.

1. Remove the output resistor or other load from the circuit.
2. Short the voltage source (on paper, of course). With this voltage source shorted, determine the total resistance seen by looking into the terminals from which the load was removed.
3. Break the short that you placed across the supply. Determine the open circuit voltage. This is the voltage at the load terminals after the load has been removed.

Using these methods, let us determine the Thevenin equivalent of the circuit in Fig. 3-19A. If the 216-ohm resistor is the load, the aim here is to determine the current flowing through and the voltage across that resistor. As a first step, remove the load from

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

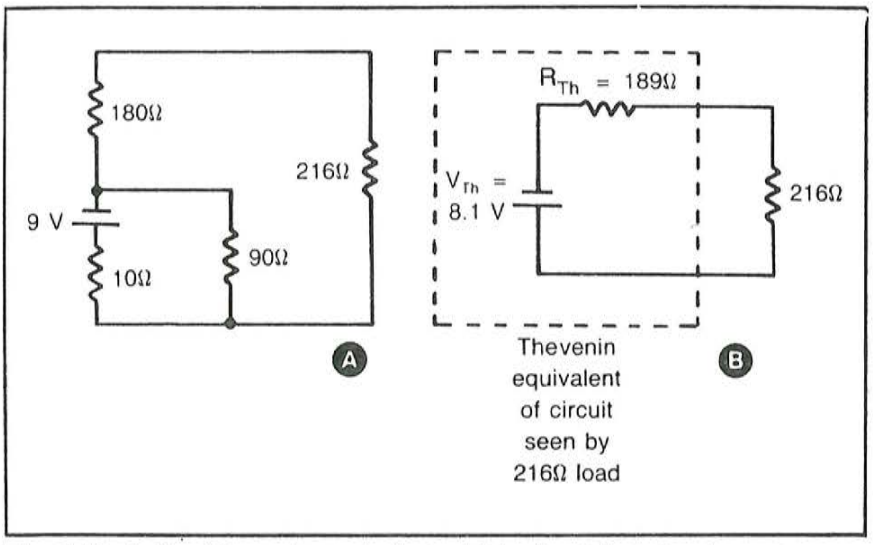


Fig. 3-19. A. The Thevenin equivalent of this circuit is to be determined. B. Actual Thevenin equivalent of circuit in A.

the circuit. Next, short the power supply. These are Steps 1 and 2 in the procedure. After this has been done, a 10-ohm resistor is in parallel with a 90-ohm resistor to form an equivalent resistance of (10) (90)/(10 + 90) = 9 ohms. Looking from the load terminals, this 9-ohm combination is in series with the 180-ohm resistor for a total equivalent circuit resistance of 189 ohms. The load will see this resistance after it has been reconnected to the circuit. Thus, 189 ohms is the Thevenin equivalent resistance, R_{Th}, of this circuit.

Continuing with Step 3 of the procedure, restore the circuit to the form shown in Fig. 3-19A, but leave the load disconnected. The open circuit voltage is the same at either side of the 180-ohm resistor because no current flows in the resistor when the load is removed from the circuit. Under these conditions, there is no voltage across the 180-ohm resistor for IR = 0 when no current flows through it. But there is always current in the 90-ohm and 10-ohm resistors, for they form a complete circuit around the battery. Because the total resistance across the battery due to these two resistors is 90 ohms + 10 ohms = 100 ohms, the open-circuit battery current using Ohm's law is 9 volts/100 ohms = 0.09 ampere. Voltage across the 10-ohm resistor is (0.09 ampere) (10 ohm) = 0.9 volt. The battery voltage, less the 0.9 volt, is supplied by the battery to the open circuit. Therefore, 8.1 volts (9 volts – 0.9 volt) is the Thevenin equivalent voltage, V_{Th}, of this circuit.

The complete Thevenin equivalent of the circuit is shown in

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Fig. 3-19B. All current in the equivalent circuit flows through the 216-ohm load resistor, and is 8.1 volts/(189 + 216) ohms = 8.1 volts/405 ohms = 0.02 ampere. Due to this current, the voltage across the load resistor is (216 ohms) (0.02 ampere) = 4.32 volts. The quantity of current considered in the equivalent circuit is only the amount flowing in the load. It is not the total current supplied by the battery.

For another example of an application of Thevenin's theorem, consider the circuit in Fig. 3-20A. The aim is to find the voltage across the 30-ohm resistor and the current flowing through it.

Start by disconnecting the 30-ohm resistor from the circuit. Looking into the balance of the circuit from the disconnected terminals, the 90-ohm and 180-ohm resistors form a voltage divider. The voltage across the 90-ohm resistor is (90/270) (9 V) = 3 volts. This is the Thevenin voltage. Now short the battery. The equivalent or Thevenin resistance looking into the open 30-ohm load is 90 ohms in parallel with 180 ohms. This is equal to (90) (180)/(90 + 180) = 60 ohms. Using this data, the new Thevenin equivalent of the original circuit is shown in Fig. 3-20B. The voltage across the 30-ohm resistor using voltage divider methods is (30/90) (3 V) = 1 volt. The current in the 30-ohm resistor is 1 volt/30 ohms = 0.033 A.

Norton's Theorem

A voltage source is considered a low impedance (or resistance) supplier of voltage. The perfect source is a battery or generator without any internal resistance. With this perfect source, the same voltage would be across different loads even if their magnitudes varied considerable. But as soon as an imperfect battery or generator is used, there is an internal resistance in its equivalent circuit. Load current flows through that resistance as well as through the load. When this happens, there is voltage developed across the internal resistance of the voltage source. The voltage left for the load is the battery voltage less the voltage developed across its internal resistance. The quantity of voltage developed across the internal resistance varies with the quantity of current demanded by the load. The larger the current through the battery resistance, the larger the voltage that is developed across it. Voltage at the battery terminals is its rated voltage less the voltage developed across its internal resistance. When more current is demanded by the load, less voltage is supplied to it due to the larger voltage drop inside the voltage source.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

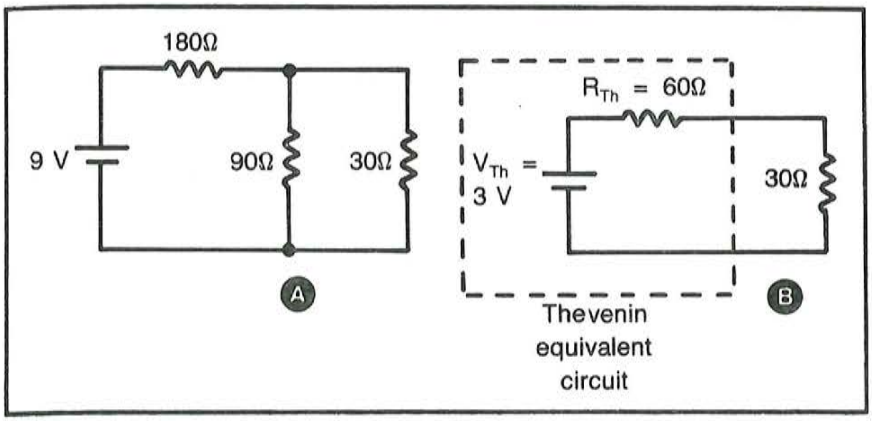


Fig. 3-20. A second example using the Thevenin equivalent of the circuit.

Now assume you have a supply that is specially designed to have a large internal resistance—let's say 1,000,000 ohms. If the supply is fixed at 10 volts and is shorted at its terminals, the current flowing into the shorted terminals is 10 volts/1,000,000 ohms = 10^{-5} amps. If the terminals are not shorted, but instead a 1000-ohm resistor is placed across them, the total resistance in the circuit and seen by the supply is 1,000,000 ohms + 1000 ohms = 1,001,000 ohms. The total current flowing from the battery is now 10 volts/1,001,000 ohms = 0.999×10^{-5} amps. If the load in a similar situation is 10,000 ohms rather than 1000 ohms, the current supplied to it is 10/1,010,000 = 0.990×10^{-5} amps. Neither of these load currents differ from the short-circuit current by any magnitude worth noting. A current source is a high-impedance (or resistance) supply providing a relatively fixed current to loads of different magnitudes. It was just shown that a supply with an internal resistance of 1,000,000 ohms is a good current source. The current supplied by any current source will change considerably from the fixed value if the load is large and comparable in size to the internal resistance of the supply. But this does not happen under ordinary circumstances.

The Thevenin equivalent circuit incorporates a voltage source—a theoretical supply with a zero internal resistance. The Norton equivalent circuit includes a current source—a theoretical supply with an infinite internal resistance. This ideal current source is shunted by the Thevenin equivalent resistance.

The steps in setting up the Norton equivalent circuit start by shorting the load resistance (on paper only). Calculate the current flowing from the supply through that short. This is the Norton current. In the drawing of the equivalent circuit, connect the Theve-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

nin resistance (as determined above) in parallel with the load resistance and then connect this combination across the current source. Using the current source as the total current in both resistors, determine the current that is flowing in the load.

For example, consider the circuit in Fig. 3-20A. The Thevenin equivalent resistance is 60 ohms. Place a short across the 30-ohm load. The total current that flows through the short is 9 volts/180 ohms = 0.05 amp. This is the total current in the Norton equivalent circuit. The Norton equivalent of the overall circuit is shown in Fig. 3-21. Using the current divider equation, the current in the 30-ohm load resistor is (60/90) 0.05 = 0.033 amp. This is the same current that was calculated by using the Thevenin equivalent of the circuit.

As for the circuit in Fig. 3-19A, Thevenin resistance has already been determined to be 189 ohms. Next, short the load resistor. The modified equivalent circuit is shown in Fig. 3-22A. To determine the current for the Norton circuit, you must first determine the voltage lost, or the voltage drop, across the 10-ohm resistor. To do this, note that the resistance of the entire circuit as seen from the battery is 180 ohms in parallel with 90 ohms, and that combination is in series with 10 ohms. Thus, the battery sees a resistance of 10 + (180) (90)/(180 + 90) = 70 ohms. The current from the battery to this combination is 9 volts/70 ohms = 0.129 amp. This total current flows through the 10-ohm resistor so there is a 10 ohms (0.129 amp) = 1.29 volt loss across that resistor. Thus, 9 volts less 1.29 volts or 7.71 volts is across the 180-ohm resistor and short, so that the current flowing through the short is 7.71

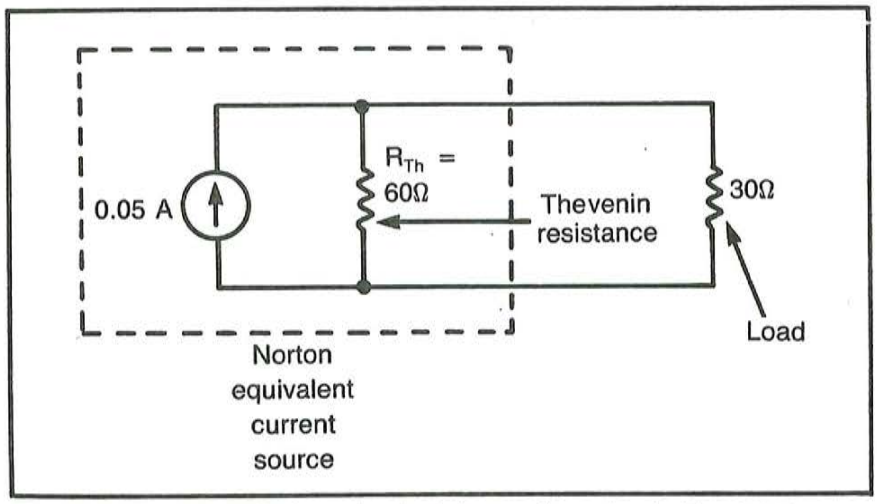


Fig. 3-21. Norton equivalent circuit of the configuration in Fig. 3-20A.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

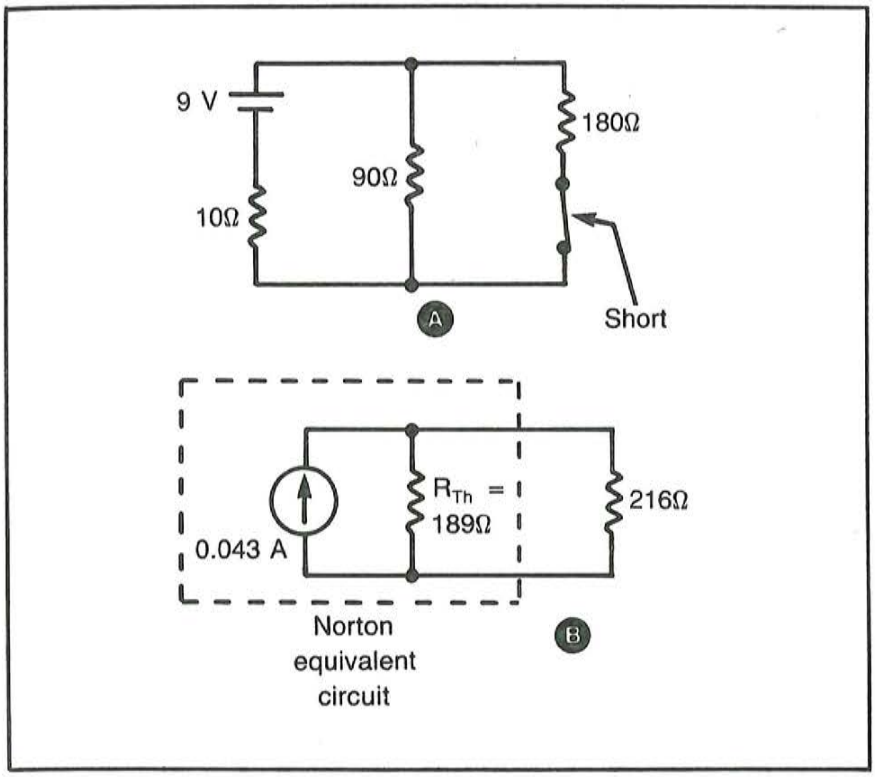


Fig. 3-22. Deriving a Norton equivalent circuit. A. Circuit with the load shorted. B. Norton equivalent of the circuit in A.

volts/180 ohms = 0.043 amp. Use this as the current supply in the Norton equivalent circuit.

With the information just determined, you can generate the Norton equivalent of the circuit. This is shown in Fig. 3-22B. Here, the 189-ohm Thevenin resistance and the 216-ohm load shunt the 0.43 amp current source. Using the current-divider equation, the current through the 216-ohm load resistor is [189/(189 + 216)] [0.043 A] = 0.02A. This is identical to the current that was determined earlier using the Thevenin equivalent circuit.

Analyzing a Bridge

The Wheatstone bridge in Fig. 3-23 is a very commonly used circuit in different devices. It is applied to measuring resistance as well as other electrical factors.

Voltage E is fed to two pair of series-connected resistors, $R_1 = R_2$ and $R_3 = R_4$. Using voltage-divider equations, the voltage between the $R_1 = R_2$ junction and the negative terminal of E (across R_2) is $R_2E/(R_1 + R_2)$ and between the $R_3 = R_4$ junction and

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

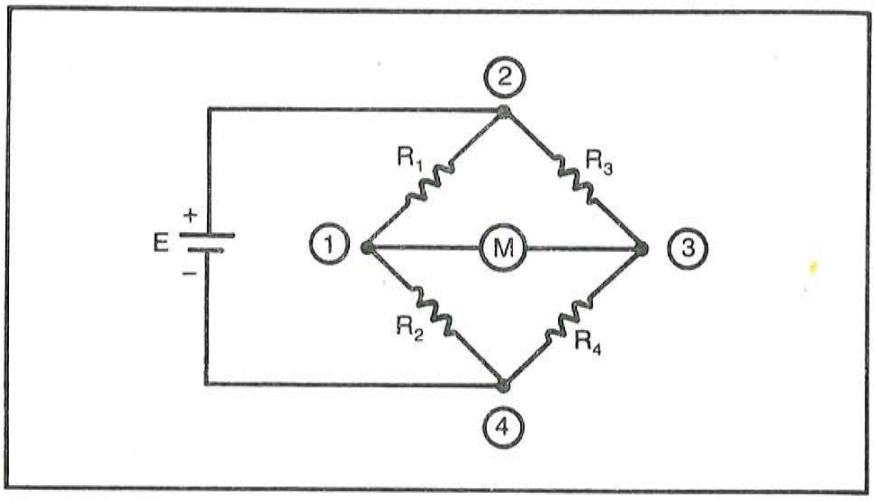


Fig. 3-23. Wheatstone bridge.

the negative terminal of E (across R_4) is $R_4E/(R_3 + R_4)$. The bridge is said to be *balanced* when the voltage across R_2 is equal to the voltage across R_4. This can be stated mathematically by setting up an equation equating the two voltages. You can therefore set $R_2E/(R_1 + R_2)$ equal to $R_4E/(R_3 + R_4)$. After doing some algebraic manipulations, it can be seen that

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \quad \text{or} \quad \frac{R_1}{R_3} = \frac{R_2}{R_4} \qquad \textbf{Eq. 3-3}$$

when the bridge is balanced.

When the voltage at the $R_1 = R_2$ junction is equal to that at the $R_3 = R_4$ junction, the voltage difference between the two points (point #1 and point #3) is obviously zero. This is no pressure to push current through the meter connecting the two junctions. So when the bridge is balanced, it can be concluded that the meter pointer does not move. It indicates 0 volt.

The relationships in Equation 3-3 indicate a method of measuring resistance through the balance of a bridge. Suppose you want to measure the resistance of an unknown component, R_x. Start by replacing R_4 in the circuit with R_x. Substitute a variable control for the fixed resistor, R_2. (A variable control is constructed of fixed resistance material with an arm or wiper moving over that resistance. The resistance between the wiper and both ends of the resistance material depends upon where the wiper rests on the fixed resistance.) Keeping the symbol R_2 for the variable control, you

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

can use an ohmmeter to measure its resistance when the wiper is set in a specific position. Vary R_2 until the bridge is balanced and no current will flow through the meter measuring it. Substitute all resistance for the three known components into Equation 3-3 and solve for the fourth resistance, R_x. An example using this method is shown in Fig. 3-24.

When the bridge is not balanced, current I flows through the meter, M. The magnitude of this current is determined through use of the Thevenin equivalent circuit. It was noted in the previous discussion that if more current than is available from one battery is required from a supply with a specific voltage, two identical batteries can be wired in parallel. Reversing this in circuit analysis, one battery can be separated into two batteries with identical voltages as long as this does not upset the voltage relationships in the circuit. In this manner, one battery is treated as if it consisted of two batteries connected in parallel. This is shown in Fig. 3-25A for the circuit in Fig. 3-23.

You can now find the Thevenin equivalent circuit around each of the supplies. This is shown in Fig. 3-25B. The Thevenin voltage in Fig. 3-25A is that at the junction of R_1 and R_2 (across R_2) when M is disconnected from the circuit. The Thevenin voltage for the circuit in Fig. 3-25B under the same conditions is equal to the voltage across R_4 at the junction of R_3 and R_4. Because the

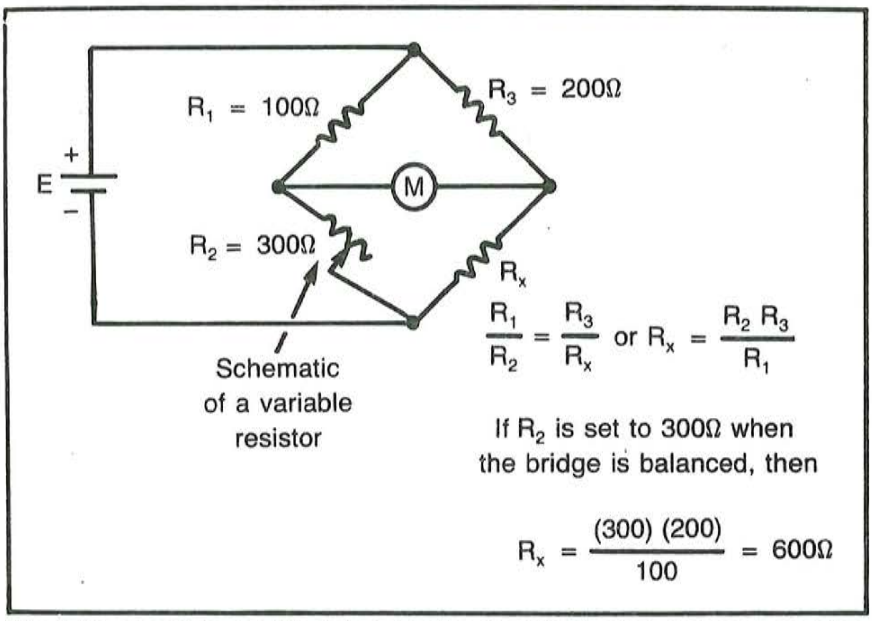


Fig. 3-24. Example used to determine the magnitude of an unknown resistor, R_x, by utilizing the Wheatstone bridge.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

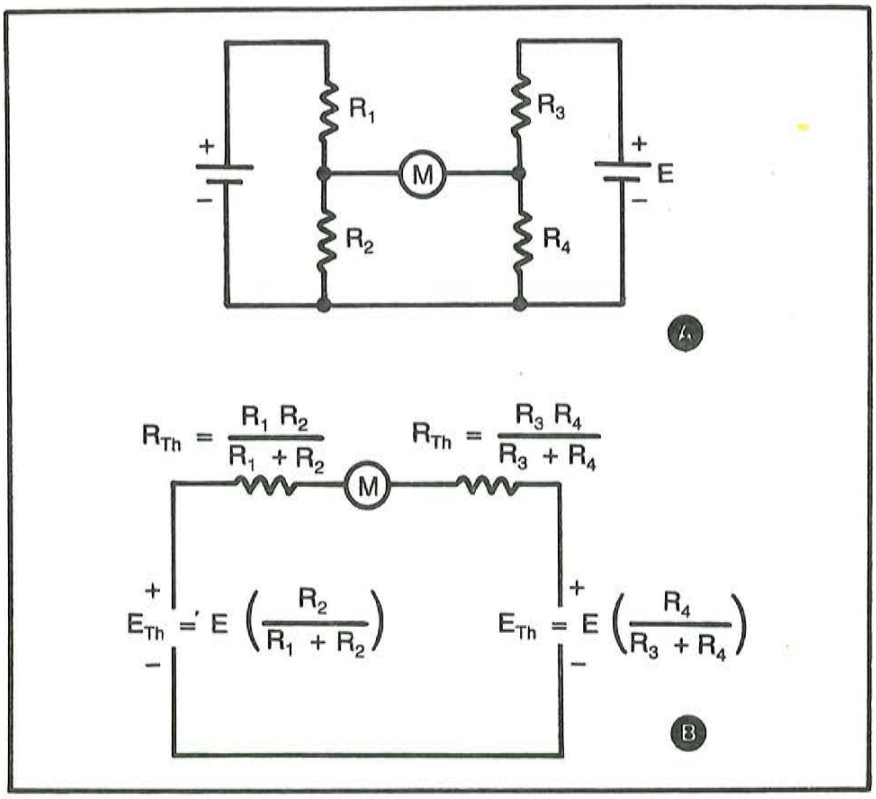


Fig. 3-25. A. Bridge circuit is divided into two parts. Each part has its independent voltage supply. B. Thevenin equivalent circuits used to determine the current in the meter when the bridge is unbalanced.

Thevenin resistance is the resistance seen by the meter when E is shorted, it is R_1 in parallel with R_2 for Fig. 3-25A and R_3 in parallel with R_4 for Fig. 3-25B. The two Thevenin circuits are drawn in Fig. 3-25B. The meter is placed between the two Thevenin equivalent circuits. The resistance of the meter is added to all Thevenin resistances in the circuit. Current flowing through the meter is calculated by dividing the total resistance in the circuit into the total of the Thevenin voltages.

POWER AND ENERGY

In physics, energy has been defined as the ability to do work. Work is not simply a force that you may apply to an object. If the object does not move over a distance, no work is being done. Work is being done or energy is expended if the object moves while you are applying the force. Energy must be supplied in order to perform work.

In physics, energy is changed to a form referred to as work.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Work is a force, F, acting over a distance, s. If there is a large amount of friction between the moving object and the surface over which it is pushed, the force must be large. The required energy must be large in order to overcome the friction and also be able to do the required job. Because of the rubbing of two surfaces due to friction, a portion of the applied energy is used to move the object and the remaining energy turns to heat.

Heat is a form of energy. So are light, electricity, chemicals, and so on. The battery supplies energy because of a chemical reaction in the cells. Steam engines perform because of the energy supplied by heat. Light energy activates photoelectric cells. And electricity is frequently used as a source of energy that is converted into heat, light, and so on. Electric energy is measured in units of *joules*.

We are constantly involved with energy utilized by electric circuits. your bill from the electric company is based upon the amount of electric energy you consume each month. But in circuit work, we deal with power rather than with energy. *Power* is defined as the rate at which work is being done. The amount of energy in joules used each second is power. Power is stated in units called *watts*, abbreviated W.

Just as was the case with volts, ohms and amperes, prefixes are used to indicate power of different magnitudes. Megawatts is the term used for millions of watts so that 1,000,000 watts = 1 megawatt, or 1 MW. Similarly, 1000 watts = 1 kilowatt = 1 kW; 1/100 of a watt = 1 milliwatt = 1 mW, and 1/1,000,000 of a watt = 1 microwatt = 1 μW.

You pay the electric company a specific amount of money for each unit of energy you use. Energy is computed by these companies as the product of watts and hours. This is energy because it is the power consumed multiplied by the time during which the power is being used. The electric companies refer to this more precisely as watt-hours of energy. They may divide this number by 1000 to get the energy in terms of kilowatt-hours. So if you use a 100-watt electric light for 72 hours during the month, you used $72 \times 100 = 7200$ watt-hours of energy or 7.2 kilowatt-hours of energy. If the price of the electric energy is 20¢ for each kW hour, the bill would be $0.20 \times 7.2 = \$1.44$.

Energy is dissipated in a resistor when current flows through it. The amount of energy dissipated each second is power. A resistor is rated by the amount of power it can dissipate. There are resistors that can dissipate less than 1/4 watt. Other resistors can

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

dissipate hundreds of watts. When selecting a resistor for use in a circuit, it is logical to calculate the power that it must dissipate due to the current flowing through it or to the voltage across it. For safety's sake, the resistor used in the circuit should be capable of dissipating about double the calculated power. Thus, if your calculations indicate that the resistor in the circuit dissipates one-half watt, you should use a one-watt component.

The amount of power being dissipated can be determined through use of Equation 3-4. If you know the voltage, V, across the resistor and the current, I, flowing through it, the power, P, that the resistor dissipates is

$$P = VI \qquad \textbf{Eq. 3-4}$$

Just as was the case with Ohm's law, the power equation can take three forms. The second version of this equation is

$$P = I \times I \times R = I^2R \qquad \textbf{Eq. 3-5}$$

because I^2 is exponential notation indicating that I is multiplied by itself. (If I^4 were in the equation, it would indicate I multiplied by itself four times, or $I \times I \times I \times I$.) The third form of the equation is

$$P = \frac{(V \times V)}{R} = \frac{V^2}{R} \qquad \textbf{Eq. 3-6}$$

Equation 3-4 is used if you know the voltage across the resistor and the current flowing through it. Equation 3-5 is used if you know the current and resistance but may not be aware of the voltage across the resistor. Equation 3-6 requires a knowledge of both the voltage across the resistor as well as the component's resistance.

In Fig. 3-26, three resistors are connected across a 12-volt supply. We do not, offhand, know the quantity of current flowing through R_1, although if you wanted you could calculate it using Ohm's law. Be you can determine the power it dissipates without knowing the current by simply knowing the resistance and voltage. power dissipated by R_1, determined by using Equation 3-6, is $12^2/20 = 144/20 = 7.2$ watts. Power dissipated by R_2, determined by using Equation 3-4, is $12 \times 1 = 12$ watts. Power dissipated by R_3, determined by using Equation 3-5, is $6^2 \times 2 = 72$ watts.

Similar methods can be used when determining the power dis-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

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Similar methods can be used when determining the power dis-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

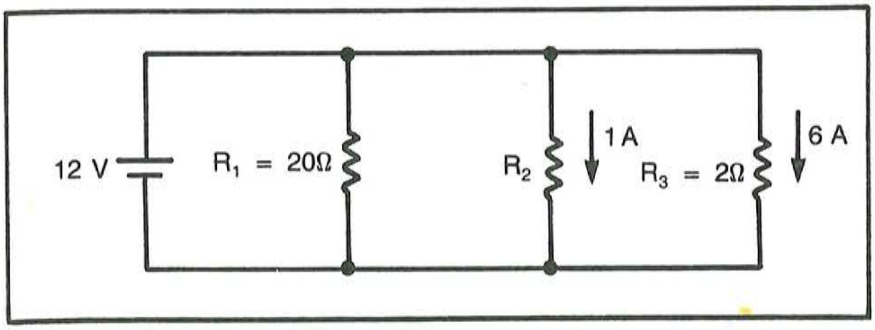


Fig. 3-26. Circuit with three resistors connected in parallel. The power dissipated by each resistor is determined.

sipated by resistors in a series circuit. Several different procedures can be used to determine dissipation by the resistors in the circuit drawn in Fig. 3-27. In one method, we can start by determining the current in the resistors. Because the total circuit resistance is 20 ohms + 4 ohms = 24 ohms, I = V/R = 12/24 = 1/2 ampere. Using Equation 3-5, the power dissipated in the 20-ohm resistor is $(1/2)^2(20) = (1/2)\,(1/2)\,(20) = (1/4)\,(20) = 5$ watts, while the power dissipated in the 4-ohm resistor is $(1/2)^2(4) = 1$ watt.

In another procedure you can use the voltage-divider equation to determine the voltage across each of the resistors. The voltage across the 4-ohm resistor is $[4/(20 + 4)]\,12 = 2$ volts. Voltage across the 20-ohm resistor is 12 volts − 2 volts = 10 volts. Using Equation 3-6, the power dissipated by the 20-ohm resistor is $10^2/20 = 5$ watts, and the power dissipated by the 4-ohm resistor is $2^2/4 = 1$ watt.

To use the third procedure you determine the current through the resistors as well as the voltages across the resistors. Using this calculated data, current through both resistors is 1/2 ampere while

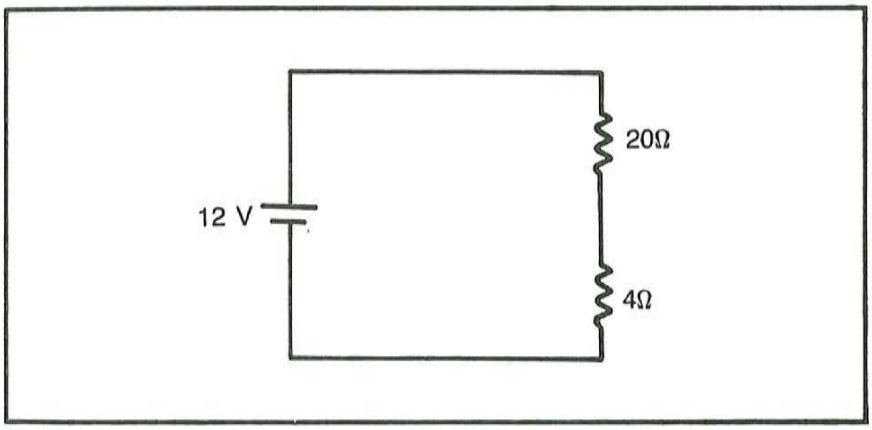


Fig. 3-27. Power dissipated by resistors connected in series.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

10 volts is across the 20-ohm resistor and 2 volts is across the 4-ohm resistor. Applying Equation 3-4, the power dissipated by the 20-ohm resistor is $10 \times 1/2 = 5$ watts, and the power dissipated by the 4-ohm resistor is $2 \times 1/2 = 1$ watt.

The calculated power dissipated by each resistor is the same regardless of the procedure used.

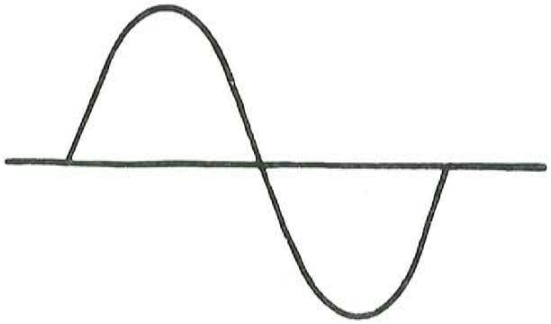
Sometimes resistors capable of dissipating a particular amount of power are not readily available. For example, assume you need a 100-ohm, 4-watt carbon-deposited resistor. This type of resistor is made only with dissipation capabilities of up to 2 watts. To fulfill the 4-watt requirement, two 2-watt resistors can be used either in a series or in a parallel arrangement. Because these are both two 2-watt components, each can dissipate 2 watts to satisfy the required capability of a total dissipation of 4 watts.

When wired in series, the two identical resistors should add up to 100 ohms. Two 50-ohm resistors can be used to satisfy this requirement. a circuit will usually behave properly if two 47-ohm resistors are used instead of two 50-ohm resistors to produce a total of 94 ohms rather than 100-ohms. This compromise may be necessary because 50 ohms is not a standard value while 47 ohms is readily available.

If a parallel combination is preferred, two 200-ohm, 2-watt resistors can be so connected to form the desired 100-ohm, 4-watt component. This can be derived using Equation 3-2, which indicates that the equivalent resistance of two 200-ohm resistors connected in parallel is equal to one-half the value of each resistor or (200 ohms) (200 ohms)/(200 ohms + 200 ohms) = 100 ohms.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Chapter 4



Alternating Current

Each voltage supply described above and shown in the associated drawing, has a specific polarity at its output terminals. One terminal of the supply is always positive and the second terminal is always negative. Current flows in one direction through a circuit when it is powered by this type of supply. Voltage never changes its polarity. When these conditions exist, the source of current and voltage is referred to as a *dc supply*, where dc is an abbreviation for *direct current*.

Supplies that keep reversing in polarity and current flow direction are also available. These sources are designated as *ac supplies*, where ac is an abbreviation for *alternating current*. Although the battery is a dc supply, ac generators and electronic circuits supplying ac are also quite commonly available. The voltage and current supplied by an electric company to its customers is seldom anything other than the ac variety.

GRAPHS AND THINGS

Ac waveforms and characteristics are best understood through use of specific individual graphs as well as through combinations of different types of drawings. A graph is essentially a drawing showing how two items that vary simultaneously are related to each other. In Fig. 4-1, you see how the voltage in a specific circuit can vary with the passage of time. It shows specific voltages at various instances of time.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

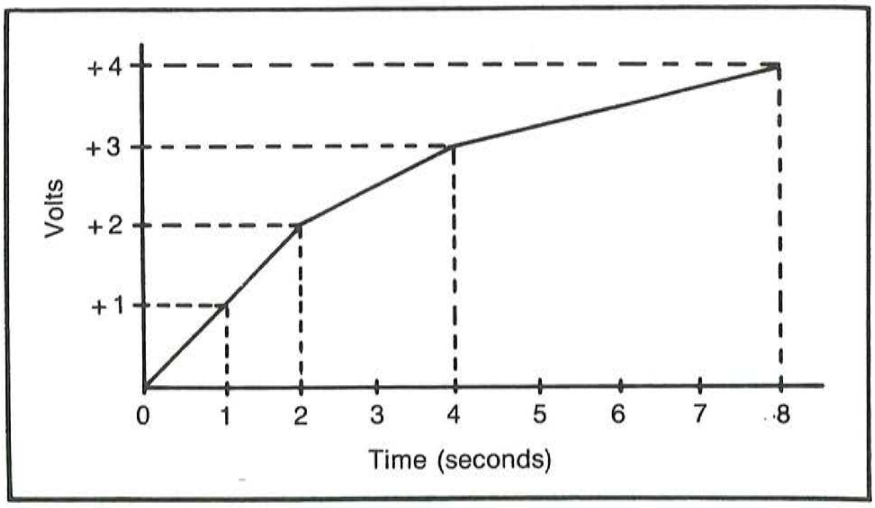


Fig. 4-1. A graph showing how voltage in a circuit may vary with respect to time.

The plot starts at the time when the voltage is at a specific level (0 volt in this graph). The voltage level at specific times after this initial start can be determined from the curve. Time is indicated on the horizontal line or axis. This is referred to as the x axis. Numbers at this axis indicate a quantity of seconds. There is a 0 at the point where the horizontal axis crosses the vertical line or y axis. All events are considered to begin at this time and not before. This point is assigned the number 0 to indicate that it is the time at which we begin our study of the voltage curve. The point marked 1 on the horizontal axis represents the time at one second after the starting point. Similarly, the points numbered 2, 3, 4 and so on indicate the times at 2, 3, and 4 seconds after the start. Because the plot of time is linear, the time between any two listed points can be estimated. Thus, 1 1/2 seconds after the count started is midway between the 1-second and 2-second markings on the scale. The 3.7-second point is between the 3-second and 4-second markings. Just add 7/10 of the distance between the two markings to the 3-second marking to find the point representing 3.7 seconds.

The scale on the vertical axis is in volts. In this drawing, the scale starts at 0 volt and continues to +4 volts. The scale and starting points depend upon the voltage to be displayed on the graph. Thus, if you were not interested in voltage variations below the 2-volt level, but only in voltage variations between 2 and 4 volts, the scale could have started at +2 volts and go up to +4 volts instead of covering the entire range from 0-volt to +4-volts. The same variation could have been used when considering the calibration

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

of the horizontal axis. Here, if only the portion of the curve under study involved the time between 5 seconds and 6 seconds after the voltage was initially applied, the scale for the horizontal axis could have started with the 5-second point rather than with 0 second and ended with the 6-second point. If that 1-second period was spread over the full length of the horizontal axis, points indicating portions (or 1/10) of a second could easily have been plotted between the 5-second and 6-second notations.

Getting back to Fig. 4-1, note that vertical lines have been drawn from several points on the horizontal axis. These lines represent the time indications on the x-axis. Similarly, horizontal lines have been drawn from voltage points on the vertical axis. These represent the voltages noted on the y axis.

The curve shows how the voltage varies with time. It crosses the axis at the 0-second/0-volt point. At the time when the plot begins at 0 second in time, 0 volt is available.

The vertical line from the 1-second designation point on the horizontal axis crosses the voltage curve at a specific point. By drawing a line from that point to the vertical axis, you can see that the point is at the 1-volt level. Thus, at the 1-second instant in time 1 volt is available.

Following a similar procedure, +2 volts is available at 2 seconds in time, +3 volts at 4 seconds in time, and +4 volts at 8 seconds in time. No information is provided as to how this voltage changes after eight seconds has elapsed. If you want to determine the voltage at the 2.5-second instant, draw a vertical line from a point midway between the 2-second and 3-second markings on the horizontal axis and note where that line crosses the voltage plot. Then draw a horizontal line from that point of intersection to the vertical axis. It is about one-fourth the way (or 0.25 of the total distance) between the +2-volt marking and the +3-volt marking. Voltage at 2.5 seconds is about 2.25 volts.

Plot Angles in a Circle

The point at the center of a circle in Fig. 4-2 is labelled O or origin. The *radius* is any line from this center point to the circumference of the circle. (The *circumference* is the actual circle or the curved line forming the circle.) Lines O to C, O to A, and O to B are all radii. (Radii is the plural of the word radius.) All radii are the same length and are equal to exactly one-half the length of the diameter.

The *diameter* is a line that connects two points on the circum-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

ference of the circle. But that line must pass through the O center point O. Consequently, it is the longest line that can be drawn in a circle. Here, it is shown as a horizontal line extending from point A to point B. It can be drawn at any angle with respect to the horizontal so long as it passes through the o point and connects two points on the circumference. Regardless of the angles they form with the horizontal, all diameters are the same length and are equal to twice the length of the radii.

The horizontal radius OB shown here is considered as being at zero degree (0°). All other radii form angles with this horizontal radius. The angle formed by any two radii starts at the center point of the circle. Radii OC and reference OB form an angle using this 0 point. This is referred to as angle COB. When radius OC is directly over radius OB, that angle formed with the reference line OB is 0°.

Radius OB is considered as being fixed in place. When another radius is drawn here, such as OC, it is also fixed in place. One setting is shown for radius OC. It is drawn in one spot, but it may be considered as a radius which can rotate inside the circle, continuously changing the angle COB. It may be imagined as rotating in a counter-clockwise direction. It starts to rotate from the 0° point where it is directly over the OB radius. It can continue to rotate in this counter-clockwise direction until it reaches and goes directly over the OA radius. But it does not have to stop there. It may continue rotating indefinitely. After OC has completed one full rotation through the entire circle and returns to its starting point, it is referred to as having completed a *full cycle*.

Suppose rotation starts when OC is directly over OB, and the angle formed by the two radii is 0°. As OC keeps rotating, angle COB increases from the 0° starting point. When it has completed the full cycle to once again reach its starting or 0° point and be over the OB radius, it is said to have rotated through an angle of 360° (360 degrees). Because the OC radius is shown in the drawing at only 1/8 of that angle, in this location it forms an angle of 1/8 of 360° or an angle of 45° with OB. As it keeps rotating, angle COB increases until one cycle of rotation has been completed through 360°. If it rotates through a second full cycle, it has gone through an angle of $360° \times 2 = 720°$. Similarly, if it went through sixty of these cycles, it has rotated through $360° \times 60 = 21,600°$. Should the time for 60 cycles be accomplished within one second, you can say that the radius rotated through 60 cycles per second or 21, 600°/second. (The symbol / indicates "per.")

When working with numbers, very few, if any, categories in-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

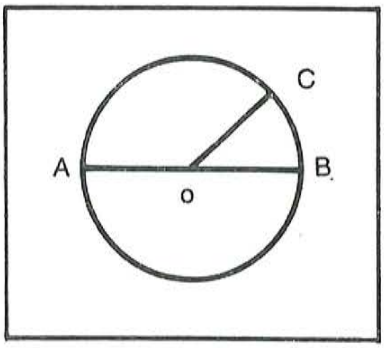


Fig. 4-2. Angles in a circle formed by its radii.

volve one system of units. When measuring length, you use either the "mile" or the "meter" as the unit. When you measure weight, it is either in units of "pounds" or units of "kilograms." Even money may be considered in "dollars" or in "yen." About the only factor that holds in all systems is time, measured in units of seconds. So as you could expect, angles (the symbol is ∢) are not measured only in degrees. It has been found very useful to refer to angles in terms of a number of radians.

In Fig. 4-2, when the OC radius travelled through 360°, you could just as easily have said that it rotated through 2π radians. The Greek letter π (pi) represents the number 3.1416. Usually 3.14 is accurate enough for most purposes, dropping the last two digits.

When the OC radius was originally over the OB radius, the angle was noted as being 0°. This is the same as saying 0 radians. At the 45° angle shown in the drawing, the OC radius travelled 1/8 of its full cycle, so that angle if forms with OB is $1/8 \times 2\pi = \pi/4$ radians. To convert from an angle in degrees to an angle in radians, multiply that angle by 2π and divide it by 360. Thus, 90° is $(2\pi)\ (90)/360 = \pi/2$ radians. Working backwards, if you know the radians and wish to convert the notation to degrees, simply multiply the number in radians by 360 and divide it by 2π. So if you start with $\pi/4$ radians, its angle in degrees is $(\pi/4)\ (360)/2\pi = 45°$. But these conversion formulas are not necessary if you simply remember that $360° = 2\ \pi$ radians and take it logically from there.

Sine of an Angle

The relative lengths of the sides of a triangle (or figure containing three angles and three sides) are related to its angles. If you consider the triangle in Fig. 4-3, the angle at the lower right corner is 90°. Because one angle is 90°, the figure has been given the special name of *right triangle*. The side opposite the right or 90° angle has been labelled h and referred to as the *hypotenuse*.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

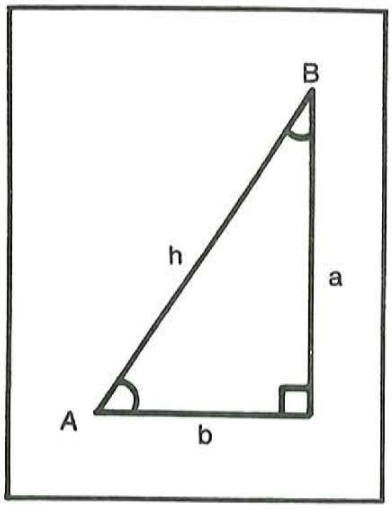


Fig. 4-3. A right triangle.

The other two sides of the triangle, a and b, are opposite angles A and B. In this discussion, I consider a, b and h as the lengths of the sides of the right triangle and A and B as the number of degrees of the two other angles.

The ratio of the lengths a to h is referred to as the *sine* of the angle opposite side a. It is written mathematically as

$$\sin A = \frac{a}{h} \qquad \textbf{Eq. 4-1}$$

For angle B, its sine is obviously b/h because side b is opposite angle B.

Another relationship you will be using in the discussion of electricity and electronics is the fraction formed by the length of a line adjacent to the angle with the length of the hypotenuse. The term for this is *cosine*. Stated mathematically,

$$\cos A = \frac{b}{h} \qquad \textbf{Eq. 4-2}$$

so that cos B = a/h. Notice how cos B and sin A are identical, while cos A is also equal to sin B.

In addition, there is also a term for relating the length a to the length b, while ignoring h. It is referred to as the *tangent* of an angle. For angle A, it is written as

$$\tan A = \frac{a}{b} \qquad \textbf{Eq. 4-3}$$

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Obviously, tan B = b/a. If you do a little simple algebra, you will see that sin A/cos A = tan A because (a/h) / (b/h) = a/b. Similarly, sin B/cos B = tan B.

Another equation useful in electronics work is the relationship between the lengths of all sides of a right triangle. It is

$$a^2 + b^2 = h^2 \qquad \textbf{Eq. 4-4}$$

showing that the sum of the squares of the lengths of two of the sides of the right triangle is equal to the square of the length of the hypotenuse.

Fractions a/h, b/h, and so on, are merely the ratios of the length of one side of a right triangle to the length of a second side. The sine, cosine, and tangent of the angle are numbers indicating these ratios. Tables are available in math books that list the ratios for different angles. For example, you will find from the table that the sine of a 60° angle is 0.866. So if A is 60° or $\pi/3$ radians, the ratio of length a to length h is 0.866. Consequently, sin A = 0.866 and a/h = 0.866. Should h be 10″ long, the length of a would be 10(0.866) = 8.66″.

Sine Waves

You can now relate the definition of the sine of an angle to lengths of lines drawn in a circle. Consider the drawing in Fig. 4-4, which is simply the circle shown originally in Fig. 4-2. Here, more radii are shown. Each radius touches the circumference of the circle. A vertical line is drawn from the point where the radius touches the circumference to the horizontal line AB.

Consider each radius as the hypotenuse of a right triangle. Each triangle is formed by three lines. These lines are 1) the radius in question; 2) the vertical line that extends from the point where the

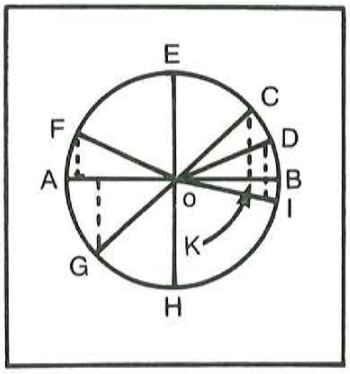


Fig. 4-4. Circle showing various radii.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

radius touches the circumference down to the horizontal line AB; and 3) the length of the portion of the horizontal line that is between the o point and the point where the vertical line touches it. One of the triangles in Fig. 4-4 that is formed by these three lines involves radius OC. Here the lines are 1) radius OC; 2) vertical line CK; and 3) line OK. Despite the fact that all radii in a circle are of equal lengths, the lengths of the vertical and horizontal lines of the triangle depend upon the angle formed by the radius under consideration with the horizontal line.

The sine of the angle formed by a specific radius with line AB is equal to the length of the vertical line divided by the length of the radius. For convenience, let us consider the lengths of the radii as being equal to unity or 1.

Starting with the radius OD in Fig. 4-4, the length of the vertical line from point D to the line OB, is the sine of angle DOB. This is because the sine of that angle is equal to the length of the line from D to line OB divided by the length of the radius. Since the radius is 1, the length of that vertical line is simply equal to the sine of the angle.

The sine of the larger angle, COB, is the length of the vertical line between C and OB. This length is larger than the one from D to the horizontal line, so the sine of this angle must be greater than the sine of the angle in the previous case.

When the angle is EOB or 90°, the length of the vertical line is at a maximum and equal to 1 (1 is the length of the radius). As the angle increases above 90°, the sine of the angle decreases. For example, the line from F to the horizontal line is the sine of angle FOB. The sine of angle FOB is identical with the sine of the smaller angle, FOA. The sine of the angle reaches zero when the angle is 180° or π radians. At this angle, the radius under consideration is coincident with or lies over radius OA.

The sines of all angles are negative when the angles exceed 180°. This can be seen in the figure. Here, the vertical lengths from G, H, and I to the horizontal are all below line AB. Because of this, these lines are negative. The radius is always considered as being positive. As a result, the ratio of a negative vertical line in the area below the horizontal axis to the positive radius is negative. Because this ratio is the sine of the angle, the sines of angles formed using any of the negative lines must also be negative.

You can make a drawing to indicate how the magnitudes of the sines of angles vary with the degrees of the angles. Because the vertical lengths are proportional to the sines of the angles, a

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

drawing showing the relative lengths of the vertical lines at the different angles is identical with a drawing showing how the magnitudes of the sines of the angles vary with the degrees of the angles. This is shown in Fig. 4-5. The height at each angle is proportional to the vertical lengths shown in Fig. 4-4 for that angle. This drawing is referred to as one cycle of a sine wave because it contains information about the sines of angles between 0° to 360°, or between 0 radians to 2π radians.

Looking at the sine wave, several factors should be noted. All points correspond to the different vertical amplitudes at the various angles. Instead of relating the amplitudes to angles, they can be related to time. Let us say it takes one second for the radius to rotate from 0° to 360° to complete one cycle of the sine wave. So if it starts at time 0 at 0°, its amplitude or height is at a positive peak at the instant that one-quarter/second of time has elapsed. The amplitude drops to 0 at 180° or at the one-half/second mark and decreases to a negative peak after another one-quarter/second has passed. It is at the negative peak at the three-quarter/second point or at 270°. The cycle has been competed when the amplitude rises from the negative peak to a zero level. This is at an angle of 360° or at the moment that 1 second in time has passed. This same cycle is repeated for the next second between 360° and 720°, for the third second between 720° and 1080°, and so on.

A cycle does not have to take only one second. It can occupy much more time than one second. If it occupies five seconds, each

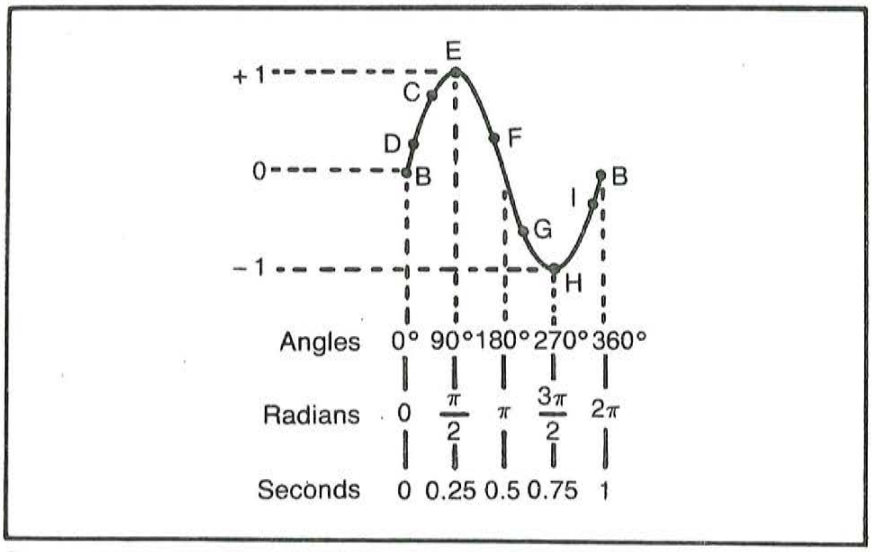


Fig. 4-5. Sine wave using data determined from Fig. 4-4. All letters correspond to points labelled in Fig. 4-4.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

length of time would be five times that shown here, so that at 180° or π radians, the time would be 2.5 seconds.

However, in electronics each cycle usually occupies much less than one second. You can have ten or even billions of these cycles in one second. Other items worthy of note are the notations used to indicate the positive and negative peak amplitudes of the sine wave. It is shown to vary from a maximum of +1 to a minimum of −1. The numbers "1" were chosen for convenience and are identical with the numbers chosen to indicate lengths of the associated radii in the circle in Fig. 4-4. Magnitudes of the sine wave at all angles are related to these positive and negative maximums.

Amplitudes at all points on the curve are identical with the vertical heights from the tip of the radius to the horizontal diameter at specific angles in the circle. These heights vary as shown on the curve. The amplitudes are one-half of the positive or negative peaks when they are at 30°, 150°, 210° and 330°.

The cosine waveshape is identical to the sine wave except that it starts at the peak point, E, rather than at B. Point E is considered as being at 0°; point F is at 90°, and so on.

If two sine waves with different amplitudes are available at the same time, they can be added to form one curve that is equivalent in magnitude to the total of the two sine waves. This can be done by considering the lengths of the radii in the two circles used to generate the individual sine waves, and then finding the sum of these radii. The radius derived from the sum of the original radii is used to generate the new wave representing the sum of the individual waves.

Another method of finding a sine wave to represent the sum of two individual sine waves is to simply add the amplitudes of both sine waves at each of the angles. This method, as well as the one discussed previously, are shown in Fig. 4-6. In Fig. 4-6A, the radius OB is added to the radius OC to get a total radius OD. This sum of the two radii is rotated in the circle as described above to generate the sine wave. In Fig. 4-6B, the magnitudes of the two smaller sine waves are added at the different angles to form the larger sine wave. The two smaller positive half-cycles add to form a larger positive half-cycle and both negative half-cycles add to establish the larger negative half-cycle.

Sine waves in Fig. 4-6 are said to be *in phase* because they all start at a zero amplitude at the same time or same angle. They go through an entire cycle in the same *period* or length of time. Should the two cycles be out of phase, the waves would be at the zero level

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

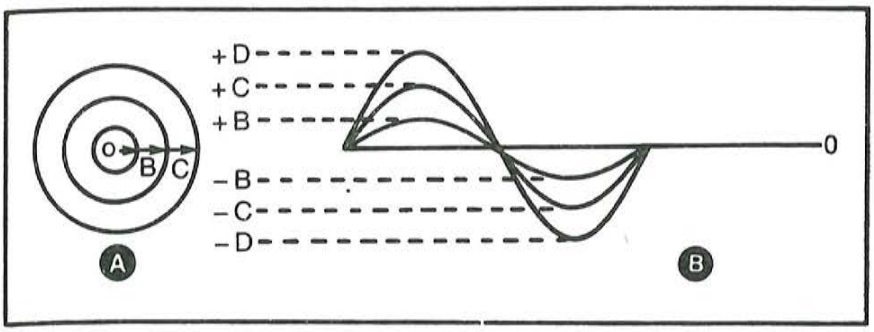


Fig. 4-6. Sum of two in-phase sine waves.

at different angles. For example, sine wave OC may start 45° before sine wave OB. The two curves may then look like those drawn in Fig. 4-7B. This phenomenon is described as sine wave OC *leading* sine wave OB by 45°.

In Fig. 4-7B, the amplitudes were added at each angle as in Fig. 4-6B. In Fig. 4-7A, the amplitudes were added vectorally using the radii as in Fig. 4-6A. Here, however, radius OC is drawn as in the previous figure, but OB is shown as being at an angle of −45° (or +315°) with respect to the horizontal. This is because the OB curve reached the 0° point 45° after the OC curve, thereby lagging behind by 45°. A parallelogram is formed using lengths OB and OC to determine the magnitude of the sum, OD, as well as the angle this line representing the sum forms with the 0° horizontal line. The line, OD, is the sum of the two out-of-phase sine waves. The angle, COD, is the angle by which the total or sum of the two out-of-phase curves lags behind the curve formed due to the OC radius. The total curve and the lagging angle are also shown in Fig. 4-7B.

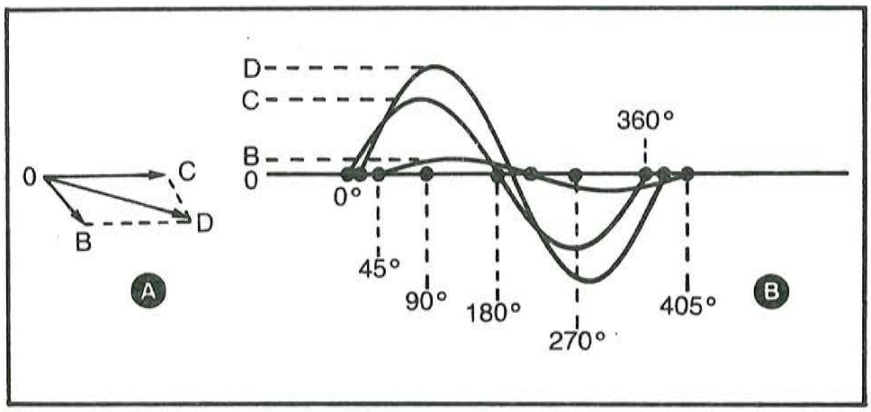


Fig. 4-7. Two out-of-phase sine waves are added. The sum and phase of the total of the two waves are derived from A in this figure.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

COMPARISON OF AC WITH DC

Using this knowledge of graphs and sine waves, I can now turn to a discussion of what ac is all about.

A battery supplies dc voltage. It is shown in Fig. 4-8A. Here, the upper terminal of the battery is positive with respect to the lower terminal. If the lower terminal is connected to ground or is at a 0-volt reference potential (potential is another word for voltage and is usually used when the voltage is referred to a fixed level such as ground) the upper terminal is E volts above the 0-volt level. This is shown graphically in Fig. 4-8B.

Should the battery be reversed in the circuit so that the plus terminal is at ground, the voltage at the minus terminal is E volts below the 0-volt level. This is shown graphically in Fig. 4-9. The voltage remains fixed at $-E$ volts for the full time during which the battery is connected to the circuit with the polarity shown on the graph.

Taking this one step further, assume the circuit in Fig. 4-10A exists. Terminals marked 1, 2, and 3 constitute a switch. When it is set in one position, terminal 1 is connected to terminal 3. In the alternate setting, terminal 2 is connected to terminal 3. Voltage at the output of this circuit is between terminal 3 of the switch and ground.

When terminals 1 and 3 are connected to each other, the out-

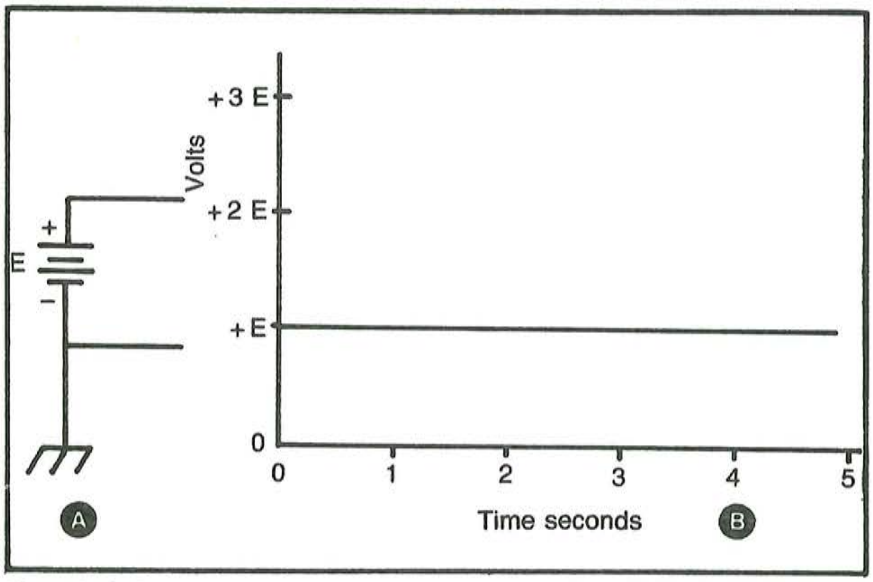


Fig. 4-8. A. Battery supplying dc voltage that is positive with respect to ground. B. Graph showing how this voltage varies with time. In this case it is constant and above the 0-volt axis because it is positive.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

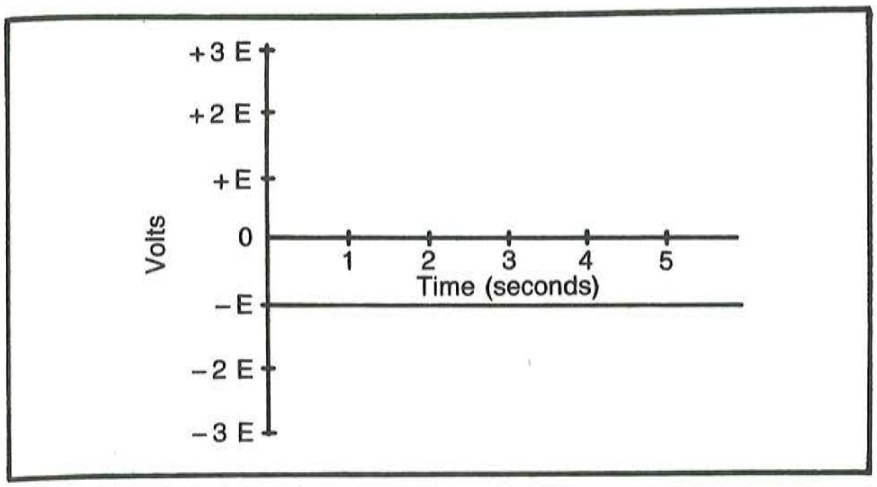


Fig. 4-9. Voltage is negative and at E volts with respect to ground.

put is as shown in Fig. 4-8B. Voltage at one output terminal of this circuit is +E volts with respect to ground. In the alternate setting of the switch, the output is −E volts with respect to ground. This is shown in Fig. 4-9.

Now assume you keep on switching back and forth between one position and the other position of the switch. Then the voltage at the output of the circuit would keep shifting back and forth from +E to −E and then back to +E. This continues as long as the switch is thrown from one setting to the other. If this is done once each second, voltage at the output is as shown in Fig. 4-10B. Voltage is no longer fixed at one polarity, positive or negative, but it keeps on alternating from one polarity to the other. This is the basis of an ac supply. Not only does the voltage keep alternating in polarity, but the current also keeps changing its direction of flow. The voltage is referred to as an *alternating voltage* and the current is an *alternating current*, abbreviated ac. The voltage is most frequently referred to as *ac voltage*. It should be noted that however correct the term alternating voltage is and however technically incorrect the term ac voltage is, the latter term is most commonly used, and I will use it here. Direct current and *dc voltage* are terms applied in a similar fashion when referring to current and voltage that are maintained at one polarity. Voltage and current with this characteristic is, of course, available from a single battery.

Ac Waveform

When the voltages are switched as shown in Fig. 4-10, you end

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

up with a rectangular or *square waveform*. Voltage remains fixed at a positive or negative peak level. It is assumed here that the voltage jumps instantly from maximum level to the other. In real life this is never the case, although the situation may be approximated.

Voltage supplied by the electric companies is not in the form of a square wave. It has the sinusoidal shape shown in Fig. 4-5. Voltage rises gradually to a positive peak, drops slowly through a zero level to a negative peak, and then once again rises slowly to repeat the cycle. If the voltage supply is connected across a resistor, the current flowing through the resistor assumes this identical shape. Because the current flowing in the resistor rises and falls in time with the applied voltage, the current is said to be *in phase* with the voltage.

If the meter shown in Fig. 2-5 were considered in another fashion, it could conceivably be used as a device to generate a sinusoidal ac voltage. Start by assuming that the spring and pointer do not exist. The two leads from the coil do not hang free. They are oriented so that they make connections with contacts mounted on a surface, as shown in Fig. 4-11. The armature is rotated by some force. As it rotates, the leads keep making connections with the fixed contacts.

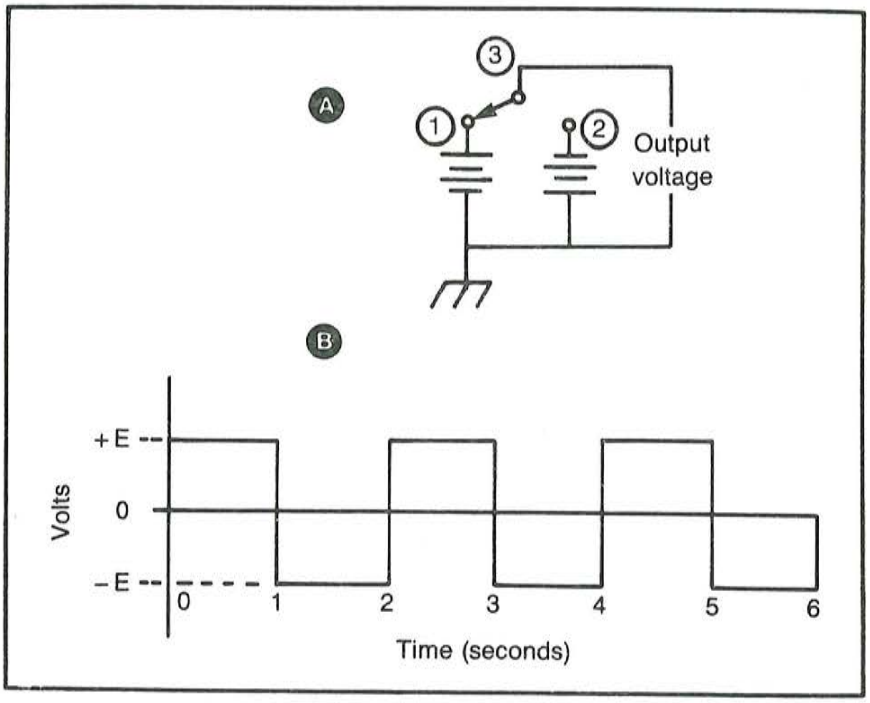


Fig. 4-10. Output voltage polarity altered by use of a switch and two batteries. A. Circuit. B. Output voltage.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

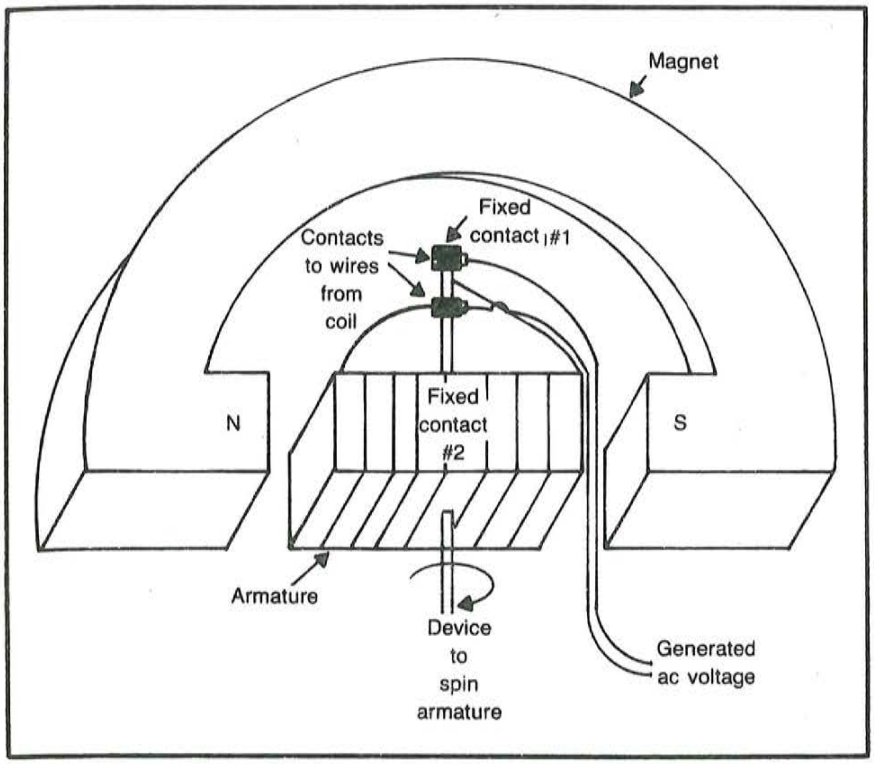


Fig. 4-11. Basic ac voltage generator. Fixed contacts rub on contacts connected to wires and mounted on rotor. The armature is rotated by some mechanical device.

As the coil rotates, it keeps breaking the magnetic field formed by the permanent magnet. A current is induced in the coil. Consequently, a voltage is available across the leads from the coil and at the fixed contacts. The instantaneous magnitudes of the voltage and current depend upon the number of magnetic lines in the field that are broken by the rotating coil. Because the number of lines broken depends upon the instantaneous orientation of the coil, the magnitude of the voltage at the fixed terminals varies with time. These variations take a sinusoidal waveform.

Average and Effective Voltage and Current

When you take an average of a group of numbers, you usually add the numbers and divide the result by the quantity of numbers involved. Thus, if you want to know the average of these six numbers, 4, 27, 10, 16, 13, and 2, you must add all numbers for a total of 72 and divide the sum by 6 for an average value of 12. This average is known as the *mean*.

All numbers in the example shown are positive. But what if

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

some numbers are positive and others are negative? Let's find the mean of the above group of numbers by changing the signs (or polarity) of some of these numbers. Use numbers -4, -27, $+10$, $+16$, $+13$, and -2. The total is $-33 + 39 = +6$. Because six numbers are involved, the mean average is $+6/6 = +1$.

Now consider the average amplitude of a sine wave. Assume it has the shape of an applied voltage with a peak amplitude of E volts. To determine this average, you must consider one full cycle. You can start by dividing the 360° into twelve equal parts, as shown in Fig. 4-12. Draw a line from each of these points to the curve. There would be twelve lines, but no lines are shown at the 180° and 360° points. This is because the amplitudes here are zero. Now add the amplitudes or heights of all the lines hitting the curve in the section between 0° and 180°. This sum is positive. Continue by adding the amplitudes hitting the curve in the section between 180° and 360°. Since all these lines are negative, the sum of these amplitudes is a negative number. Because both halves of the sine wave are identical, the sums of both groups of amplitudes are identical. They differ only in one sum being positive and the second sum being negative. The total amplitude of an overall sine wave is zero because the sum of a positive number with an identical negative number, is zero. Dividing this by 12 because 12 amplitudes are considered, leaves you with the information that the average amplitude of an entire sinusoidal cycle is equal to zero. So whether the cycle represents current or voltage, the average current or voltage present over a complete cycle is zero.

Note that the sine wave was divided into twelve parts in Fig. 4-11. It could just as easily have been divided into more sections.

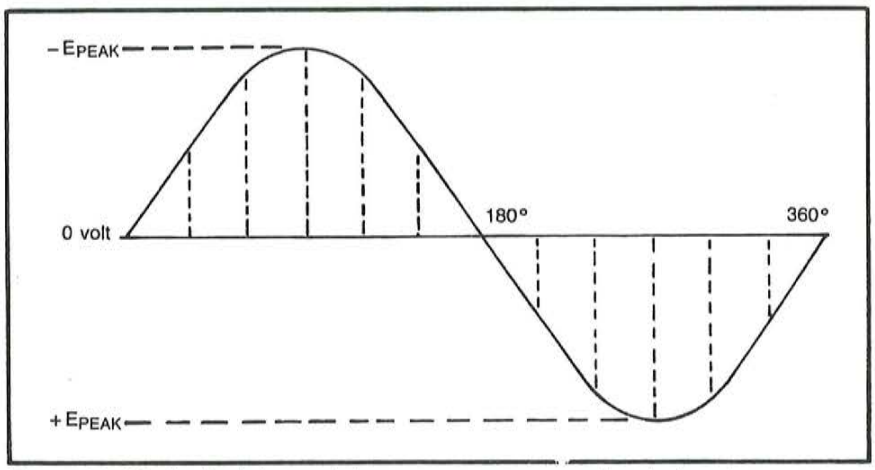


Fig. 4-12. Method of determining mean or average level of a sine wave.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

The average number for each positive or negative peak achieved by considering more and consequently smaller, parts is more accurate. Here, less parts were considered because of convenience and ease of explanation. In any event, the *mean* average voltage or current of an entire sinusoidal cycle, is zero.

If we consider the case when a voltage or current is present during only one half of a sinusoidal cycle, an actual average does exist that differs from zero. Here, the amplitudes in the first half of the cycle are noted as they were above. All amplitudes in the second half of the cycle are zero. To determine the mean amplitude for the entire cycle, just add the six amplitudes that exist in the active half-cycle and divide that sum by twelve. The sum must be divided by twelve because there are six amplitudes of zero magnitude in the second half-cycle that cannot be ignored. They must be added to the six amplitudes in the first half-cycle. If the curve discussed here were divided into an infinite number of sections to enable you to get an exact average, you would find it to be

$$e_{AV} = \frac{E_{Peak}}{\pi} \qquad \textbf{Eq. 4-5}$$

where E_{Peak} is the peak amplitude. I will not show how this infinite division and averaging is done, but it is possible with calculus. E_{Peak} can be positive or negative. Its polarity depends upon the half-cycle being considered as active. This mean type of average is applied when rectified power supplies are being considered.

Another type of average considers the sum of the squares of all amplitudes. Unlike the mean average, this average does not ignore the fact that the total power dissipated in a circuit is due to voltage and current present in both halves of the cycle. Twelve amplitudes are involved when determining a close approximation to this average. Six are positive and six are negative. Unlike the procedure used to find the mean of the 360° curve, each amplitude is squared (or multiplied by itself) before being averaged. Thus, if an amplitude is +3 volts, the square of 3 volts is $3^2 = 3 \times 3 = +9$. In the half of the sine wave between 180° and 360° the amplitudes are negative. But the square of each amplitude is positive for it is the product of two negative numbers. Thus, if the amplitude here is −3 volts, $(-3)^2 = (-3) \times (-3) = +9$. All the squares of the individual amplitudes are added and the sum is divided by twelve to determine the average value of these squared numbers. The square root of this average is then determined to

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

establish what is referred to as the *root mean square* average of the amplitudes. The abbreviation for this is rms. If there were an infinite number of sections of the sine wave used to determine the rms average, using calculus you would get an exact rms number equal to

$$E_{RMS} = \frac{E_{Peak}}{\sqrt{2}} = \frac{E_{Peak}}{1.414} = 0.707\ E_{Peak} \qquad \textbf{Eq. 4-6}$$

Root mean square voltage and current are important when analyzing ac circuits. If a dc voltage produced a specific amount of heat in a resistor, the rms ac voltage must be numerically equal to the dc voltage if it is to do the same job. Thus, if 10 volts of dc brings the temperature of a resistor up to 55° Celsius, it would take 10 rms volts of ac across the same resistor to bring its temperature up to the same 55 °C. The peak ac voltage must then be $10 \times \sqrt{2} = 14.14$ volts if it is to supply the 10 rms volts.

Similarly, dc and ac power and current correspond to each other if the rms values are used for each. As for current, the rms values are:

$$I_{RMS} = \frac{I_{Peak}}{\sqrt{2}} = 0.707 I_{Peak}$$

Rms power is derived by multiplying the rms voltage by the rms current.

$$P_{RMS} = (0.707E_{Peak})\,(0.707I_{Peak}) = 0.5\ V_{Peak}I_{Peak}.$$

Frequency

The duration of the single cycle shown in Fig. 4-5 is from 0 to 2π radians. The time for a cycle differs with the application in which the ac is being used. If one cycle is completed in one second, the sine wave is referred to as having a frequency of one cycle per second or 1 cycle/second. In modern notation, the term cycle/sec has been assigned the name *Hertz*, abbreviated Hz. Thus, if there is 1 cycle/sec, it is the same as saying that the frequency is 1 Hz. If there are ten of these cycles during each second, the sine waves are referred to as having a frequency of 10 Hz.

Ac power is supplied by electric companies. In some places in the world, the frequency of the power can be 25 Hz or 50 Hz. Over

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

most of the United States, the power line frequency is 60 Hz. This means that the electric company is supplying 60 of these cycles each second, 60 Hz × 60 secs or 3600 cycles each minute, and 3600 cycles × 60 = 216,000 cycles each hour. That sounds like a lot of cycles, but in reality 60 Hz is a very low frequency.

When you listen to sound from the radio, hi-fi, or television set, you hear these cyclic variations in various forms. They comprise music, speech, sound effects, and so on. This audible material can be composed of frequencies between 16 Hz and 15,000 Hz. It often ranges to above 20,000 Hz. As we grow older, the frequencies that the human ear can hear, fall far below 20,000 Hz, possibly to as low as 6,000 Hz. But the higher frequencies are there regardless of our capabilities of hearing them. In the hi-fi world, a range of 20 Hz to 20,000 Hz is considered the minimum necessary frequency response.

The highest audible frequency, 20,000 Hz, is in reality a very low frequency. Consider radio frequencies. Frequencies from about 550,000 Hz to 1,600,000 Hz are transmitted on the AM broadcast band. Citizen's Band radio operates at about 27,000,000 Hz. FM broadcasts are transmitted on frequencies between 88,000,000 Hz and 108,000,000 Hz; television stations broadcast signals between 48,000,000 Hz and 890,000,000 Hz while radar and other similar devices transmit at frequencies which exceed the 1,000,000,000 Hz range by large factors. The frequency or the number of sinusoidal cycles present each second can be quite high.

Just as in the case with voltage, resistance, and so on, prefixes can be used as abbreviations for large frequency numbers. A 1000 Hz tone is at a 1 kilohertz or 1 kHz frequency. Similarly, 800 Hz and 0.8 kHz are identical frequencies. One million Hertz and 1 megahertz or 1 MHz are identical. A radio station that broadcasts at a frequency of 1200 kHz is supplying 1.2 MHz. The prefix for one billion Hertz is giga so that 16,000,000,000 Hz = 16,000,000 kHz = 16,000 MHz = 16 gigahertz or 16 GHz. If you want to go further, 1000 GHz = 1 THz where THz is an abbreviation for terahertz. Tera is a prefix indicating trillion.

Period

The time it takes for the sine wave to complete the entire cycle from 0 to 2π is referred to as the *period*. Thus, if the frequency is 1 Hz, the time duration of one cycle is 1 second. Should the frequency be double this, or 2 Hz, it takes half of the previously noted time for the sine wave to go through a complete cycle. There are

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

two cycles in each second. Thus, the time for each cycle of a 2 Hz sine wave is one-half second. If you continue with this, you will find that the time for a single cycle at any frequency can be determined using the simple relationship

$$t = \frac{1}{f} \qquad \textbf{Eq. 4-7}$$

where t is the period in seconds, and
f is the frequency in Hz or cycles/sec.

Thus if a radio station broadcasts at 1 MHz, the period or time duration of each cycle is t = 1/1 MHz = 1/1,000,000 Hz = 10^{-6} secs.

As always, prefixes and abbreviations can be used here. A chart showing a relatively complete listing of these prefixes and abbreviations is shown in Table 4-1. Using this table, the period of a 1 MHz signal is 10^{-6} secs = 1 microsecond = 1 μsec. From this it can be seen that if frequency is considered in kHz rather than in Hz, the period using equation 4-7, is in msecs; if f is in MHz, t is in μsecs; if f is in GHz, t is in nsecs; and if f is in THz, t is in psecs.

TRANSFORMERS

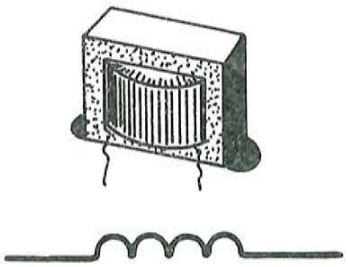
Resistors are passive components that can be used in both ac or in dc circuits. Other components perform their functions only when a variable voltage (or continuously varying voltage such as ac) or current is applied. The transformer falls into this category.

Table 4-1. Abbreviations of Prefixes for Time and Frequency.

Prefix	Abbreviation	Portion of Seconds or Hertz	
		Fraction or Multiple	Exponential Form
pico	p	1/1,000,000,000,000	10^{-12}
nano	n	1/1,000,000,000	10^{-9}
micro	μ	1/1,000,000	10^{-6}
milli	m	1/1000	10^{-3}
---	---	---	---
kilo	k	1000	10^{3}
mega	M	1,000,000	10^{6}
giga	G	1,000,000,000	10^{9}
terra	T	1,000,000,000,000	10^{12}

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Chapter 5



Passive Components in AC Circuits

The resistances in a circuit affect the voltage and current in that circuit. This is true regardless of whether the applied power is ac or dc. But there are components that impede the flow of current only when ac voltage is applied. Two passive components of this type are capacitors and inductors.

INDUCTORS

Coils are turns of wire that resist the flow of ac current. This is because of the fluctuating magnetic field established when ac current flows in the turns of wire. Should only a dc voltage be placed across the inductor, the amount of dc current in the coil is determined by the resistance of the wire forming this component. The coil behaves like an ordinary resistor. But when ac current flows, there is also a reactance, X_L. *Reactance* is a term used to describe by how much a coil (or capacitor) opposes the flow of ac current. For an inductor, the reactance is determined by Equation 5-1.

$$X_L = \omega L \qquad \textbf{Equation 5-1}$$

Here, $\omega = 2\pi f$ or 6.28 times the frequency in Hz of the ac applied to the circuit, while L is the inductance of the coil.

If a coil and/or capacitor is in an ac circuit along with a resistor, the term *impedance*, rather than reactance or resistance, is applied. Impedance is a combination of a resistance and a reactance.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

It indicates how the flow of ac current is impeded by the presence of these two types of components in one circuit.

The inductance shown in Equation 5-1 is a basic property of a coil. The unit of inductance is the *Henry*. A coil with a large number of turns has a large inductance and a big number of Henrys just as a large resistance would have a large number of ohms. An inductor with very few turns is given in terms of millihenrys (mH), or 1/1000 of a Henry, or in terms of microhenrys (μH), or 1/1,000,000 of a Henry.

Although the resistance of a component may be substituted directly into Equation 2-3 to determine the current in the device when a specific voltage is applied to it, this is not true of the inductance. Information about a coil's inductance, expressed in Henrys, must first be substituted into Equation 5-1 to determine the reactance of the coil. Once the reactance has been calculated, the current in the inductor can be determined using the ac equivalent of Ohm's law, where $e = iX_L$. Ac voltage, e, is the rms or root-mean-square voltage applied to the inductor, and i is the rms current flowing through the inductor when X_L is its reactance.

Equivalent Circuits

A pure inductor has only reactance to limit the flow of current. Real physical inductors also involve resistance. This is the actual resistance, R_S, of the wire forming the coil. An equivalent circuit of a real inductor is a resistor, R_S, in series with the inductor, L, as shown in Fig. 5-1. Here, R_S and L form what is known as the *series equivalent circuit* of an inductor. Its resistance is an important factor in determining the quality of Q or the coil.

When current flows through the inductor wired in a circuit, energy is applied to it by the power source. This energy causes a magnetic field to be formed around the coil. After the power

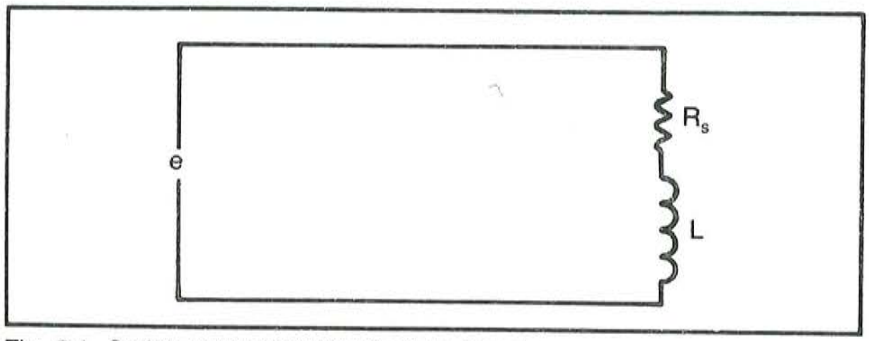


Fig. 5-1. Series equivalent circuit of an inductor.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

source has been removed, all the energy should be returned from the coil to the circuit. None of the energy is dissipated by a perfect coil. But energy is dissipated by the resistance of the coil itself and the resistance of the circuit in which it is being used. Q relates the energy originally applied to the coil to the energy returned from the coil to the circuit. For the inductor itself, the Q or quality of the device when considering its series equivalent circuit is

$$Q = \frac{\omega L}{R_S} \qquad \textbf{Eq. 5-2}$$

Note that in this equation Q is inversely proportional to the magnitude of R_S. Consequently, if R_S is large, the Q of the coil is small.

A parallel resistor-inductor circuit can also be used to represent an inductor. This equivalent circuit is shown in Fig. 5-2. Here the resistance, R_P, is in parallel with the inductance. If this resistance is large, it has less effect on the overall circuit than it does if it is small. Consequently, it is desirable for R_P to be large—much larger than R_S in the series circuit. If the inductance in the two equivalent circuits is identical, the Q's of the two circuits are the same when R_P is equal to Q^2R_S. Thus, if R_S is 3 ohms in the series circuit and the Q of the circuit is 25, R_P must be equal to $(25^2)(3) = 1875$ ohms if the Q's of both circuits are to be identical. Actually, the Q of the parallel circuit is

$$Q = \frac{R_P}{\omega L} \qquad \textbf{Eq. 5-3}$$

It should be noted that the relationship between R_P and R_S given here is approximate. It is sufficiently accurate if Q is more than 3. If it is less than 3, then the relationship $R_P = (1 + Q^2)R_S$ should be used in its stead.

Through use of Equation 5-2, you can see that if Q = 25 in

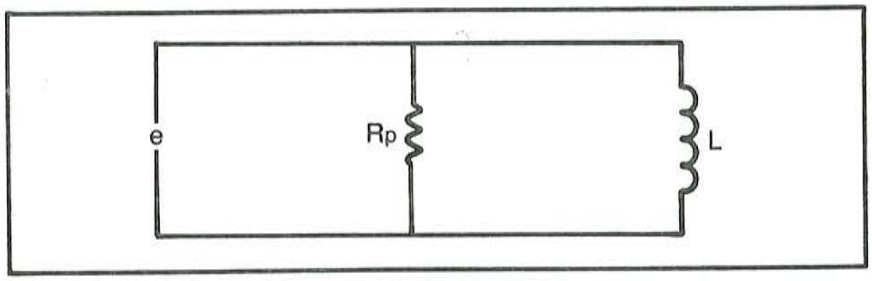


Fig. 5-2. Parallel equivalent circuit of an inductor.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

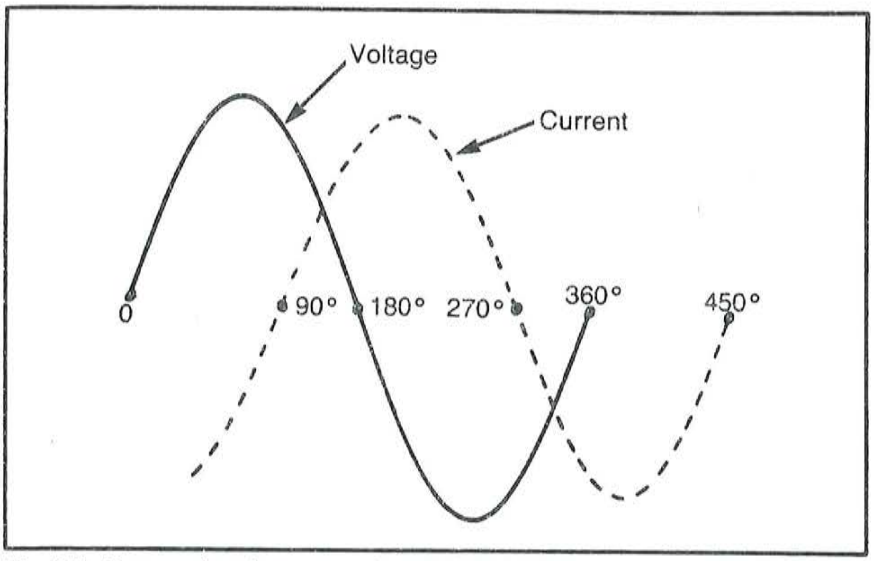


Fig. 5-3. Curves showing current in a coil lagging the applied voltage by 90°

the series equivalent circuit and R_S = 3 ohms,then ωL in this situation must be $Q \times R_S = 25 \times 3 = 75$ ohms. Substituting 1875 (calculated above) for R_P and 75 ohms for ωL into Equation 5-3, you will find that the Q of the parallel equivalent circuit is 1875/75 = 25. This is identical to the Q specified for the series equivalent circuit. It proves our original assumption that $R_P = Q^2 R_S$ when Q is greater than 3.

Relative Phases of Current and Voltage

When an ac voltage is applied across a resistor, cyclic current variations are *in phase* with the applied voltage. At the instant in the cycle when the voltage is at a peak, the current is also at a peak. This is shown in Fig. 4-6 where two in-phase sine waves are illustrated. In this case just disregard the sum.

The situation is different when an ac voltage is applied across an inductor. Voltage and current are not in phase. For a pure inductor, the current lags the voltage by 90° or $\pi/2$ radians. This is shown in Fig. 5-3. Here, the voltage cycle starts at 0° and goes through its complete sequence to 360°. The current cycle starts at 90° and is not complete until it reaches the 450° point.

Because current and voltage are out of phase, the real power dissipated (product of voltage and current) by an inductor is zero. This can be deduced from the curves in Fig. 5-3. At 0°, the instantaneous voltage is zero, while the instantaneous current is at a maximum. The product of the two, or power, is zero watts at this

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

moment. The product is also zero at the 90° point where the voltage is at a peak and the current is at zero. The product of zero keeps repeating itself at 90° intervals for as long as the voltage and current cycles exist. In between these points, the negative product of current and voltage cancel the positive product to produce a zero average power over the entire cycle. This is obvious from the curves. Because the voltage is positive between 0° and 90° while the current is negative during this interval, the product of the positive and negative numbers, which equals power, is negative. The reverse situation exists between 180° and 270° where the voltage is negative and the current is positive. This product is also negative. Between 90° and 180°, both current and voltage are positive and between 270° and 360° both current and voltage are negative, so that both products are positive. Because the sum of the positive numbers indicating power in two quarters of the cycle is equal to the sum of the negative numbers in the two alternate quarters of the cycle, the sum of the positive and negative groups of numbers is zero. Thus, there is an average of zero watts of power over an entire cycle.

It is obvious from the equivalent circuits, that there is no pure inductor without an undesirable resistance. Because of the resistance in the overall circuit along with the inductance, the actual current does not lag the voltage by a full 90°. The angle of this lag is related to the relative magnitudes of the resistance and the reactance of the inductor, as well as to the frequency in question. This angle can be determined from a diagram showing the relative magnitudes of X_L and R as well as their relation to each other.

Phasor Diagrams

As in all circuits with components connected in series, the current flowing through both components in the series circuit in Fig. 5-1 is identical. The phase of the current in the inductor with respect to the supply voltage is identical to the phase of the current in the resistor with respect to the supply voltage. This is because the same current flows through both components in the circuit. Because current is identical throughout the entire circuit, this current is used as a reference in a diagram indicating how voltages are related to this current. As was discussed in Chapter 4, the reference is a horizontal line from a specific point. When the circle was discussed, this reference point was the center of the circle. Here too, it is considered as the "0" starting point. The line representing this reference current is shown in Fig. 5-4A. It is shown as a

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

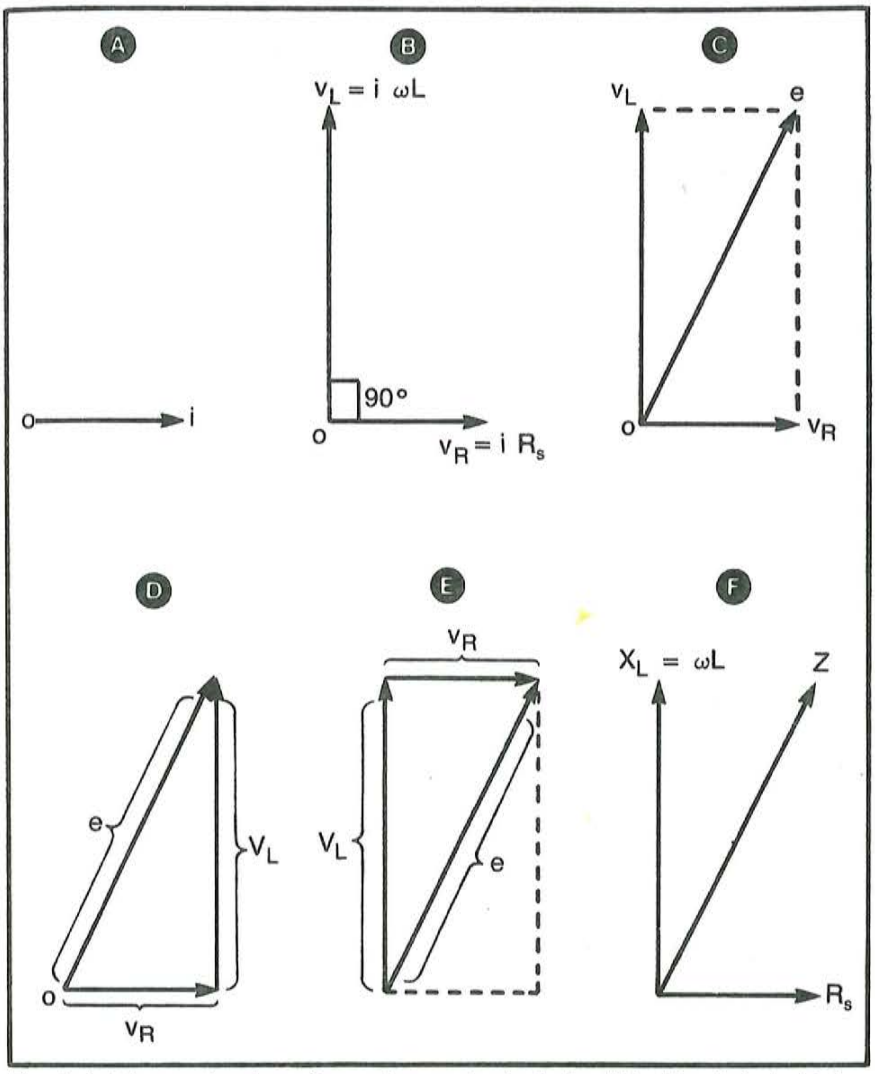


Fig. 5-4. Phasor drawings for series equivalent circuit in Fig. 5-1. A. Reference current. B. Voltages across R and L. Voltage across L leads the voltage across R by 90°. It also leads the current flowing in both component parts by the same 90°. C. Vector sum of v_R and v_L is equal to the supply voltage, e, D and E. Method of adding voltages. F. Adding the resistance, R, to the reactance, X_L, to get a total impedance, Z.

horizontal line with an arrow pointing to the right.

Voltage across the resistance section of the series equivalent circuit is in phase with the current, i, flowing through it. This voltage, v_R, is equal to iR_S. (Note that the voltage across the resistor is not in phase with the supply voltage.) Because i and v_R are in phase, the line representing the voltage developed across R is coincident in direction with the line representing the current.

Voltage across the inductance leads the circuit current by 90°

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

as shown in Fig. 5-3. (This is the same as saying that the current lags the voltage by 90°.) When the current in the inductor is at the 0° point, the voltage, v_L, across L is already 90° ahead of the current. In Fig. 5-4B, v_L is at the 90° point at this instant. The horizontal line representing the inductive current (and v_R), must rotate 90° in a counter-clockwise direction before reaching the line shown as representing the voltage, v_L. By that time, the voltage will have also rotated through another 90° to the 180° point, so that the voltage remains 90° ahead of the current in the inductance at all times.

Because the reactance, X_L, of the inductor section is ωL, the voltage, v_L across the inductive portion of the circuit is $i\omega L$. (This is derived by applying Equation 2-3 to the ac circuit.) The phase relationship of the voltage across the resistor, v_R, with the voltage across the inductor, v_L, is shown in Fig. 5-4B. Here it is assumed that v_L is twice the size of v_R. In ordinary circuits they can have any relative magnitudes.

The total voltage across the resistance and inductance, $v_R + v_L$, is equal to the supply voltage, e, because the inductance and resistance in a series circuit are wired across the supply. But the two individual voltages cannot be added directly. You must obtain a sum involving the phase angle, just as I did in the series-connected voltages shown in Fig. 4-7. This sum of v_R and v_L is shown in Fig. 5-4C. It is equal to e, the rms supply voltage. All we did here was complete a rectangle with v_R and v_L as two of its sides. The broken lines are equal in magnitude and are parallel to the two sides representing v_R and v_L. The sum or supply voltage e, is the line drawn from the 0 point to the opposite corner of the rectangle.

Another way of adding two voltages is shown in Fig. 5-4D and E. Here you add the quantities directly. In D, first draw the length representing v_R. Where v_R ends, v_L begins, so you should start the v_L line at the arrow on the line representing v_R. The total voltage, e, is the line from the beginning of v_R at the 0 point to the arrow of v_L. A similar procedure is shown in Fig. 5-4E where v_L is drawn first and then v_R starts at the arrow on the v_L line. In C, D, and E of the figure, the sums are all equal to voltage e.

Now note the diagram in Fig. 5-4F. It looks exactly like the one in Fig. 5-4C, but the lines have different labels. Instead of line v_R, it shows an R_S; instead of line v_L, it shows an X_L that is equal to the impedance of the inductance or equal to ωL; and instead of e there is a line labelled Z. Z is the reactance of the circuit and is equal to the vector sum of R_S and X_L.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

The diagrams in F and C of Fig. 5-4 provide the same information. Because the current is identical in R_S and L, it is consequently identical to the current supplied by the voltage, e. The voltages across R_S and L, as well as the voltage, e, can be divided by this current without upsetting the proportional lengths or relative angles of lines representing these voltages. When the voltages shown in Fig. 5-4C are divided by the current, you are left with resistance, inductive reactance, and total circuit impedance. You know this from Ohm's law, Equation 2-2. Because of this, you are able to add the impedances in a series circuit in the same way you previously added the voltages.

Power Factor and Dissipation Factor

Let's pull the drawing out of Fig. 5-4F and redraw it as Fig. 5-5. But this time let us add information about the angles to the figure. Use R_S as the 0° reference. You do know that R_S and X_L are at 90° with respect to each other, but Z (as well as e in Fig. 5-4C) is at another angle, θ, with respect to the 0° reference. This angle, θ, is shown in the drawing. For convenience, I also labelled the remaining portion of the 90° right angle as $(90 - \theta)$ because it is 90° less the θ occupied by the angle between R_S and Z.

Now I can state several definitions used in the industry to specify inductors and more often to specify capacitors.

I have discussed the 90° phase difference between the current flowing in a pure inductor and the voltage across it, and indicated that the real power dissipated by an ideal inductor is zero. But you can still perform arithmetic and have a product of the voltage across the inductor with the current flowing through this component. It is not a power that is dissipated by the inductor so it is given the

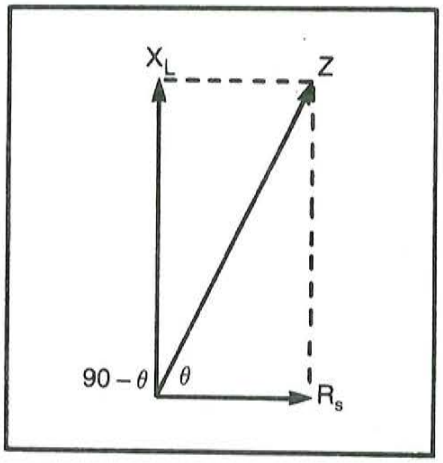


Fig. 5-5. Phasor diagram with information about leading and lagging angles.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

name *reactive power*. It is not stated in units of watts, but in terms of *vars*.

The real power is dissipated by the resistance of the inductor or by any resistor that may be wired into the circuit in series with the inductor. Using Equations 3-4 and 3-5, this *active power* is the product of the current and v_R. This is identical to the product of the square of the current and R_S.

Using the real power as the 0° reference, the reactive power is at a 90° phase angle with respect to the real power. The power that the supply seems to provide is the vector sum of the active and reactive powers. This *apparent power* is the product of the current with e, or the product of the square of the current with Z.

Power factor is defined as the ratio of the actual power to the apparent power. Because the same current flows through R_S, X_L and Z, it is

$$\text{Power factor} = \frac{R_S}{Z} \cos \theta \qquad \textbf{Eq. 5-4}$$

The fact that it is related to the cosine of an angle can be seen from Equation 4-2.

Dissipation factor is the ratio of the amount of energy dissipated in the real inductor to the amount of energy stored in the inductor during one cycle. While the Q of an inductor shows how good it is, dissipation factor (and power factor) show how poor it is. Mathematically, dissipation factor is 1/Q or

$$\text{Dissipation factor} = \frac{R_S}{X_L} = \tan\ (90 - \theta) \qquad \textbf{Eq. 5-5}$$

This relationship to the tangent of the angle $90 - \theta$ can be derived using Equation 4-3. Another trigonometric relationship is the cotangent of an angle or *cot*. It is equal to 1/tan of that angle so if tan A is an a/b in Equation 4-3, cot A is b/a. Then cot A = tan (90 – A). Using this definition, the dissipation factor can be stated as being equal to cot θ.

The power factor is just about identical to dissipation factor when the impedance of the circuit is very large compared to its resistance. Now Z approaches X_L in magnitude so that R_S/Z is approximately equal to R_S/X_L.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Calculating Impedance

Equation 4-4 relates the magnitudes of the sides of a right triangle to each other. In Fig. 5-5, R_S, ωL and Z form a right triangle. Using Equation 4-4 and Fig. 5-5, you can determine how the impedance of an inductor is related to its reactance and resistance. The formula is

$$Z^2 = R_{S^2} + X_L{}^2 \text{ or } Z = \sqrt{R_S{}^2 + (\omega L)^2} \qquad \textbf{Eq. 5-6}$$

because $X_L = \omega L$. Of all the equations, this one and the one defining Q are the most frequently used when working with circuits that involve inductors.

Parallel Equivalent Circuit

In the analysis of the series equivalent circuit, the current was used as the reference or 0° angle because the same current flows through all components in the circuit. As for the $R_P = L$ parallel circuit in Fig. 5-2, the same rms voltage, e, is across the two components. You can logically conclude that the phasor diagram of a parallel circuit should use e as the reference. Current through all components can be determined from Ohm's law so that the current in the resistor is $i_R = e/R_p$, and current in the inductor is $i_L = e/\omega L$. But as always, the current in the inductor lags the current in the reactor by 90°. All this is shown in Fig. 5-6A.

With the supply voltage as the reference, the current through

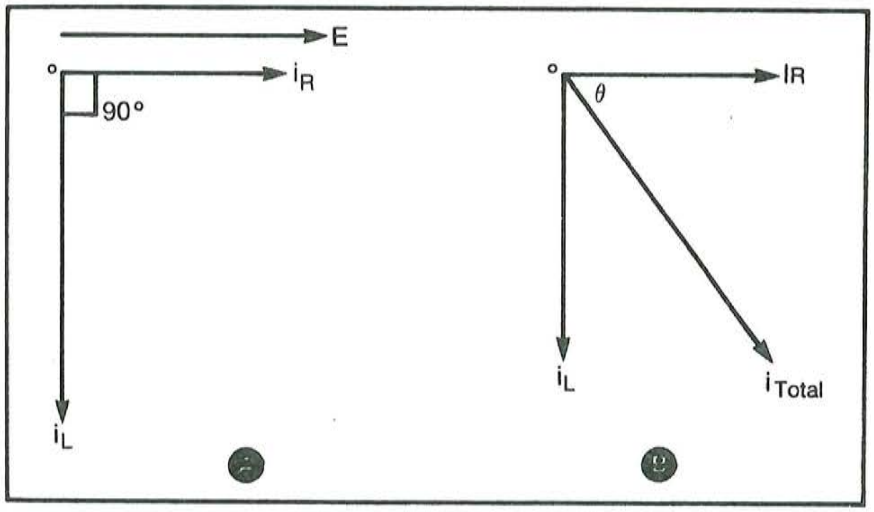


Fig. 5-6. Phasor diagram for parallel circuit. A. Current in inductor lags current in resistor by 90°. B. Vector addition of the current components.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

the resistor is in phase with the voltage from the supply. Hence they are both drawn in the same direction starting at the zero point. Current in the inductor lags the reference voltage by 90°, so it is drawn at that angle with respect to the supply voltage. The line representing the current in the inductor must rotate 90° in a counter-clockwise direction before it can reach the e or 0° reference line. Hence as drawn, it shows i_L lagging the supply voltage by 90°.

The total current flowing through both components in the circuit, as well as the angle by which this total lags the supply voltage, is determined by adding currents in a manner similar to that previously used for adding the voltages of the series circuit. This is all shown in Fig. 5-6B. If the parallel equivalent circuit under consideration happens to be the parallel equivalent of the series circuit, angles, θ, are identical in both instances.

Identifying Inductors

Inductors come in many shapes and sizes. Some of the small inductors used in radio frequency circuits look just like low voltage resistors. The inductance of each component is determined by using the same color code, with minor exceptions, as was listed for resistors in Table 2-5. When inductance is less than 10 μH, the significance of each color band is as shown in Fig. 5-7A. Should the inductor be 10 μH or more, the significance of each band is as illustrated in Fig. 5-7B. It's easy to determine which sequence applies to a particular inductor. If there is a gold band located between two other bands, sequence A applies. If only the last band (marked "tolerance" in both drawings in the figure) is gold, or there is no gold band, or no fourth narrow band at all, then the sequence in Fig. 5-7B applies. In both cases, the inductance determined from the code is in microhenrys (μH).

When determining the inductance, disregard the wide silver band. Use the next band, the narrow band next to the wide one, to start the sequence for determining what the inductance is.

For example, assume you have a component with a narrow band sequence of yellow, gold, violet, gold. Using the drawings in Fig. 5-7 along with Table 2-5, you will find that this component is 4.7 μH, 5%. Here the gold band between the yellow and violet bands represents the decimal point between the 4 and 7, while the last gold band indicates that the component has a 5% tolerance, (See Fig. 5-7A). Should there be no last band so that the sequency of the narrow bands is yellow, gold, violet, the component is still 4.7

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

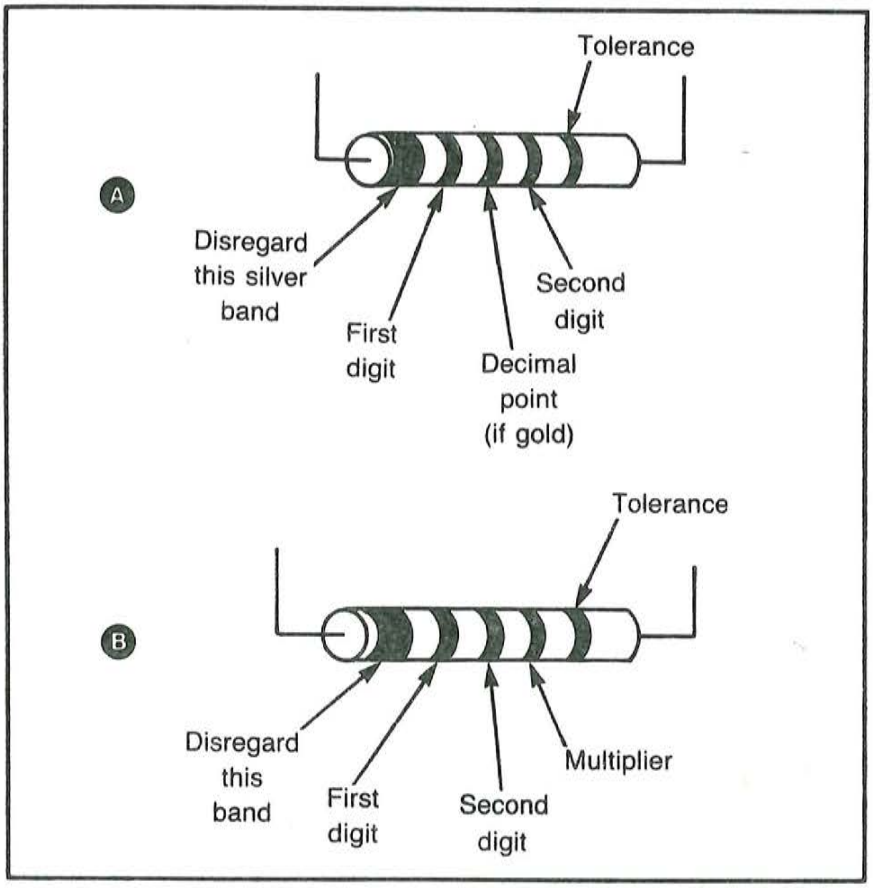


Fig. 5-7. Inductors that resemble 1/2-watt resistors. A. Component with less than 10 μH inductance. B. Component with 10 μH or higher inductance.

μH in inductance, but its tolerance is now 20%.

In another example, assume the color code sequence of the narrow bands is blue, gray, red, silver. Because there is no gold band between the first and third color, the drawing in Fig. 5-7B applies. The inductance of this component is 6800 μH and its tolerance is 10%.

Some typical physical forms of other inductors are shown in Fig. 5-8. Figure 5-8A shows samples of coils or chokes used primarily in radio-frequency circuits. One of these is shown with a screw protruding from its body. This screw is attached to some magnetic material. It rides up and down inside the coil form as the screw is turned. This maneuvering of the material is used as an adjustment to set the inductance of the coil to a desired value. Figure 5-8A shows an example of an inductor in a can. A screw adjustment may also be in this can to enable you to adjust the inductance to some required value.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

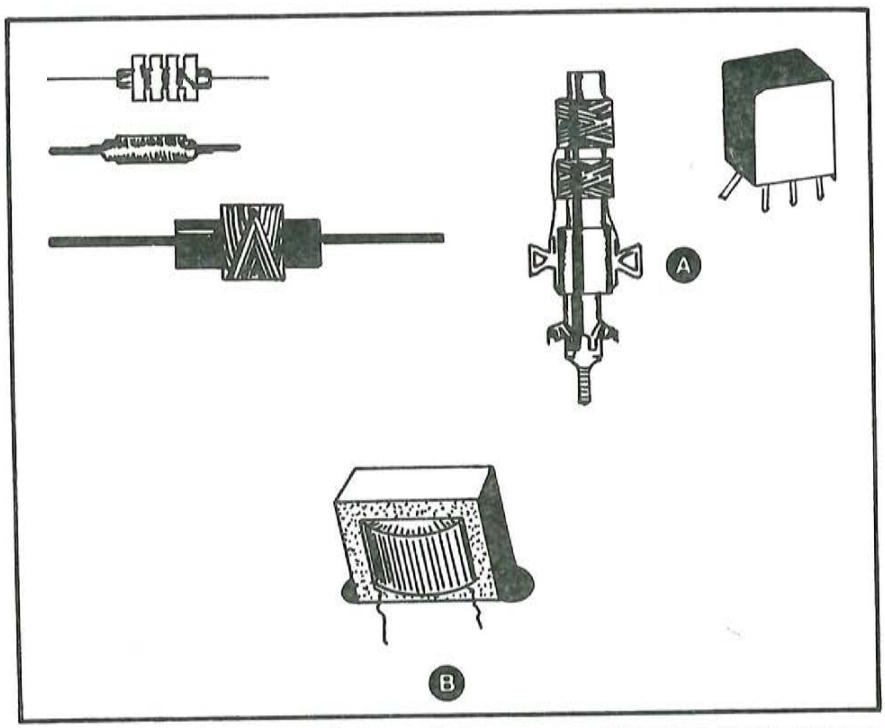


Fig. 5-8. Physical inductors. A. For radio-frequency applications. B. Choke used in power supplies.

The inductor shown in Fig. 5-8B is large and looks like a transformer. This type has a large inductance that is useful as a filter in a power-supply circuit. Although it is used in a supply designed to provide large quantities of power, it is seldom if ever found in the smaller power supplies found in radios, TV sets, and so on.

No color codes are used to indicate the inductance of any of the components shown in the drawing. The manufacturer usually supplies a separate piece of paper to indicate the inductance.

Examples

The reactance of an inductor can be determined using Equation 5-1. For example, assume you have a 1 mH (10^{-3}H) inductor. Its reactance at 100 Hz is $\omega L = 2\pi(100)(10^{-3}) = 0.628$ ohms. Should you want to use this inductor at 1 MHz, its reactance increases to $2\pi(10^6)(10^{-3}) = 6280$ ohms.

Another way of looking at this is by assuming you need an inductor to operate at 10 MHz, and it should have a reactance of 1000 ohms at that frequency. Using Equation 5-1, you find that you must get a component with an inductance of $L = X_L/\omega = 1000/6.28(10^6) = 10^{-3}/6.28 = 0.16 \times 10^{-3}$ μH to satisfy your needs.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Should the individual inductors you have in your possession be the wrong values for use in the particular circuit you are working on, you can wire several inductors in series or in parallel to add to the inductance you need. The final inductance achieved using these methods is determined using procedures similar to those used when combining groups of resistors. The inductance of several inductors wired in series is the sum of the inductances of the individual components. If two inductors—one with an inductance of 10 mH and the second with an inductance of 20 mH—are wired in series, the inductance of the combination is 10 mH + 20 mH = 30 mH. Should these two inductors be wired in parallel, the resulting inductance of this circuit is (10 mH)(20 mH)/(10 mH + 20 mH) = 6.67 mH. Equations 3-2 and 3-3 are used here with the inductance being substituted for resistance.

Circuits in Figs. 5-1 and 5-2 were referred to as the equivalent circuits of actual real inductors. Methods used to analyze these circuits can be applied to circuits consisting of an inductor with a separate resistor. For example, assume you have an ideal component (0-ohm resistance) with a 10 mH inductance wired in series with a 10,000 ohm resistor. This combination is connected across a 120-volt source supplying 1 MHz. You want to determine the quantity of current flowing in this circuit, the voltage across each component, and the angle by which the current in these components lags the applied voltage. Initially, this circuit may seem as if it is only being used as an example of how the theory works. In actuality, this circuit is a very practical and commonly applied arrangement. Methods used to solve this problem can be applied to circuits used in practical applications.

At any rate, the solution is straightforward. The reactance of the 10 mH inductor at 1 MHz is $6.28(10^6)(10 \times 10^{-3}) = 6.28 \times 10^4$ ohms = 62,800 ohms. Using Equation 5-6, the impedance, Z, of the overall circuit is $\sqrt{62{,}800^2 + 10{,}000^2}$ = 63,600 ohms. Applying Ohm's law, Equation 2-1, you will find that the total current in the circuit is $120V/63{,}600\Omega = 1.89 \times 10^{-3}$ A. Using Equation 2-3, the voltage across the resistor is $(1.89 \times 10^{-3}\ A)(10^4\Omega)$ = 18.9 volts, and the voltage across the inductor is $(1.89 \times 10^{-3}\ A)(62.8 \times 10^3\Omega)$ = 118.69 volts. Note that if you add the voltages across L and R_S, the total voltage is 118.69 + 18.9 = 137.59 volts. This number is greater than the supply voltage. It seems impossible that the sum of the voltages across the two series-connected components in the circuit, should be greater than the voltage applied to the series circuit. In fact, it is impossible. The

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

voltages cannot be added as shown, because the voltage across the inductor is out of phase with the voltage across the resistor. The phasor diagram illustrating this is in Fig. 5-9.

Using this drawing, you can determine by what angle, θ, v_R lags the supply voltage, e_{In}. Because $\tan \theta = v_L/v_R = 118.69/18.9 = 6.28$, $\theta = 81°$. Because the current and v_R are in the same direction or phase, the current lags the supply voltage, e, by this same 81° angle. Using Equation 4-4, you can see that with this phase lag the total voltage adds to the 120-volt supply or is very close to that value. The fact that the result of this computation may not be exactly 120 volts is due to some arithmetic tolerances in the calculations.

As a final example, assume that a 200,000 ohms (200×10^3 ohms) resistor is wired across (in parallel with) a perfect 15-mH inductor, and that they are both supplied 120 volts at 1 MHz. Now, you want to know the current in each component and the phase relationship of these currents to the supply voltage. The diagrams in Fig. 5-6 apply.

Using Equation 5-1, the reactance of the 15 mH inductor at 1 MHz is $6.28(10^6)(15 \times 10^{-3}) = 94.2 \times 10^3$ ohms. The current flowing through the inductor is $120/94.2 \times 10^3 = 1.27 \times 10^{-3}$ A. This current lags the supply voltage by 90°. The current in the resistor is $120/200 \times 10^3 = 0.6 \times 10^{-3}$ A. This current is in phase with the supply voltage. If the two currents were in phase, the total current required from the supply would be the direct sum of the currents in the two components. But they are out of phase. As

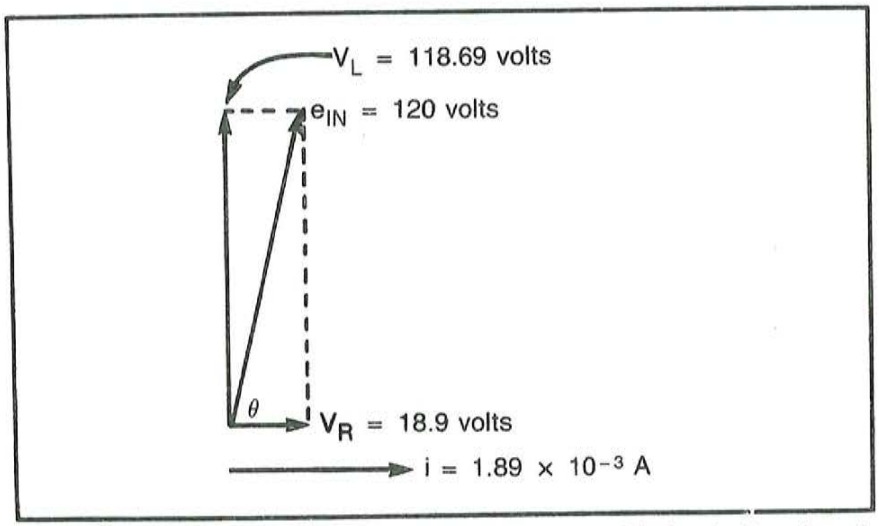


Fig. 5-9. Phasor diagram for problem involving series RL circuit. Supply voltage e = 120 V at 1 MHz, L = 10 mH, R = 10 kΩ.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

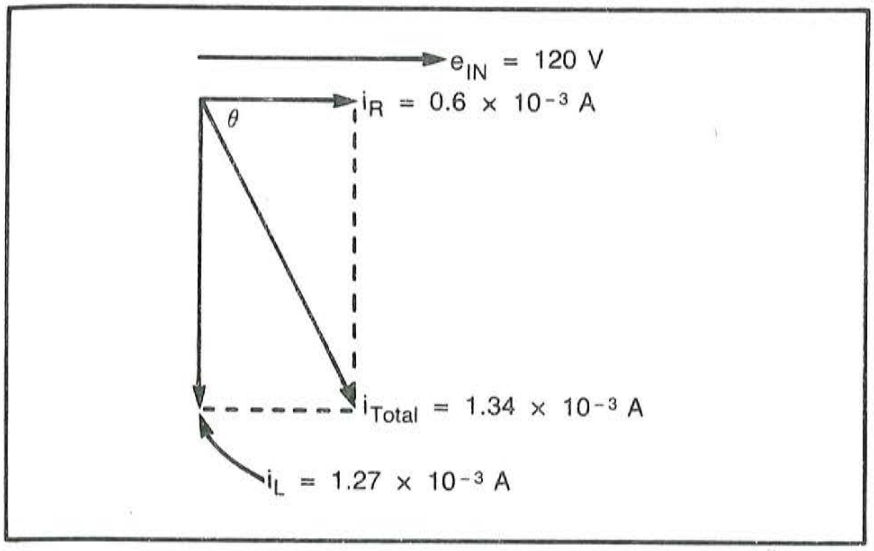


Fig. 5-10. Phasor diagram for problem involving parallel RL circuit. Supply voltage e = 120 V at 1 MHz, L = 15 mH, R = 200 kΩ.

a result, you must add the two currents vectorally as shown in Fig. 5-10. Using Equation 4-4, the total current is equal to

$$\sqrt{(1.2 \times 10^{-3})^2 + (0.6 \times 10^{-3})^2 - 1.34 \times 10^{-3}\ \text{A}}.$$

Because $\tan \theta = i_L/i_R = 1.27 \times 10^{-3}/0.6 \times 10^{-3} = 2.12$, $\theta = 64.7°$. Also, i_{Total} lags i_R by this angle. Since i_R is in phase with e_{In}, the total current supplied to the circuit lags the supply voltage by this same 64.7°. But it is important to remember that the current in the inductor itself lags the supply voltage by 90°, while the current in the resistor is in phase with the supply voltage and leads the current in the inductor by this same 90°.

CAPACITORS

The capacitor is a very frequently used circuit component. Next to the resistor, it is the most common electronic component. They are very common in ac circuits, especially in tuning and filtering applications. Capacitors are even more useful than inductors, and are simpler to understand.

Structure

A capacitor consists of two metal plates separated by some type of insulator. That insulator can be paper, mica, ceramic, and so on. It may even be air. This arrangement is shown in Fig. 5-11.

With no voltage applied to the two metal plates of a capacitor,

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

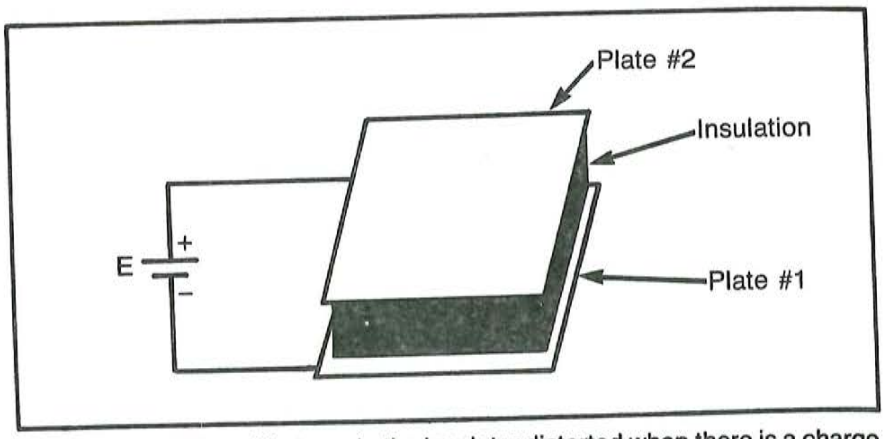


Fig. 5-11. Capacitor. All atoms in the insulator distorted when there is a charge on the plates.

the atoms in the insulating material retain their usual shapes. The electrons rotate in their usual orbits around the positive nucleus of the atom. When a dc voltage is applied to the plates, the orbits of the electrons in the atoms of the insulating material are warped. This is due to the field set up in this material by the presence of the positive battery voltage on one metal plate and the negative voltage on the second metal plate. The positive nuclei in the atoms are attracted to the negative metal plate, while the negative electrons in the orbits are attracted to the positive plate. This distorts the shape of the atom. This distortion remains even after the battery has been removed from the metal plates, because the individual charges on the plates have no where to go. The charge remains because the electrons cannot pass through the insulating material from one plate to the other. The capacitor is discharged only by connecting one metal plate to the other with a conductor (piece of wire) or by leakage through an imperfect insulator. After the capacitor has been discharged, the atoms in the insulator return to their normal shapes. But until this happens, the voltage across the plates remains the same as the voltage, e, originally supplied by the dc source.

Because of the insulator, capacitors do not conduct dc current. In fact, that is the reason the component retains the charge. However, the capacitor does conduct ac. The capacitor conducts current more readily at high frequencies than it does at low frequencies just the opposite of the inductor. The reactance of a capacitor, X_C, at any frequency, is

$$X_C = \frac{1}{\omega C} \qquad \textbf{Eq. 5-7}$$

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

where C is the capacitance in farads.

The basic unit of capacitance is the farad, abbreviated F. The farad is a very big number. It is usually seen as 1/1,000,000 = 10^{-6} of a farad or in microfarads (μF). Even this is a large number, so many capacitors are made in 1/1,000,000 of that size or in micro-microfarads ($\mu\mu$F) = 10^{-12} farads. But this is an old way of denoting 10^{-12} farads. It has been assigned the relatively new name, picofarads (pF). Therefore 1 pF = 1 $\mu\mu$F = 10^{-12} F. A more frequently used dimension between these two numbers is the nanofarad (nF), and is equal to 10^{-9} F.

Quality Factor

The insulators between plates of a capacitor are not perfect. There is always some minute amount of leakage. The equivalent circuit of a real capacitor with some leakage is a resistance in parallel with the capacitance. If this resistance, R_P, is present, as it normally is, the Q of the capacitor is

$$Q = \omega C R_P \qquad \textbf{Eq. 5-8}$$

This resistance is almost always very large so that the Q of a capacitor is very large. An equivalent circuit can also be formed where the resistance, R_S, is in series with the capacitance rather than in parallel with it. In this case, the resistance is extremely small. Here

$$Q = \frac{1}{\omega C R_S} \qquad \textbf{Eq. 5-9}$$

While the capacity, C, is the same in both equations and both equivalent circuits. R_P is approximately equal to Q^2R_S.

Because Q is very large, it is seldom used to identify the quality of a capacitor. Instead, the dissipation factor shown as Equation 5-5 is used. Because it is equal to 1/Q, it is desirable that these numbers be as small as possible.

Dc Characteristics

Equations 5-7 through 5-9 define the ac characteristics and ac behavior of a capacitor. But when a dc voltage is applied to the component, it takes time for the capacitor to charge. Because there is no voltage across the capacitor at the instant the dc is applied, the capacitor behaves as if it had a resistance of zero ohms. Large

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

quantities of current flow to charge the capacitor. As it continues charging, its apparent resistance increases while the current flow is reduced. Also the voltage across the component keeps increasing with time. After a period of time, usually several milliseconds, the capacitor is fully charged. Total applied voltage is now across the capacitor. If it is an ideal component, no current flows. It behaves as if it were presenting an infinite resistance to the dc supply.

The action of a capacitor in a dc circuit can be summarized by saying that at the outset, the voltage across the capacitor is zero and the maximum current the dc source can supply, is conducted to the component. After a short period of time has elapsed, the voltage across the capacitor is equal to that of the dc source and the current flow drops to zero.

Electrical Properties

Many different materials are used as insulators in capacitors. These materials are referred to as *dielectrics*. Each dielectric has a different characteristic. Capacitors with some dielectrics perform well at high frequencies, while others are good only at low frequencies. When a voltage greater than that specified by the manufacturer of a particular capacitor is applied to the metal plates, the dielectric may break down or short. When some types of dielectrics are used, the capacity of the component will change radically with temperature.

Electrolytic capacitors perform well up to about 1000 Hz but are usable in some applications up to 10 MHz. This type of capacitor uses aluminum oxide as the dielectric material. They are made with capacities up to 0.5 farads. The maximum voltage that may be applied to this type of capacitor, or its maximum rated voltage, is limited to 500. There are, of course, some electrolytic capacitors that cannot accept anything near this voltage. The voltage limit rating of a specific component is supplied by its manufacturer. Leakage of this type of component is high. Despite this, electrolytic capacitors are very useful as filters in power supplies and as coupling devices in transistor circuits.

Capacitors using tantalum as the dielectric are much smaller physically than the electrolytics. Their capacities are limited to about 1200 μF with breakdown peaks of 300 volts. They have the same high frequency limits as do the electrolytic devices.

Capacitors using paper or mylar as the dielectric material are quite useful up to 10 MHz. The maximum breakdown voltage is

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

about 600 for both of these devices. They are made with capacities up to 10 μF, but capacitors with capacities above 0.5 μF are the exception rather than the rule. A variation on both types, metalized paper and metalized mylar, usually have a somewhat higher dissipation factor than do the ordinary paper and mylar capacitors, but are usually satisfactory. The later capacitors are frequently desirable because of their small size when compared to the size of regular paper and mylar components.

High frequency capacitors usually make use of ceramic, mica, or glass as the dielectric. They are usually limited to breakdown voltages below 1000 although there are certain ceramic capacitors that will take up to 40,000 volts. Although mica and glass capacitors are quite stable, the capacity of ceramic devices may vary considerably with temperature. Specifications are usually supplied to show the percentage of variation for the different capacitors.

There are many more different shapes and sizes of capacitors. Some of the more common ones are shown in Fig. 5-12.

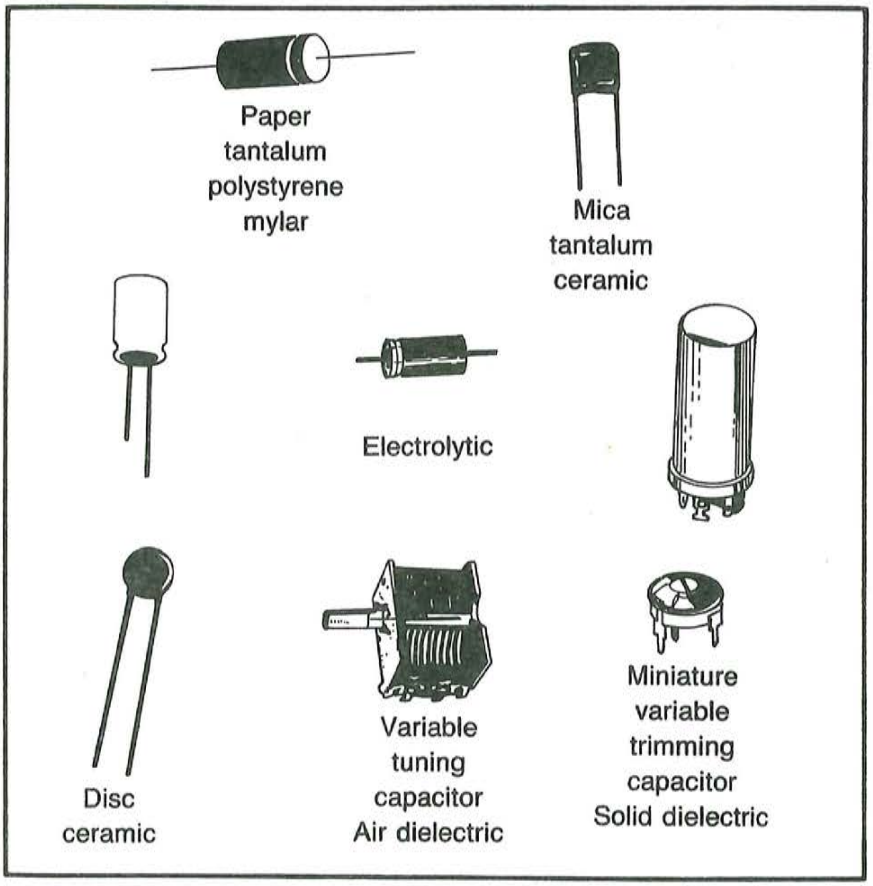


Fig. 5-12. Typical capacitors.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

The size of the capacitor is usually stamped on the component. If an electrolytic is rated at 500 μF at 450 V, these numbers can usually be read directly from the inscription on the case of the component. In some instances, especially on disc ceramic and other small capacitors, its magnitude is noted as three digits. The first two digits are the significant figures, while the last one is a multiplier. So if 273 is imprinted, the capacity is 27,000 pF, which is equal to 0.027 μF.

When color dots are shown on the component to denote the capacity, the colors refer to the same numbers as for resistors. There is usually some arrow showing in which direction to read to colors. For example, a mica capacitor using six dots for the color code is shown in Fig. 5-13. So if the sequence of the top row of

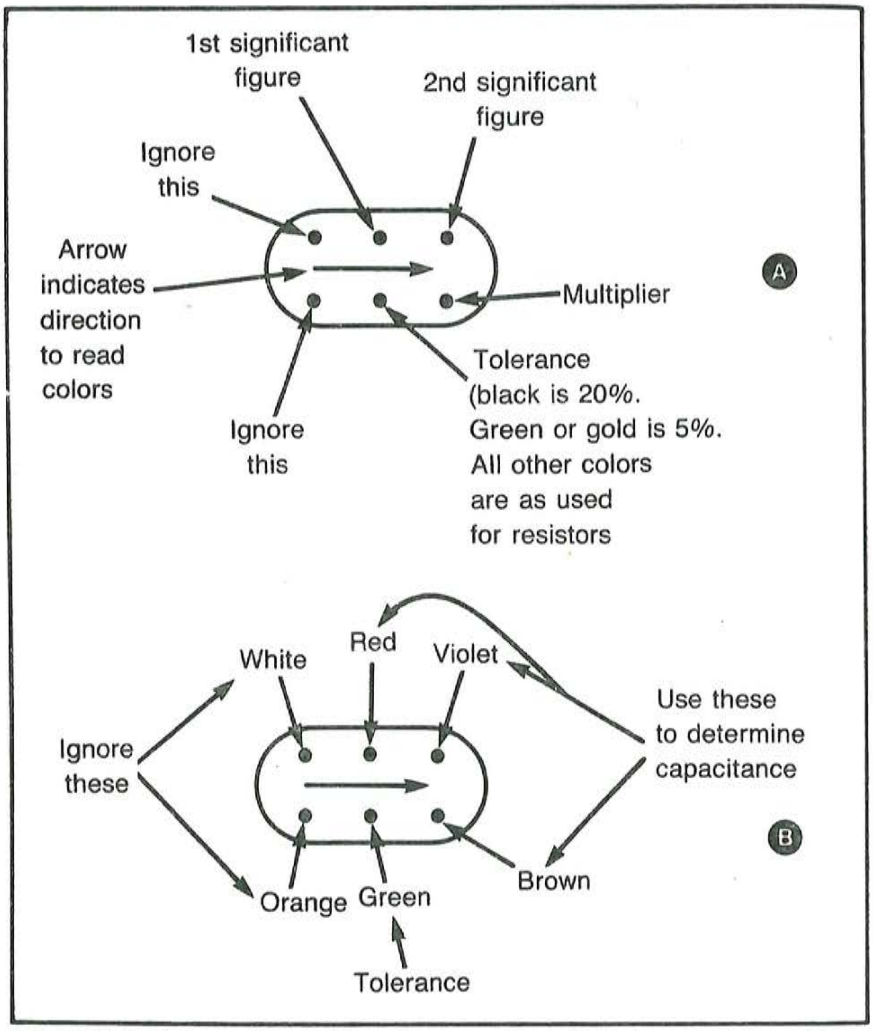


Fig. 5-13. A. Color code used for mica capacitors. B. Colors used in problem.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

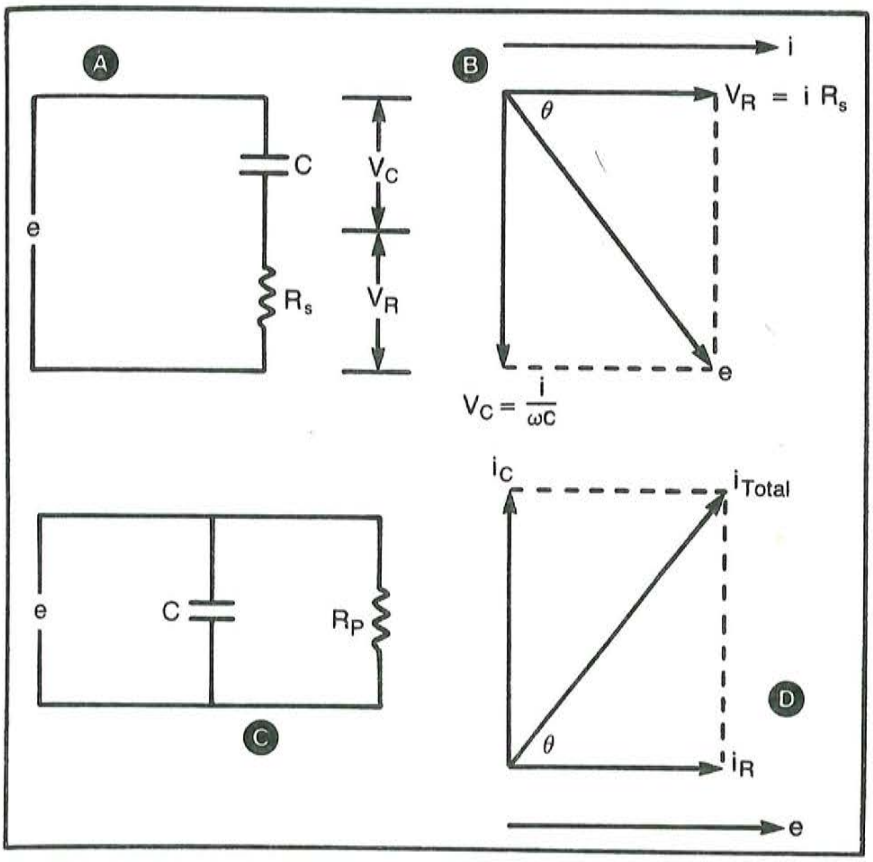


Fig. 5-14. Circuits and their phasor diagram. A. Series circuit. B. Phasor diagram for circuit in A. C. Parallel circuit. D. Phasor diagram for circuit in C.

colors, from the left to the right, is white, red, violet, and the colors in the bottom row are orange, green, brown, then the capacitance of the component is determined from the red, violet and brown colors, or 270 pF, and the tolerance is determined from the green, or 5%. The white and orange colors are ignored. This is shown in Fig. 5-13B.

Phasor Diagrams

A perfect capacitor has a characteristic that is just the opposite of a pure inductor. The primary characteristic that should be noted is that the current in a capacitor leads the applied voltage by 90°, while the current in an inductor lags the voltage by 90°. This is because ac current starts to flow through a capacitor at the instant that voltage is applied to its plates, but it takes time for the voltage to build up across the device.

A diagram of a voltage applied to a circuit consisting of a ca-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

pacitor and resistor in a series circuit is shown in Fig. 5-14A. Figure 5-14B shows the phasor diagram. A similar representation of a voltage applied to a parallel resistor-capacitor combination, along with its phasor diagram, is in Figs. 5-14C and D. These are not unlike the diagrams in Figs. 5-4 and 5-6 for the inductors. Note that R_S and R_P may be resistors wired into the circuit with a capacitor, or they may represent the leakage resistance of the component.

Examples

Let us assume you have a mica capacitor such as the one shown in Fig. 5-13. The sequence of the top band of colors is white, brown, and red, while the sequence of its bottom band is orange, brown, and red. What is the reactance of this capacitor at 15 MHz?

The capacity is 1200 pF = 1200×10^{-12} F. The impedance, found by using Equation 5-7, is $1/6.28(15 \times 10^6)(1200 \times 10^{-12}) = 0.113$ ohms.

Now assume that a 0.2 ohm resistor, R_S is wired in series with the capacitor to form the circuit shown in Fig. 5-14A. If e = 0.02 volt, what current flows through the components and what is the phase angle?

The total impedance that this circuit presents to the voltage source is determined by using an Equation similar to Equation 5-6:

$$Z^2 = X_C^2 + R_S^2 \text{ or } Z = \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2} \qquad \textbf{Eq. 5-10}$$

Using this relationship, $Z = \sqrt{(0.2)^2 + (0.113)^2} = 0.23$ ohms. If e is 0.02 volts, 0.02 volts/0.23 ohms = 0.087A = 87 mA must flow through the capacitor and resistor. The voltage across the resistor, using Equation 2-3, is $0.087 \times 0.2 = 0.0174$ volts. The voltage across the capacitor is $0.087 \times 0.113 = 0.0098$ volts. Because the current is not in phase with the applied voltage, the sum of the voltages across the capacitor and resistor, 0.0174 + 0.0098 = 0.0272, is greater than the applied 0.02 volt. This is identical to the case of the inductor and resistor in a series circuit where the total of the individual voltages is greater than the applied voltage. But this is just as impossible here as it was in the previous instance. The sum must be equal to the supply voltage. This sum is illogical because the voltages across the components are not added vectorally. When added in this fashion, using Equation 4-4 and shown in Fig. 5-15, e is equal to 0.02 volt. The current in the components

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

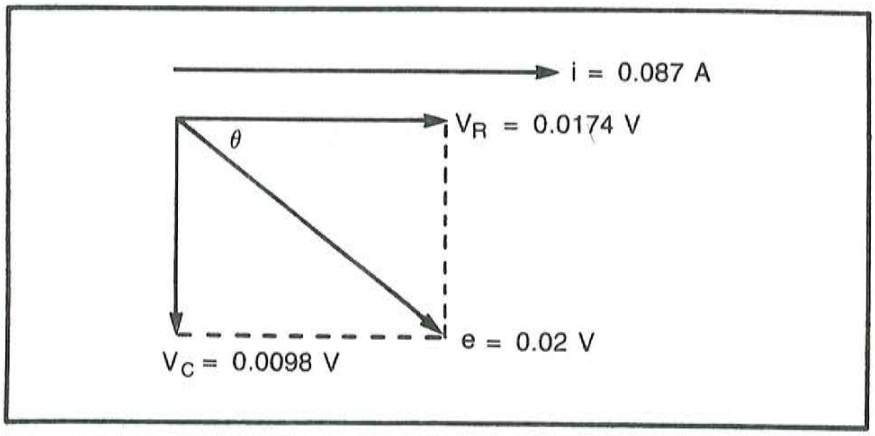


Fig. 5-15. Vector sum of voltages.

as well as v_R, lead the applied voltage by $\theta°$. Because tan θ = 0.0098/0.0174 = 0.5632, and θ = 29.4°.

The circuit has a Q because there is a resistor and a capacitor. Using Equation 5-9, Q is equal to $1/6.28(15 \times 10^6)(1200 \times 10^{-12})(0.2)$ = 0.023 so that the dissipation factor is 1/0.023 = 44.23. This would be very poor if there were only a capacitor in the circuit. But here you have a resistor wired in series with the capacitor so that 44.23 is the dissipation factor of the overall circuit and not solely the capacitor.

Instead of having a resistor connected in series with the capacitor, assume it is wired across the capacitor and assigned the symbol R_P. Assume R_P to equal R_S of the series circuit, or 0.2 ohm. If the same 0.02 volt, 15 MHz supply is used as in the previous example, the current through the resistor is 0.02V/0.2Ω = 0.01A, and the current through the capacitor is 0.02V/0.113Ω = 0.177A. The total current is determined from the vector sum of the individual currents as well as through use of Equation 4-4. This is shown in Fig. 5-16. It is $i_{Total} = \sqrt{0.01^2 + 0.177^2} = 0.1773$ A. This is obviously less than the sum would have been had the phase angle not been taken into account. The phase angle is determined from the relationship tan θ = 0.177/0.01 = 17.7, so that θ = 86.77°.

Series and Parallel Combinations

At times it is convenient or even necessary to wire several capacitors in series or in parallel. If they are wired in parallel, the capacitance of the combination is equal to the sum of the capacitances of all capacitors in the circuit. Should three capacitors be wired in parallel, one with a capacitance of 5 μF, the second 8 μF and the

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

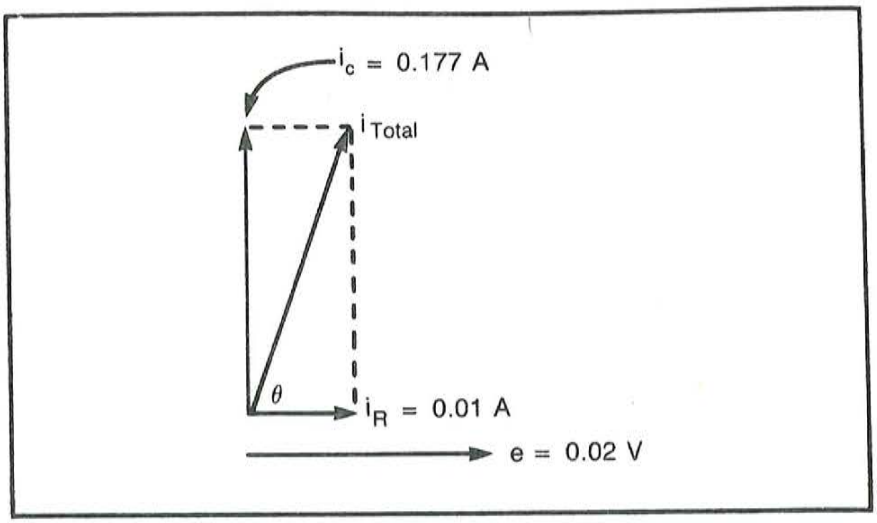


Fig. 5-16. Vector sum of currents.

third 10 μF, the capacitance of the parallel combination is 5 μF + 8 μF + 10 μF = 23 μF.

Should the capacitors be wired in a series circuit, an equation similar to 3-2 applies. Even though this equation was for a parallel resistor combination, it can be used for a series capacitor arrangement. Just substitute the C's or capacitances for the R's or resistances in the equation.

Let us say that the 5 μF, 8 μF, and 10 μF capacitors are in a series rather than a parallel circuit. The capacitance of only the 5 μF and 8 μF series combination is $C_{s1} = (5 \times 8)/(5 + 8) = 3.08$ μF. This is the capacitance of only two of the three components connected in series, but a 10 μF capacitor is also in series with this combination. The capacitance of the entire combination is $C_S = (3.08 \times 10)/(3.08 + 10) = 2.36$ μF. Note that this capacitance is less than that of any one of the capacitors in the series circuit and is certainly less than the capacitance of the parallel combination encompassing all these capacitors.

Power Dissipated

In all cases, the real power dissipated by an ideal capacitor or ideal inductor is zero. This is because of the 90° phase difference between the current through and the voltage across the component. Imaginary power is dissipated by the capacitor or inductor. It is the product of the current in the capacitor (or inductor) with the voltage across the component. The only real power dissipated is by the resistance in the circuit, which is equal to the product of

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

the current flowing through R with the voltage that is across the resistor.

FILTERS

Up to now, it was always assumed that voltages applied to a circuit were either of the dc variety or at least a specific ac frequency. This is frequently the case. Power supplies usually provide voltages only at 60 Hz or else a pure dc similar to what is available from a battery.

But this is not the situation when audio signals or radio frequency (rf) signals are involved. Many different frequencies occur at the same time in any one group or *band*. The audio band consists of frequencies we can hear, covering the range from 20 Hz to 20,000 Hz. All these frequencies are available simultaneously for much of the time. In the radio broadcast band, almost all frequencies between 550 kHz and 1600 kHz are continuously present.

It is frequently desirable to reduce the voltage that is present at a specific frequency in a band or to reduce voltages that are present at frequencies above or below a particular frequency. This is most obvious on the audio band. In order to reduce voltages of the bass or low frequency portion of the audio band, a *bass* control on an amplifier is adjusted to accomplish this goal. In a similar manner, a *treble* control is used to reduce the ear-piercing high-frequency end of the audio band. In the rf band, it is always desirable to select the one frequency that is being broadcast by a specific radio station while eliminating frequencies broadcast by all other radio stations. Circuits that perform these functions are referred to as *filters*. Rf filters will be described in the discussion on *resonance*.

Signals in the band of frequencies are usually fed to amplifiers. These amplifiers produce gain and so amplify these input signals. After being amplified, a higher voltage or power at these signal frequencies is produced at the output of the amplifier than at the input. The amount by which the amplifier increases the input signals, is known as its "gain." Filters are designed to reduce the gain of a particular segment of these frequencies.

Audio filters are usually constructed using a series RC network. If you want to reduce the gain or relative signal levels of the low-frequency end of the band, you would use the circuit in Fig. 5-17A. Here capacitor C does not let the low frequencies pass as easily as the high frequencies. I noted this characteristic above when I discussed the fact that reactance is lower at high frequencies than at low frequencies. R and C form a voltage divider for the signals

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

fed to the input of the network. Because X_C is greater at the low frequencies than it is at the high frequencies, less of the signal present at the input remains to be developed across R at these low frequencies after the signal has passed through C than at high frequencies. This can be deduced by using an equation similar to voltage divider Equation 3-1.

In Fig. 5-16B, the same voltage divider theory applies, only now, because the capacitor is across the output, the output is reduced as the frequency rises. Since X_C is reduced in magnitude with the increase in frequency, only a small portion of the input signal can be developed across the capacitor in the divider at the upper end of the band. Less signal is developed across C as the frequency rises.

The formula that is used to determine the reduction in the signal or gain at various frequencies in both circuits is

$$f_0 = \frac{1}{2\pi RC} \qquad \textbf{Eq. 5-11}$$

The output is reduced to 0.7 of its maximum magnitude or to 70% of maximum at frequency f_0. In Fig. 5-16B, the output drops to 0.45 of its maximum at $2f_0$ or at double f_0. It is reduced to one-quarter of its maximum at $4f_0$, one-eighth of its maximum at $8f_0$, and one-sixteenth of its maximum at $16f_0$, and so on. Thus, each time a specific frequency is doubled, the magnitude of the output signal is reduced by one-half.

Ideal audio amplifiers have identical gain at all frequencies between 20 Hz and 20 kHz. Assume you have an amplifier with a gain of 100. This indicates that when no filter is in the circuit, the input signal to the amplifier will be magnified 100 times by the circuit inside the amplifier before the signal reaches the output. Now the output signal is 100 times greater in magnitude than the input. A filter is used to reduce this gain at specific frequencies.

If you want to reduce the high frequency gain, you can add a network such as shown in Fig. 5-17B to the circuit. Let us design the network by making R equal to 10,000 ohms (or 10^4 ohms) and C equal to 0.0159 μF, which is identical to 1.59×10^{-8} F. Using Equation 5-11, you will find that f_0 is equal to $1/6.28(10^4)(1.59 \times 10^{-}) = 1000$ Hz. At this frequency, the gain has been reduced from 100 to $0.7 \times 100 = 70$. At double this frequency or 2000 Hz, the gain is now $0.45 \times 100 = 45$. At 4000 Hz, gain is $1/4 \times 100 = 25$; at 8000 Hz gain is $1/8 \times 100 = 12.5$; at 16,000 Hz gain is

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

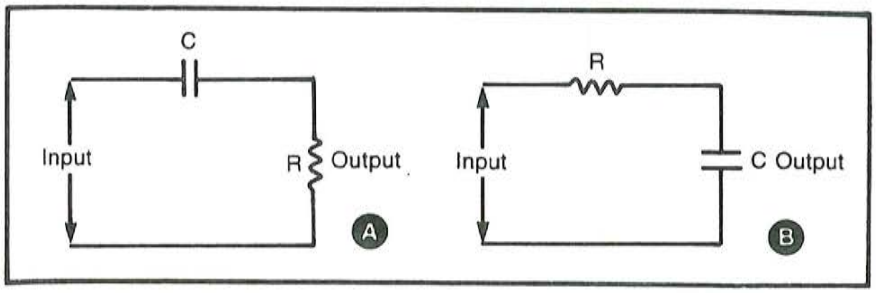


Fig. 5-17. Filters. A. High Pass. B. Low Pass.

1/16 × 100 = 6.25. The next frequency that can be used to calculate the gain, 32,000 Hz, is outside the audio band and is consequently of no interest to us. The gain of frequencies between those indicated above can be estimated or interpolated from the known gains at the specific frequencies shown.

A similar situation exists when you want to reduce low-frequency gain using a filter circuit such as that shown in Fig. 5-17A. Here, gain is reduced to 0.707 of its maximum at f_0 Hz, to 0.45 of its maximum at $f_0/2$ Hz, to 0.25 of its maximum at $f_0/4$ Hz, to 0.125 of its maximum at $f_0/8$ Hz, and to 0.0625 of its maximum at $f_0/16$ Hz, and so on.

RESONANCE

Capacitors and inductors are usually combined in a circuit to do a specific job. They may be in a series circuit as shown in Fig. 5-18A or in a parallel circuit as in Fig. 5-18B. Both circuits have their individual characteristics. These characteristics vary with frequency. In both circuits R is the resistance of the coil. The resis-

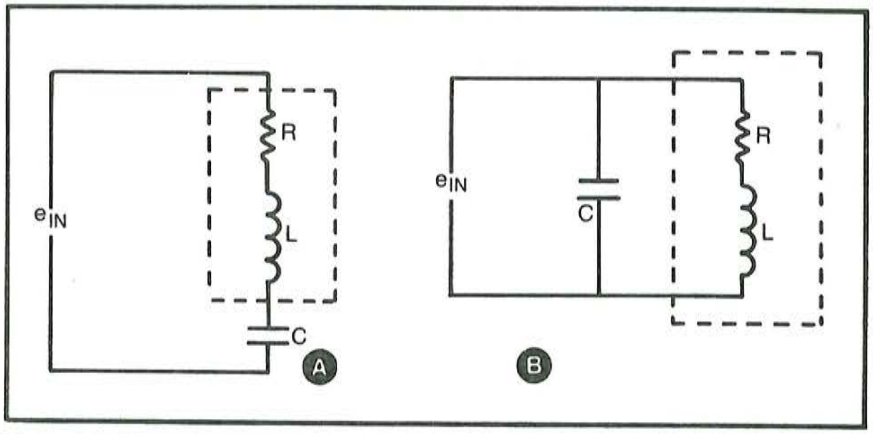


Fig. 5-18. Resonant circuits. A. Series resonant circuit. B. Parallel resonant circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

tance of the capacitor is presumed to be of no significant magnitude in our discussion. One frequency, f_0, common to both circuits, is known as the resonant frequency and is equal to

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad \textbf{Eq. 5-12}$$

Its significance will be described below. For now, let us return to our circuits. Both circuits can be analyzed using phasor diagrams.

Series Resonance

Three different frequency groups will be considered here. In one, the frequencies are so low that the reactance of the inductor is lower than the reactance of the capacitor. This is illustrated in Fig. 5-19A. Here, X_C is larger than X_L. They are drawn in such a manner as to show the proper phase relationships with respect to R. Because R is in phase with the current in the circuit, X_C and the voltage across the capacitor are shown as lagging this current by 90°, while X_L and the voltage across the inductor are shown as leading the current by 90°. These are the usual current-voltage phase relationships associated with inductors and capacitors.

In Fig. 5-19B, the magnitude of X_L is subtracted from X_C. This is quite simple because they are both on the same straight line but with arrows pointing in opposite directions. To determine the total impedance of the circuit, R must be added vectorally to this difference. The resulting line, $X_C - X_L$, added to R_S depicts the magnitude of the total impedance, Z, of the circuit at a relatively low frequency. It also depicts the angle, θ by which the current leads the input voltage, e_{In}.

A similar procedure can be employed if X_L is larger than X_C. This occurs at a relatively high frequency above resonant frequency f_0. The vector sum illustrates this situation in Fig. 5-19D. Here the impedance and supply voltage lead this current by an angle θ.

Finally, if the applied frequency is such as to make X_L equal to X_C, the situation shown in Fig. 5-19E exists. Because $X_C - X_L = 0$, only R is left after one reactance is subtracted from the other. The voltage and current left in the circuit are in phase with each other. The total voltage is across R and is due to the current flowing through the circuit. The resonant frequency must be applied to the circuit to establish this condition. This frequency is determined using Equation 5-12. At this frequency, the impedance

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

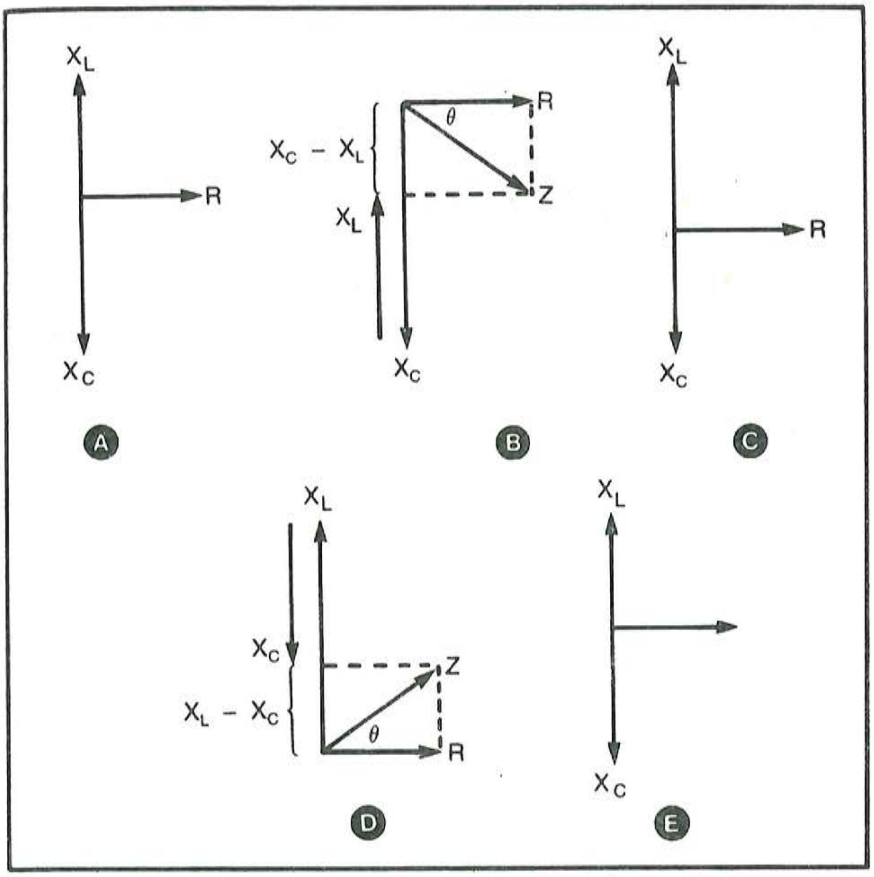


Fig. 5-19. Phasor diagram for series RLC circuit. A and B. Phasor diagrams when the frequency is less than f_O, C and D. Phasor diagram when the frequency is greater than f_O. E. Phasor diagram when the frequency is at resonance, f_O.

presented by this circuit is at a minimum and is equal to R. Because R is usually very small, the impedance presented to e_{In} by this circuit is very small at f_O. Note that f_O, the resonant frequency, is the dividing point between where the diagram in Fig. 5-19A applies and where the drawing in Fig. 5-19C applies. The impedance of the overall circuit is higher at the frequencies on either side of f_O than at f_O, as shown in Figs. 5-19B and D.

For example, assume you have a 1000 pF capacitor and a 500 μH inductor with a resistance of 1 ohm. At what frequency will the impedance of the circuit be 1 ohm? Will the current lead the voltage at 50 kHz or lag it? How about at 500 kHz?

First let's determine the resonant frequency. Substituting the data about the components into Equation 5-12,

$$f_O = 1/6.28(\sqrt{(500 \times 10^{-6})(1000 \times 10^{-12})}).$$

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

This is obvious when you remember that 1 μH = 10^{-6} H and that 1 pF = 10^{-12} F. You must multiply the 500 μH by 10^{-6} to get the inductance in Henrys and the 1000 pF by 10^{-12} to get the capacity in farads before substitution into the equation. By doing all the arithmetic, you will find that f_O, the resonant frequency, is equal to 225,193.24 Hz or about 225 kHz. At this frequency, the resistance of the circuit is equal to the resistance of the inductor. In this example, it is 1 ohm.

At 50 kHz, X_C is greater than X_L. You can calculate this from Equations 5-7 and 5-1, respectively. Here, X_C = 1/6.28(50 × 10^3)(10^{-9}) = 3185 ohms, and X_L = 6.38(50 × 10^3)(500 × 20^{-6}) = 157 ohms. The fact that X_C is greater than X_L can also be derived from the previous discussion which indicated that this situation exists at frequencies below resonance. Because X_C predominates, the current leads the voltage that is applied to the circuit.

The opposite situation exists at 500 kHz. This frequency is above f_O. In this case, X_L must be greater than X_C. Current in the circuit lags the applied voltage. This can be verified by noting that X_L at this frequency is 6.28(500 × 10^3)(500 × 10^{-6}) = 1570 ohms, and X_C = 1/6.28(500 × 10^3)(10^{-9}) = 319 ohms.

Parallel Resonance

The parallel resonant circuit in Fig. 5-18B is only slightly more difficult to analyze than is the series resonant circuit. The proper sequence for doing this is shown in Fig. 5-20.

Because this is a parallel circuit, e_{In} is used as the reference voltage. As I noted earlier, the current in the capacitor leads this voltage by 90°. This is shown in Fig. 5-20A.

Next consider the equivalent circuit of the inductor. It is a series circuit consisting of the inductance, L, and the resistance, R, of the component. As I noted earlier, the current, i_L, in a series circuit is used as the reference in the diagram. The voltage across the resistance, v_R, is in phase with the current. Voltage across the inductance, v_L, leads the current by 90°. The two voltages add vectorally. The sum is equal to the supply voltage, e_{In}. All this manipulation is shown in Fig. 5-20B.

But e_{In} in both figures is identical because the capacitor and the inductance/resistance combination are supplied power from the same source.

Now combine the sketch in B with that in A. Because e_{In} is the same in both diagrams, it is used as the reference. That means that the diagram in A remains as is, but in B it must be rotated θ degrees

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

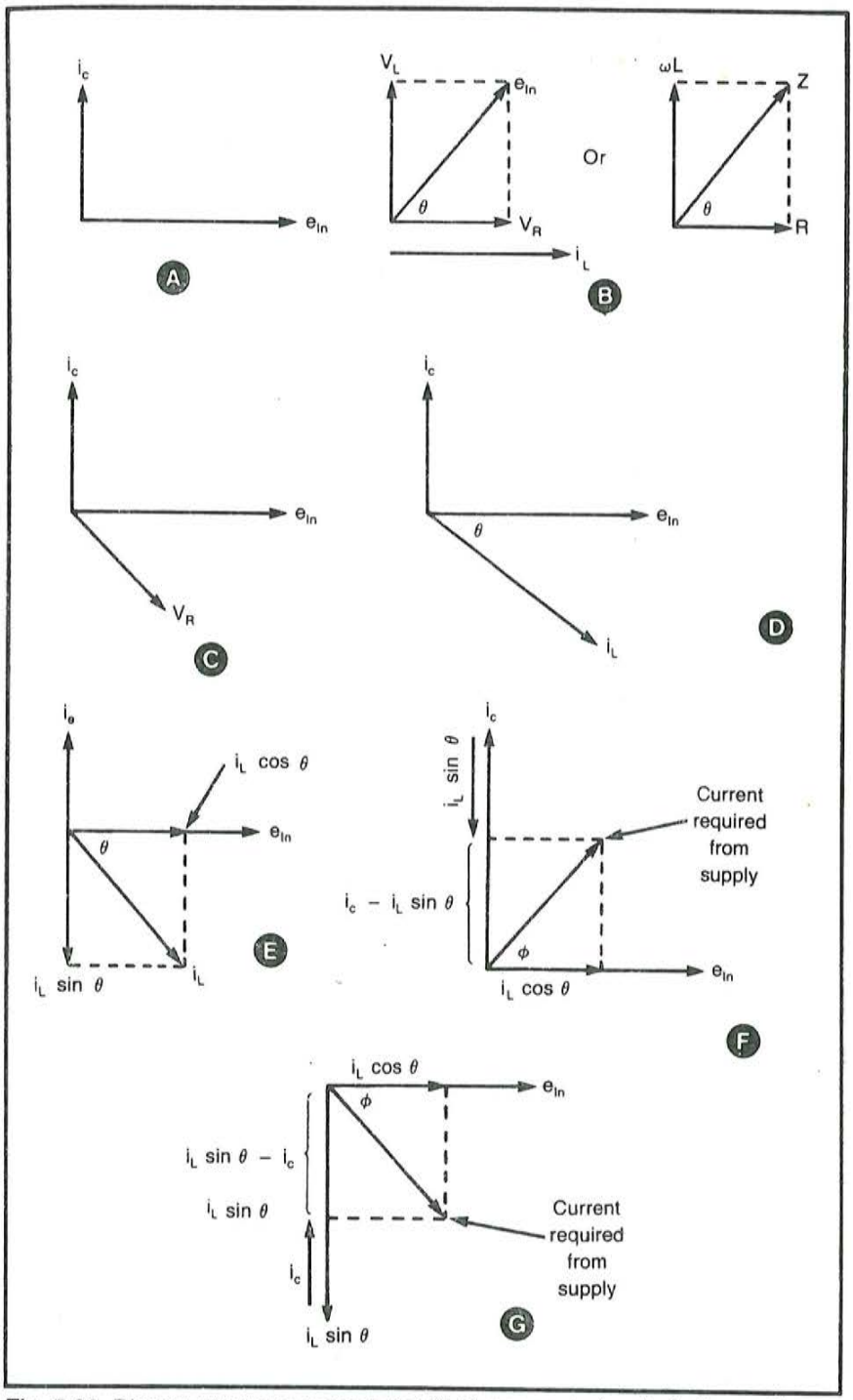


Fig. 5-20. Phasor diagrams for parallel RLC resonant circuit. A. Current in capacitor leads supply voltage by 90°. B. Vector sum of V_L and V_R and V_R is e_{in} because V_L leads i_L and V_R by 90°. C. Combination of diagrams in A and B. D. Replacing V_R with i_L. E. Horizontal and vertical component of i, are illustrated. F. The case where ic is greater than $i_L \sin \theta$. G. The case where ic $i_L \sin \theta$.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

clockwise so that e_{In} in B can be placed over the e_{In} in A. Because v_L and v_R were added to give the total of e_{In}, you no longer need v_L in the figure. By knowing v_R and e_{In}, you can always calculate what v_L is if you should need this information at any time. So I'll combine the drawings but omit v_L.

To make life easier, you will want to utilize the various currents in the circuit to depict the effect of the capacitor and the effect of the inductor on the overall arrangement. Since i_L is already in the diagram, you need only replace v_R and e_{In} with currents in those phases. Because i_L is in phase with v_R, you can replace the v_R line with a line representing i_L. This is shown in Fig. 5-20D.

You can leave e_{In} as is, but it is necessary to split up i_L to show the component of i_L that is in phase with e_{In} and the component of i_L that is 180° out of phase with I_C. This is shown in Fig. 5-20E. Here $i_L \cos \theta$ is the portion of i_L that is in phase with e_{In}, while $i_L \sin\theta$ is the portion of i_L that is 90° out of phase with e_{In} and 180° out of phase with i_C.

I can now state three conditions that can exist in the parallel circuit. These conditions will occur in three different frequency ranges, and are analyzed using the diagrams in Fig. 5-20E.

i_C is greater than $i_L \sin \theta$. This situation is shown in Fig. 5-20F. $i_L \sin \theta$ is subtracted from I_C. The current required from the supply is the vector sum of $(i_C - i_L \sin \theta)$ with $i_L \cos \theta$. This current is more than $i_L \cos \theta$. The total current required from the supply leads the supply voltage by an angle ϕ°. Since i_C is greater than the reactive portion of i_L, X_C is ideally less than X_L. This situation exists at the high-frequency end of the band or at frequencies above f_O.

i_C is less than $i_L \sin \theta$. As shown in Fig. 5-20G, i_C is subtracted from $i_L \sin \theta$. Here too, the supply must provide more current than is in phase with e_{In} or more than $i_L \cos \theta$. But now the total current lags the supply voltage by an angle labelled ϕ. Since the reactive portion of i_L is greater than i_C, you would ideally suspect that X_C is greater than X_L. This situation exists at low frequencies below the resonant frequency, f_O.

i_C is equal to $i_L \sin \theta$. Now the only current left to flow through the circuit is $i_L \cos \theta$. This current is in phase with e_{In}. Current $i_L \cos \theta$ is less than the current in the previous two situations. Because the same voltage is supplied to the circuit in all cases, the network must present a higher impedance in this situation than it did under conditions 1 and 2. This follows from Ohm's law which states that with a fixed voltage applied to a circuit, the impedance

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

of that circuit is inversely proportional to the current flowing through it. With a fixed supply voltage, the impedance presented to the circuit must be higher with a lower current than with a higher current. This occurs at the resonant frequency.

Equation 5-12 is used to determine the resonant frequency of a parallel circuit, just as it was previously used for the series circuit. This is true with one exception. If R^2C/L is greater than one-tenth, then the following equation is a more accurate indication of the resonant frequency.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L}} \qquad \textbf{Eq. 5-13}$$

A parallel resonant circuit presents its highest impedance to the supply at the resonant frequency. This impedance drops at frequencies above and below resonance. This is the opposite of the situation with the series circuit where the impedance was at a minimum at resonance and increased at frequencies on both sides of f_0.

An example will illustrate the methods used to determine the impedance of a parallel LC circuit such as that shown in Fig. 5-18B. Assume e_{In} is 100 volts. Using the components and data from the series resonant circuit example, $L = 500 \times 10^{-6}$ H, and $C = 1000 \times 10^{-12}$ F. But this time let R = 100 ohms. This is a pretty large number for R, but its use here is desirable for illustrating the calculation procedure. Using Equation 5-13,

$$f_0 = \frac{1}{6.28}\sqrt{\frac{1}{(500 \times 10^{-6})(1000 \times 10^{-12})} - \frac{100^2}{500 \times 10^{-6}}}$$

$$= \frac{1}{6.28}\sqrt{2 \times 10^{12} - (2 \times 10^5)^2}$$

$$= 222{,}817 \text{ Hz}$$

At 50 kHz, it was determined that $X_L = 157$ ohms and $X_C = 3185$ ohms, while at 500 kHz, $X_{L\$} = 1570$ ohms and $X_C = 319$ ohms. Now using this data, determine the current in the capacitor and its phase with respect to the voltage applied to the circuit. Also determine the current in the inductor and the phase of this current with respect to e_{In}, the magnitude of the current from the supply and its phase with respect to the applied voltage, the impedance

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

of the circuit at the various frequencies, and the apparent, real, and reactive power in this circuit at the various frequencies. (Refer to Fig. 5-20 for the basic sequence used in calculating these factors.) Let's start working at 50,000 Hz. Information using data specified here is shown in Fig. 5-21.

At 50 kHz, $i_C = e_{In}/X_C = 100/3185 = 0.0314A = 31.4$ mA. It is at an angle of 90° with respect to e_{In}, as shown in Fig. 5-21A.

In the series inductor-resistor circuit, the relationship between the current in the LR combination and the voltages developed across the resistor and inductor are as shown in Fig. 5-21B. Again, e_{In} is the sum of these voltages, and i_L lags e_{In} by θ°. The tangent of θ is equal to v_L/v_R. In Fig. 5-19B, the ratio of X_L to R was equal to the ratio of v_L to v_R. So you can rewrite this tangential relationship as $\tan \theta = X_L/X_R = 157/100 = 1.57$. Then $\theta = 57.5°$.

To determine i_L, you must first use Equation 5-6 to calculate the impedance of the RL circuit, which is $Z_L = \sqrt{R^2 + X_L^2} = \sqrt{100^2 + 157^2} = 186$ ohms. Then $i_L = e_{In}/Z_L = 100/186 = 538$ mA. A diagram showing the magnitude and phase relationships of currents in the inductor and capacitor, is shown in Fig. 5-21C.

Current i_L can be split into its horizontal and vertical components. This is shown in Fig. 5-21D along with I_C. The horizontal component of i_L is i_H. It is equal to 538 cos 57.5° = 289 mA. The vertical component of i_L, i_V, is 538 sin 57.5° = 454 mA. Subtracting I_C from i_V (454 mA − 31.4 mA = 422.6 mA) and taking i_H into account, the total current, i_{In}, provided by the supply is

$$\sqrt{289^2 + 422.6^2} = 512 \text{ mA}$$

This is shown in Fig. 5-21E. (It could just as readily have been summed up in the fashion shown in Fig. 5-21F.) Input current lags the input voltage by ϕ°. This angle is determined from the equation $\tan \phi = 422.6/289$. Here, $\phi = 55.6°$.

Using Ohm's law, you will find that the impedance of the circuit is $e_{In}/i_{In} = 100$ V/0.512A = 195 ohms. The apparent power at this frequency is $e_{In}i_{In} = 100$ V × 0.512 A = 51.2 watts. But this is not the actual power demanded from the supply and dissipated by the circuit. This is because a portion of the apparent power is due to the product of a voltage and a current that are 90° out of phase with each other. Using the diagram in Fig. 5-21G, you can determine that the real power or power dissipated in the resistor is $P \times \cos \phi = 51.2 \cos 55.6° = 29$ watts, while the reactive or imaginary power across the circuit is 51.2 sin 55.6° = 41.3 watts.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

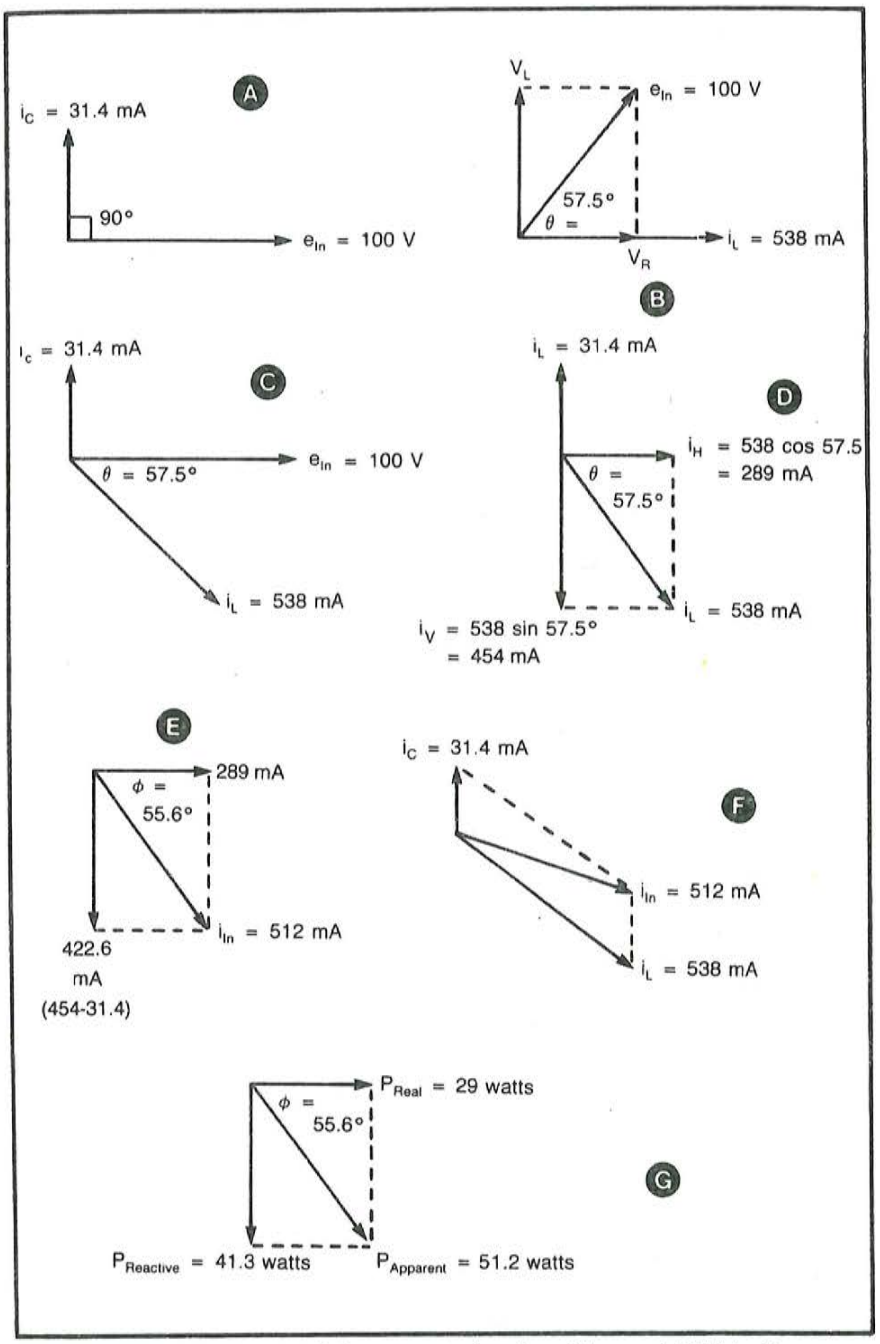


Fig. 5-21. Diagram for parallel-resonant-circuit problems at 50 kHz. Sequence shown in Fig. 5-20 is followed here with the addition of numbers.

Only the real power is actually being dissipated by the circuit because only here are the current and voltage in phase. Imaginary power is not drawn from the supply. The 51.2 watts is just an apparent power.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Repeating these calculations at 500 kHz and using Fig. 5-22, $i_C = e_{IN}/X_C = 100\ V/319\Omega = 313$ mA. Current i_C lags e_{In} by 90°. This is shown in Fig. 5-22A.

Because $X_L = 1570$ at this frequency and R = 100 ohms, the angle by which i_L lags e_{In} can be determined from the equation tan $\theta = X_C/R = 15.7$. Now $\theta = 86.4°$. The impedance of the RL circuit is $\sqrt{R^2 + X_L^2} = \sqrt{100^2 + 1570^2} \approx 1573$ ohms so that $i_L = V/Z_L = 100/1573 = 63.6$ mA. This is shown in Fig. 5-22B. The information in A and B are combined to form Fig. 5-22C.

All vertical and horizontal current portions of the diagram in Fig. 5-22C are shown in D. The vertical and horizontal sections of the currents are combined and summed vectorally, as shown in E. Here, ϕ is determined from the ratio 249.5/4, for this ratio is equal to tan ϕ. ϕ is 89°. The current at this frequency leads the supply voltage by 89°.

Finally, you can see the power dissipated at 500 kHz in Fig. 5-22F. Here, the apparent power, $e_{In}i_{In} = 24.95$ watts. This is very close to the reactive power because this is equal to the apparent power multiplied by sin 89°. The real power is very small—only 0.44 watts.

At resonance of 222,817 Hz, you will use the sequence of diagrams in Fig. 5-23. At this frequency, $X_L = 700$ ohms, while $X_C = 714.29$ ohms. Unlike the series circuit case, X_L is not equal to X_C. In some instances, their values are extremely close, but they are never absolutely equal. They would be identical if R were equal to zero ohms, and Equation 5-12 could have been used to determine the resonance frequency of the parallel circuit just as it was used for the series circuit. In fact, when R is very small, Equation 5-12 gives a very good approximation to the resonant frequency of a parallel circuit.

Note that Fig. 5-22A through 5-22D follow the same sequence as was shown originally in Figs. 5-21 and 5-22. But here, i_V and i_C are equal so all current that must be supplied to the circuit at the resonant frequency is i_H. This is the current that is in phase with the input voltage. There is no reactive power supplied here. The apparent and real powers are equal—P = 100 V × 0.01995 A = 1.995 watts.

The impedance provided by this circuit at resonance can be determined by applying Ohm's law. It is the input voltage divided by the total current, i_{In}. At resonance, it is 100 V/19.95 mA = 5012.5 ohms. At 50 kHz is 100 V/512 mA = 198.3 ohms, and at 500 kHz it is 100 V/249.5 mA = 400.8 ohms. Note how much higher

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

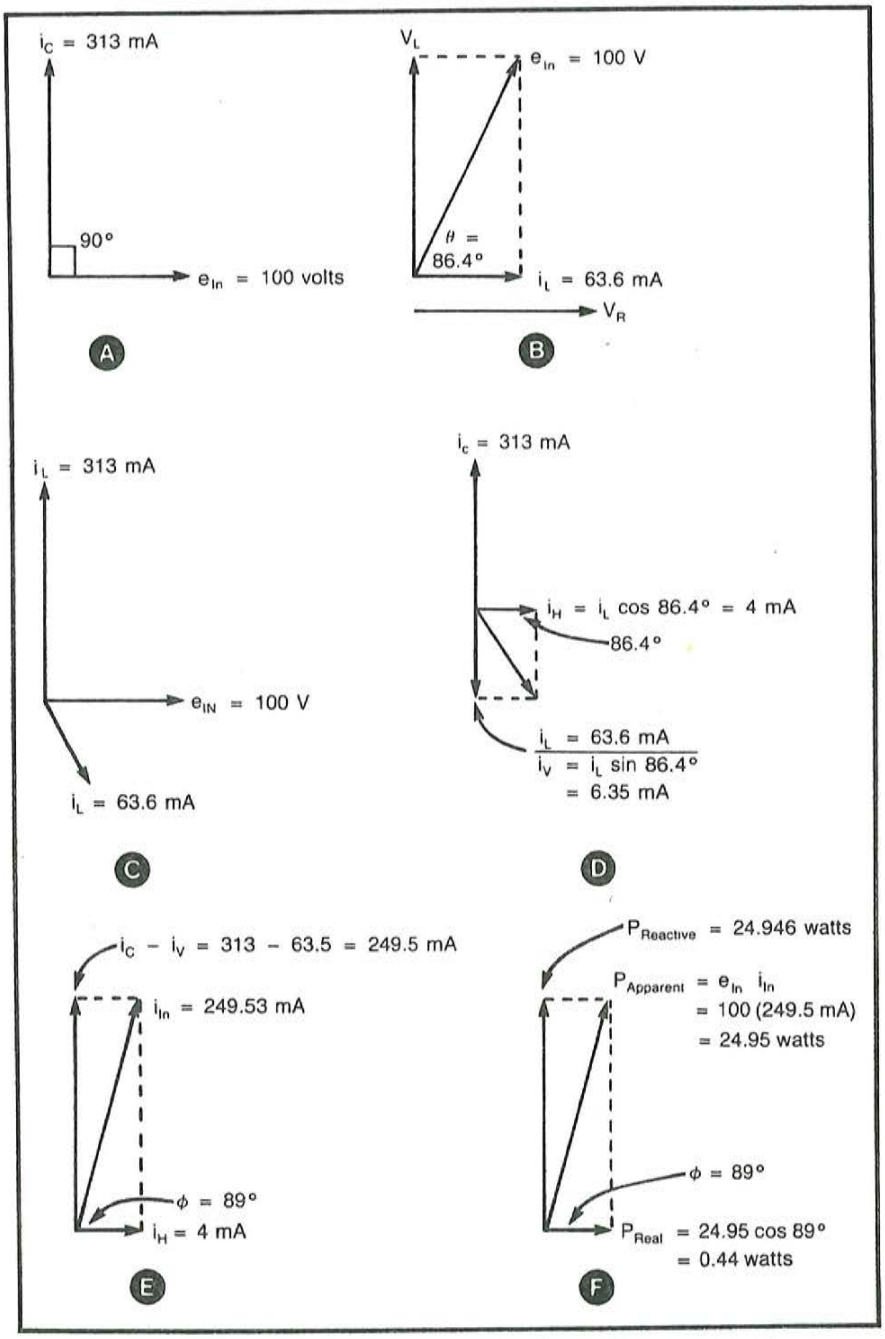


Fig. 5-22. Diagrams for parallel-resonant-circuit problem at 500 kHz.

the impedance is at resonance than at the other frequencies. The important thing to remember here is that for parallel resonant circuits, the impedance presented by the circuit is at a maximum at the resonant frequency while for series resonant circuits the impedance is at a minimum at that frequency.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Q of Resonant Circuits

Q is determined by the losses in a circuit. In resonant circuits, the only loss of significance is the resistance, R, of the coil. Therefore, the Q of the coil is effectively the Q of the resonant circuit.

In the series resonant circuit, R was specified in the example as being equal to 1 ohm. Here, as in the parallel circuit, the coil could have had any resistance. At resonance, the reactance of the inductor is $X_L = 6.28(225{,}193 \text{ Hz})(500 \times 10^{-6} \text{ H}) = 707.5$ ohms. Using Equation 5-2, $Q = X_L/R = 707.5/1 = 707.5$.

At resonance, the voltages across both the series-connected inductor and capacitor are higher than the voltage provided by the supply. In both cases, the magnitude of the voltage across each of the components, is equal to the supply voltage multiplied by Q. When Q is very high, the voltage across each component is also very high.

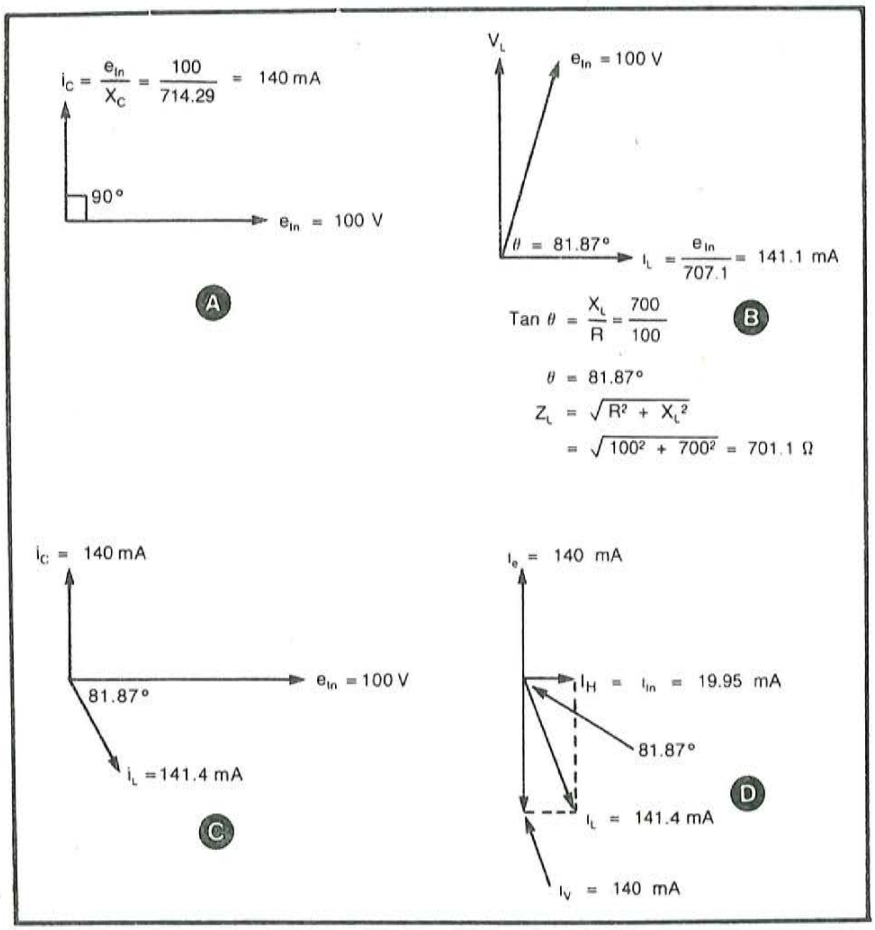


Fig. 5-23. Diagrams for parallel-resonant-circuit problems at the resonant frequency, f_o.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

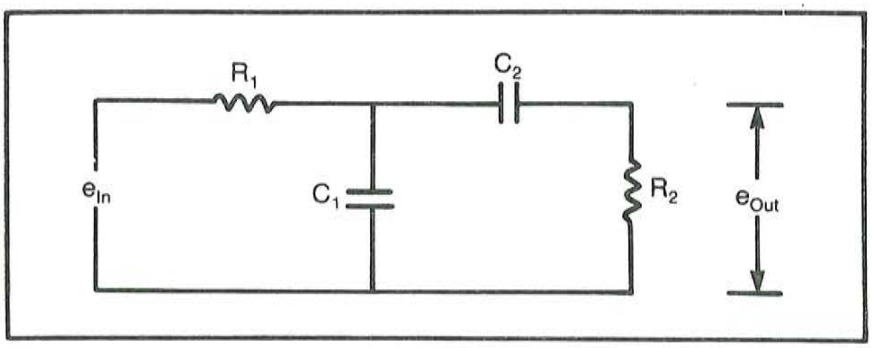


Fig. 5-24. Bandpass RC filter.

In the parallel resonant circuit, Q is determined in the same manner as in the series circuit. In our example, R was chosen to equal 100 ohms and X_L at the resonant frequency of 222,817 Hz was 700 ohms. Q in this case is 700/100 = 7. The resistance presented to the supply by this circuit at the resonant frequency is approximately equal to Q^2R. In this example, it would be $7^2 \times 100 = 4900$ ohms. This is quite close to the resistance of 5012.5 calculated above. This difference is small enough so as not to be of any practical significance.

At resonance, the currents in both the inductor and capacitor in the parallel arrangement are close to being equal to Q times the input current, i_{In}, demanded by the entire circuit. In our example, the input current is 19.95 mA. Multiply this by 7, the Q of the circuit. The product, 140 mA, is the current flowing through each component. It is a close approximation to data found in our previous calculations.

Filters

RC filters are used to attenuate either the upper end or the lower end of a band of frequencies. Two filters can be combined into one circuit to let only one group of frequencies in the band pass. A circuit of this type is shown in Fig. 5-24. Here the R_1-C_1 network rejects the upper of high frequency end of the band, while the R_2-C_2 network rejects the lower frequency end of the band. Only frequencies between the two rejected groups can pass with a minimum of attenuation.

RC networks are often used in low-frequency applications to perform this function and are known as *bandpass filters*. The actual passband is usually quite wide when these circuits are used and the *rolloff*, or the amount of frequency attenuation on either side of these frequencies, is low. Even the rejected frequencies pass

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

through with but a barely acceptable amount of attenuation in most applications.

Resonant LC circuits do this job more efficiently. They will pass the center frequencies with a minimum of loss while rejecting, to a considerable degree, frequencies on either side of the passed band. The amount of frequencies passed in any band depends upon the Q of the circuit.

Resonant circuits can also serve as *band-rejection* filters. All frequencies are passed except those in the rejected band, so this filter behaves just the opposite of a *bandpass* filter. Basic diagrams of circuits for both types of filters using series and parallel resonant circuits, are shown in Fig. 5-25.

The resonant circuit in Fig. 5-25A has a low impedance at or near the resonant frequency and has a high impedance at all other frequencies. Because of its low impedance, the circuit lets voltages at frequencies in the vicinity of F_0 pass rather freely from the input to the output. At the other frequencies, the high impedance of the circuit impedes the flow of signal. If the Q of the circuit is high, this circuit behaves as an ideal bandpass filter. It will perform its function only if a resistor or load is connected across the e_{Out} terminals.

The LC circuit in Fig. 5-25C shunts frequencies at and around f_0 to ground. This is because of the circuit's low impedance when presented with frequencies in this group. Because the impedance of the circuit is high at frequencies outside of this narrow band, it has no or little effect on signals at the remaining frequencies. This arrangement consequently behaves as an ideal band-rejection filter. Resistor R is in the circuit to isolate e_{Out} from e_{In}.

The parallel-resonant circuits in Figs. 5-25B and D are also ideal as filters. This is due to the high impedance presented by the LC circuit at and around the resonant frequency and the low impedance presented by the circuit at frequencies above and below f_0. In Fig. 5-25B, the resonant circuit shunts signals at all frequencies except those near and at f_0 while presenting a high impedance to frequencies at and near f_0. Because it lets only a narrow band of frequencies pass from e_{In} to e_{Out}, this circuit is an excellent bandpass filter. Resistor R serves the same function here as it did in the circuit in C of the figure.

The parallel-resonant circuit shown in Fig. 5-25D, does not let signals pass from e_{In} to e_{Out} at and around f_0 because it presents a high impedance to signals in this group of frequencies. Signals at all other frequencies pass rather freely. Consequently, the reso-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

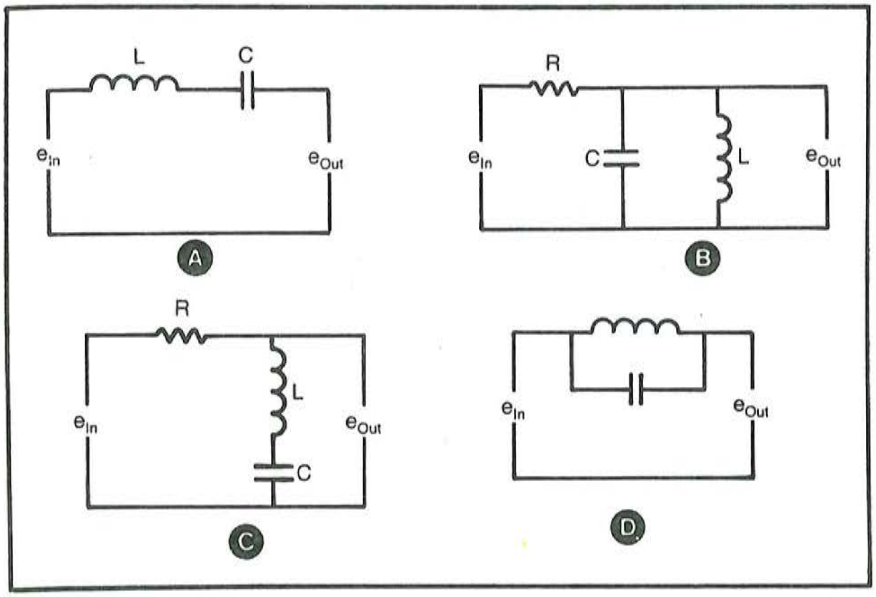


Fig. 5-25. Circuits in A and B are bandpass filters, while circuits in C and D are band-elimination or band-rejection filters.

nant network in this circuit arrangement behaves as a band-rejection filter. As in Fig. 5-25A, a load must be wired across the e_{Out} terminals if the circuit is to function properly.

A frequency-response curve due to the action of a bandpass filter in a circuit is shown in Fig. 5-26. The center frequency, f_O, is passed most readily by the resonant circuit. Output at frequency f_L below f_O and at f_H above f_O is 0.7 of the maximum output possible from the circuit, or is 0.7 e_{Max}. When the level of the signal has dropped to 0.7 e_{Max}, the gain of the circuit is considered as not having dropped to a noticeable degree. Therefore, in Fig. 5-26, the portion of the band between f_L and f_H is considered as the portion of the band passed by the components involving the resonant circuit. The gain at frequencies below f_L and above f_H is relatively low because they are outside of this passband.

The size of this passband is related to the Q of the circuit. It can be determined from the equation

$$f_H - f_L = \frac{f_O}{Q} \qquad \textbf{Eq. 5-14}$$

where all quantities are identical to those indicated in Fig. 5-26. The Q of the resonant circuit is substituted for the Q in the equation.

For example, consider the series-resonant circuit discussed earlier. Because f_O = 225,193 Hz and Q = 707.5, f_H-f_L =

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

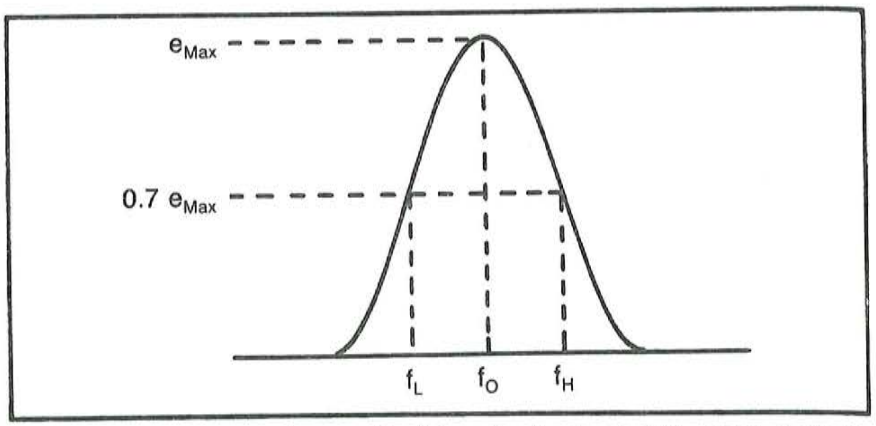


Fig. 5-26. Curve that can be used to determine the bandwidth and Q of a resonant circuit.

225,193/707.5 = 318 Hz. If f_L is as much below f_O as f_H is above it, f_H is 225,193 + 318/2 = 225, 352 Hz, and f_L is 225,193 – 318/2 = 225,034 Hz. Therefore, the bandwidth of this circuit is from 225, 034 to 225, 352 Hz. This is an extremely narrow band around a 225, 193 center frequency. If you want to widen it, you would have to add a resistor in series with L to reduce Q. If you should want to make the passband narrower for some strange reason, you would then need a different coil with a higher Q than 707.5. This coil must then have less than a one-ohm resistance.

Next consider the parallel-resonant circuit where f_O is equal to 222,817 Hz and Q = 7. Now $f_H - f_L$ = 222, 817/7 = 31,831 Hz so that f_H = 222,817 + 31, 831/2 = 238, 733 Hz and f_L = 222,817 – 31, 831/2 = 206,902 Hz. The passed band from 206, 902 Hz to 238,733 Hz is extremely wide when it is considered around a center frequency of 222,817. It can be reduced only by replacing the coil with one exhibiting a lower resistance and a higher Q.

A Q of about 100 is quite common for many of the coils. If you are working at frequencies around 200,000 Hz, the bandwidth or f_H-f_L would then be 200,000/100 = 2,000 Hz.

Let us finally determine what coil to specify if the bandwidth should be 10,000 Hz with 455,000 Hz as the center frequency. Substituting the numbers into Equation 5-14, you will find that 10,000 = 455,000/Q. Solving for Q, it must be equal to 45.5. This is a requirement for a coil that may be used in one section of an ordinary radio.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Chapter 8





Bipolar Junction Transistors

Circuits using only ordinary junction diodes as active devices cannot provide voltage or current gain. Transistors, however, can perform as amplifiers in conjunction with the other components in the circuit. Various arrangements using transistors are used to take the signal voltage, current, or power present at the input of a circuit and magnify it. A magnified version of the input signal will then be present at the output of the amplifier.

There are other amplifying devices besides transistors. A number of years ago, before the advent of transistors, the vacuum tube was the most important amplifying device. Now it is essentially an outdated component, although it is still used in some special applications. Two types of transistors have superseded the vacuum tube. These are the bipolar junction transistor and the field-effect transistor. The bipolar junction transistor will be discussed in this chapter, while details about the field-effect transistor will occupy our attention in Chapter 9. Another type of transistor, those in the point contact group, may still be found in equipment designed in the 1950s. This device is no longer in current use.

THE JUNCTION TRANSISTOR

Junction diodes are constructed from two different types of semiconductors—an n-type and a p-type. A depletion region exists between these slabs. The structure of the junction transistor

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

elaborates on that of the diode. It consists of three semiconductor slabs and two depletion regions.

One type of transistor consists of two sections of n-type material with a very thin piece of p-type material placed between the two n-type slabs. A second type of transistor has the opposite structure with a thin n-type slab sandwiched between two p-type slabs. Using the structure with the slabs to identify the transistor groups, the first type with two n-type slabs and one p-type slab is referred to as an *npn transistor*. The second type is a *pnp device*. Structural diagrams of both types of transistors are shown in Fig. 8-1.

The schematic representation of the two groups of junction transistors is shown in Fig. 8-2. The semiconductor that is sandwiched between the outer two slabs is referred to as the *base*. The outer two slabs are the *emitter* and the *collector*. (See Fig. 8-2.) The emitter lead is denoted by an arrow. It points away from the base in the schematic of an npn transistor and points towards the base in the drawing of a pnp device. As for the diodes, the arrow here indicates the direction of conventional current flow and *not* the direction of the electron current.

Using a diagram of the structure of the pnp transistor, you can determine how a transistor works. In Fig. 8-3A, the three semiconductor slabs are shown. There are two depletion regions in this device. One is at the base-to-emitter junction and second is at the base-to-collector junction. Two depletion areas exist because there are two p-n junctions. There is only one of these junctions in a diode so it has only one depletion region.

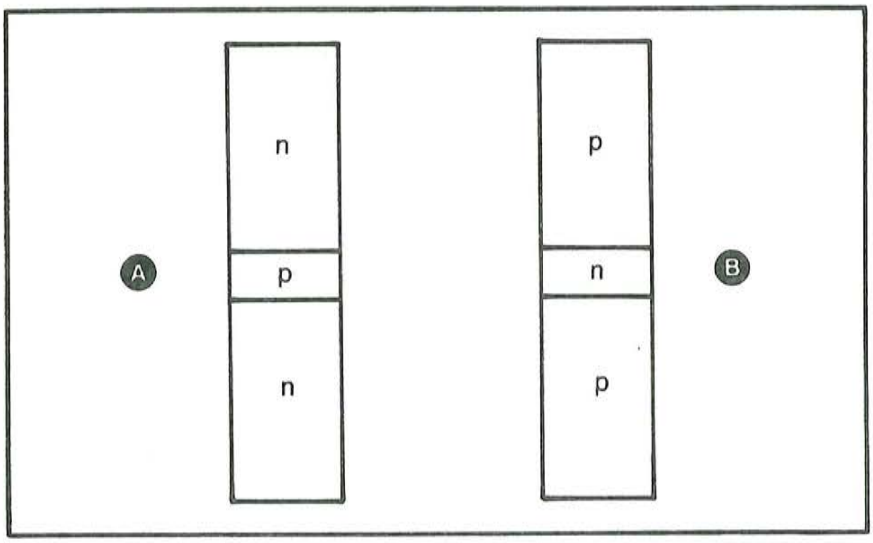


Fig. 8-1. Structure of junction transistor. A. Npn type. B. Pnp type.

EX-1043
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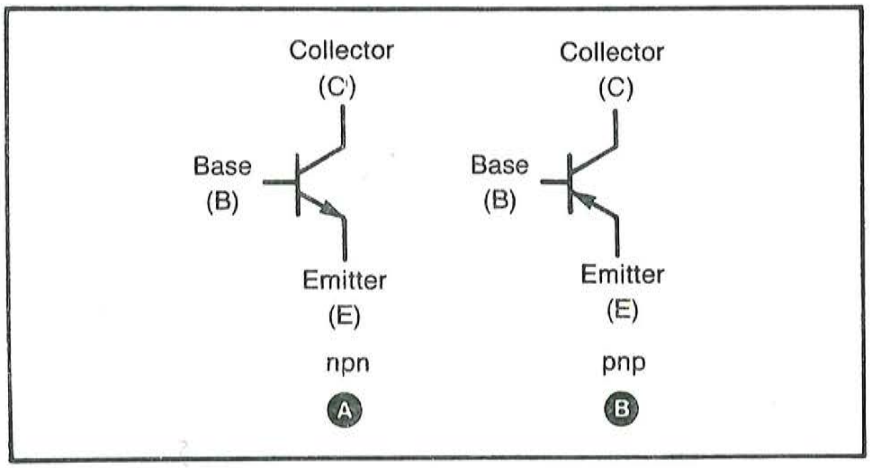


Fig. 8-2. Schematic representation of transistors. A. Npn. B. Pnp.

Now note the diagram in Fig. 8-3B. The dc voltages applied to the base and collector are both negative with respect to ground. This polarity is used only when a pnp device is involved. Voltages of opposite polarities are applied to the transistor when an npn device is used in the circuit. In either case, E_{CC} is higher with respect to ground that the voltage at the base of the transistor.

With no voltage applied to the transistor slabs, the depletion regions shown in the figure are formed. Now apply $-E_{CC}$ volts to the collector. With the collector, C, at a negative voltage with respect to the emitter, E, no current can flow between these terminals. This is because of the depletion regions between these semiconductors. The same condition would exist even if the emit-

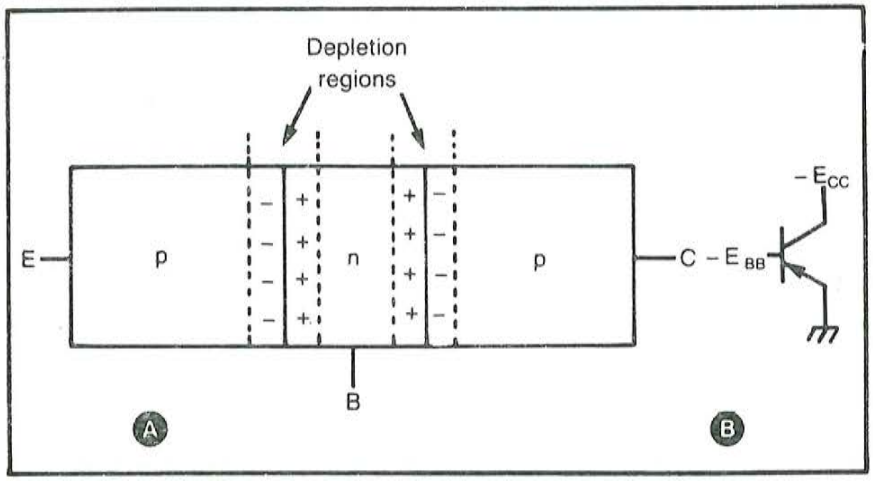


Fig. 8-3. The pnp transistor. A. Structure of transistor including the depletion region. B. Schematic showing relative voltages with respect to ground, applied to terminals for conventional use.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

ter were negative with respect to the collector. In either case, the depletion regions resist current flow.

Now connect the negative base voltage supply, $-E_{BB}$, to the B lead. The depletion region between the base and emitter is eliminated. Because the n-slab forming the base is more negative than the p-slab of the emitter, conventional current flows from the emitter to the base. It was the same voltage polarity that helped establish a flow of current in the junction diode. But here current cannot flow from the base to the collector: the n-p junction is reverse biased because the magnitude of $-E_{BB}$ is always less than $-E_{CC}$.

The voltage between the emitter and collector exerts a pressure on electrons to flow from one terminal to the other. Before the base voltage is applied, two depletion regions exist and current could definitely not flow between the emitter and collector. By applying voltage to the base, you eliminate one barrier to current flow—the depletion region between E and B. But there is still a second barrier—the depletion region between B and C.

Once current flows from the emitter to the base, an excess number of holes builds up in the narrow base region. They have nowhere to go and so force their way into the collector slab.

The holes present in E are transferred to the base. These holes are attracted to the negative collector. Because of this attraction, the base-collector depletion region is almost eliminated. The bulk of these holes travels to the collector. A lesser number passes into the base lead.

If an npn transistor is used rather than a pnp device, voltage applied to the collector is positive with respect to the emitter. The base must be made positive with respect to the emitter if the base-emitter depletion region is to be cancelled and current is to flow from the emitter to the base. Because more electrons are in the base than it can absorb, the bulk of the electrons is attracted to the highly positive collector. Under these conditions, the effect of the base-collector depletion region is almost nonexistent.

In considering the npn transistor, electrons originate at the emitter. They are divided between the base and collector. What portion goes to each slab depends upon the transistor being used. A small current in the base-emitter circuit appears as a much larger current in the collector-emitter circuit. For each transistor, there exists a certain ratio of collector to base current. This is the basis of operation of a transistor. Current is fed to the base. Because of the base current, current flows in the collector. The collector current base is equal to the current magnified by a certain factor. This

EX-1043
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"magnifying factor" is the ratio of the total current from the emitter that flows in the collector to the amount of current that is in the base. When the base current is magnified by this amount, the produce gives the current flowing in the collector. The ratio of the collector current to the base current is the current gain of the transistor. The bipolar junction transistor is basically a current amplifier.

Here, I used an npn device in the description of the current amplifier. The same facts apply to the pnp device, except that here the holes from the emitter divide up between the base and collector rather than the electrons. By making the base negative with respect to the emitter, a small current flows in the base. Because of this current, a larger current flows in the collector-emitter circuit if the collector is made negative with respect to the emitter. The collector current is related to the base current by this current-magnifying factor.

In the discussion that follows I will concentrate primarily on the npn transistor. Just keep in mind that the facts also apply to the pnp device. In the latter device, the applied voltages must be reversed in polarity from those applied to the npn transistor. Later, however, I will show how a pnp transistor is used in conjuction with an npn device in one circuit.

The following circuit description and operation will be based on the use of silicon transistors. When the base-emitter junction is forward biased, there is 0.7 volt across this junction. This is the same as the voltage across the forward-biased silicon diode junction. Therefore, if a germanium transistor is to be used in a circuit, the only difference between that device and the silicon transistor that must be considered is the base-emitter voltage. For the germanium transistor, it is assumed that this voltage is around 0.3 volt or 0.4 volt.

CURRENT GAIN OR LOSS

Junction transistors are basically current amplifying devices. You produce voltage gain by sending the currents through resistors or resistances of appropriate magnitudes. The ratio of voltages developed across the resistances due to the flow of the currents in these components is the voltage gain of the transistor circuit. This is illustrated in more detail below.

The current-gain characteristic of a particular transistor can be described by either one of two numbers. One number relates the amount of current flowing in the collector of the transistor, to

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

the amount of current flowing in its base. This ratio is referred to as the transistor's *beta*, or β. Stated mathematically,

$$\beta = \frac{I_C}{I_B} \qquad \text{Eq. 8-1}$$

where I_C is the collector current and I_B is the base current.

The beta of different transistors ranges from less than 10 to more than 800. If the beta of a particular transistor is 10 and 10 mA of current is fed to its base, its collector current is βI_B = 10(10 mA) = 100 mA. If you need 100 mA of collector current from this transistor, you must feed an $I_B = I_C/\beta$ = 100 mA/10 = 10 mA to the base. All this can be determined from Equation 8-1.

In a similar fashion, if the transistor you are using has a beta of 800 and you feed 100 μA to the base, the collector current is 800(100 μA) = 80,000 μA = 80 mA. Just before, if you want a current of 80 mA in the collector circuit of the transistor, you must apply 80 mA/800 = 0.1 mA = 100 μA to the base of the device.

Current gain in either instance is obviously equal to the ratio of the collector to the base current. Equation 8-1 is essential for determining the performance of a transistor and should be remembered.

The beta of every transistor is different. Because transistors are so variable, no two transistors will have identical betas—if they did, it would be a fluke. To establish some sort of order, similar types of transistors are grouped in accordance with their betas. (By "similar type," I mean devices that have the same characteristics in all respects except for current gain.) For example, consider the five groups of transistors that fall into the same category and have been assigned numbers 2N5824 through 2N5828. The group with number 2N5824, has betas that range from 60 to 120; the 2N5825 group has a beta range of 100 to 200; the 2N5826 group has a beta range of 150 to 300; the 2N5827 group has a beta range of 250 to 500, and the group numbered 2N5828 has a beta range of 400 to 800. All these transistors are identical in every way except for the beta category into which individual devices may fall. They have the same maximum voltage rating, the identical power dissipation capabilities, identical limits on the highest frequency that they can amplify, and so on.

If the beta of a particular device is within a specific range, the manufacturer of the transistor must assign the number to it that is used for transistors in that beta range. Thus, if the beta of a tran-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

sistor in the 2N5824 to 2N5828 group is 115, it may be assigned either number 2N5824 or 2N5825 and not any other number. If it had a beta of 225, it would have assigned the number 2N5826.

A second number which describes the current capabilities of the transistor is its *alpha*. The Greek letter α is used to represent this current ratio. Alpha relates the collector current to the emitter current by the formula

$$\alpha = \frac{I_C}{I_E} \qquad \textbf{Eq. 8-2}$$

All transistor current flows in the emitter. It is split between the base and collector with the bulk of the current from the emitter flowing into the collector. Therefore, less current flows in the collector than in the emitter. The alpha, the ratio of the collector to emitter currents, is consequently less than 1. It is almost always very close to 1, usually between 0.98 and 0.999. If a specific current is fed to the emitter, less current than I_E flows through the collector.

Because alpha and beta are both related to the currents in the transistor, and all transistor currents are related to each other, alpha and beta are related to each other. If you only know the alpha of a particular transistor, you can determine its beta by using Equation 8-3.

$$\beta = \frac{\alpha}{1 - \alpha} \qquad \textbf{Eq. 8-3}$$

Similarly, if you need to know the alpha of a transistor but only know its beta, you can determine this gain through Equation 8-4.

$$\alpha = \frac{\beta}{1 + \beta} \qquad \textbf{Eq. 8-4}$$

CIRCUITS WITH TRANSISTORS

There are basically three circuit arrangements in which transistors are used. All other circuits are simply variations on these. Each circuit type is designated by the transistor terminal used as the reference point for the dc or for the ac signal voltages at the other two terminals. In our initial discussion, this reference terminal was chosen as the emitter. Here, I will start our analysis by using the base as this reference point.

EX-1043
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Common Base Circuit

The basic circuit used in the *common-base* arrangement is shown in Fig. 8-4. The base terminal is the common or reference point. A negative voltage is applied to the emitter with respect to the base so that this junction is forward biased. Voltage between the collector and base is of such polarity as to reverse bias this junction. Resistor R_E in conjunction with E_{EE} sets the emitter current, I_E. The arrow at I_E shows the direction in which conventional current flows in the base-emitter circuit.

Because current flows through the base-emitter circuit 0.7 volt is across this junction. The total voltage in this section of the circuit outside the transistor is $E_{EE} - 0.7$. The emitter current is equal to this voltage divided by the total resistance in this circuit. Here, this resistance is only R_E.

Emitter current is equal to the sum of the base and collector currents. Because very little base current flows compared to the collector current, the collector current, I_C, is essentially equal to the emitter current, I_E. With the current at the input equal to the current at the output, the current gain, I_C/I_E, is just about equal to 1. It is actually equal to the alpha of the transistor, which is close to 1. Voltage at the collector with respect to the base is equal to E_{CC} minus the voltage developed across R_C due to I_C, or $E_{CC} - I_C R_C$.

Transistor circuits are usually designed to amplify an ac input voltage rather than dc current. In this type of arrangement, the ac is superimposed on the dc. The dc is used to establish specific quiescent emitter and collector currents. These *bias currents* should set the idling voltage (voltage before ac is applied to the circuit) at the collector at one-half of E_{CC}. Because the collector voltage, V_C, is equal to $E_{CC} - I_C R_C$, V_C should be idling at about $E_{CC}/2$.

Now lets place an ac voltage, V_{In}, in series with the existing dc voltage in Fig. 8-4. This is illustrated in Fig. 8-5. Here, it is as-

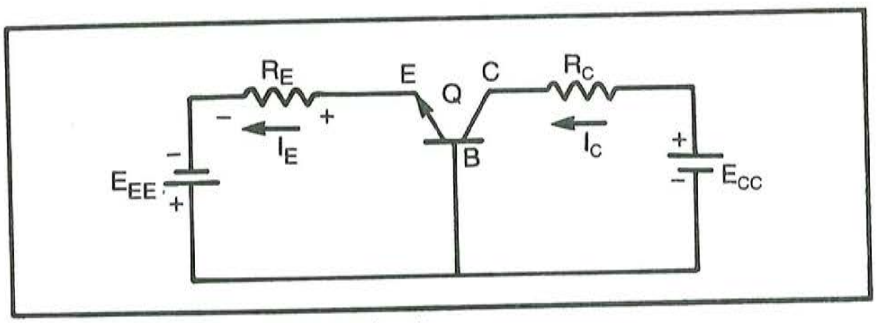


Fig. 8-4. Basic common-base circuit.

EX-1043
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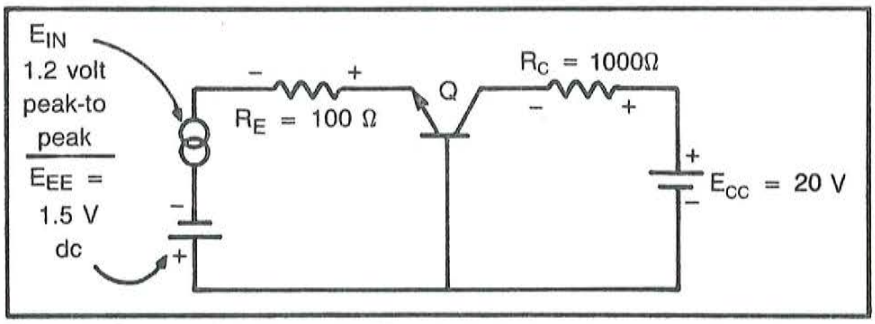


Fig. 8-5. Common-base ac amplifier.

sumed that the emitter supply voltage is fixed at 1.5 volt and that an ac with a 1.2 volt peak-to-peak level is superimposed on the dc. This combination is applied to the base-emitter circuit.

Adding ac sinusoidal voltage to dc voltage can be accomplished graphically. An example of this is shown in Fig. 8-6. For this illustration, it is assumed that the ac input signal varies from 0 volt to a peak of +1 volt and to a crest of −1 volt. The dc voltage, E_{EE}, is chosen at different fixed levels.

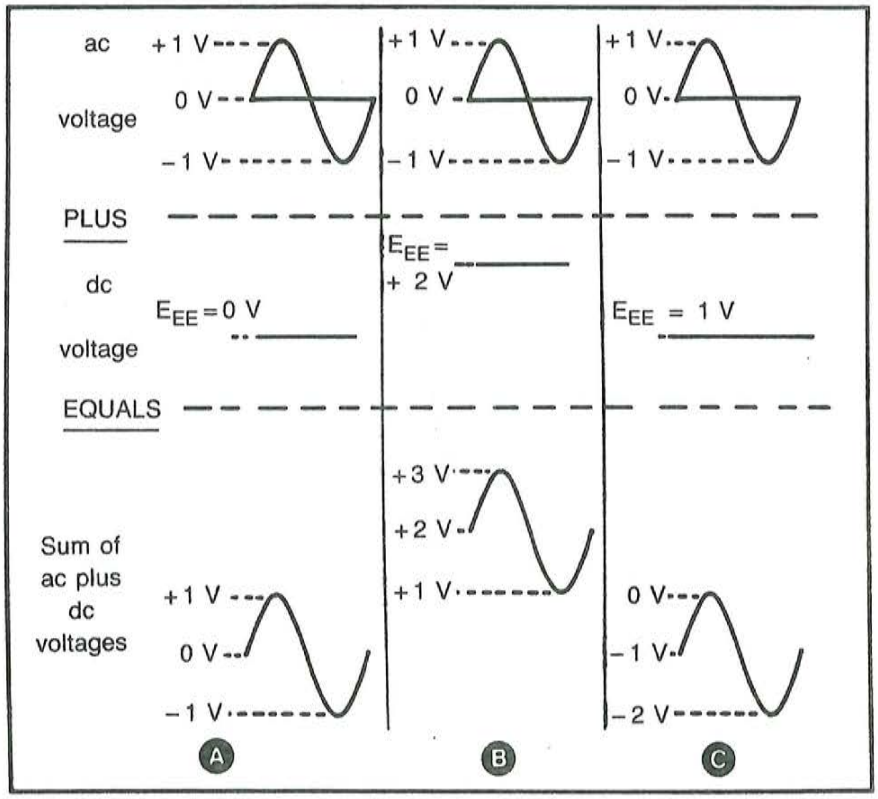


Fig. 8-6. Ac voltage added graphically to a dc voltage. A. Dc is 0 volt. B. Dc is +2 volts. C. Dc is −1 volt.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

In Fig. 8-6A, E_{EE} is set at 0 volt. The total ac superimposed upon this is thereby equal to and due entirely to the ac voltage. There is no dc to add to it because the dc is at 0 volt. In Fig. 8-6B, the dc level is +2 volts. With +1 volt to −1 volt peak-to-peak of ac superimposed upon this, the sum of the peaks of the ac signal with dc is +2 volts dc plus +1 volt ac or +3 volts, and the sum at the crest of the ac signal is +2 volts dc plus −1 volt ac or +1 volt. In Fig. 8-6C, the identical situation exists except that now the dc voltage is negative and equals −1 volt. Adding the ac to this gives a peak of −1 volt dc, plus 1 volt ac, or 0 volt and a crest of −1 volt dc, plus 1 volt ac, or −2 volts. In all instances, the total output voltage varies between the crest and peak during different parts of the cycle. It follows the cyclic variations of the pure ac at the input.

Getting back to the circuit in Fig. 8-5, let us use the numbers there to illustrate the addition of the ac signal to the dc bias voltage and discuss how the circuit performs its amplifying function. The ac-input-signal voltage is given here as 1.2 volt peak-to-peak. The peak voltage is one-half of this or 0.6 volt, so the ac varies from a −0.6 volt crest to a +0.6 volt peak for a total variation of 1.2 volt. The rms average, E_{RMS}, of this voltage is 0.6 volt/1.414 = 0.42 volt. Also note that, as before, E_{EE} is negative with respect to the common terminal, the base.

Bias or idling conditions are established when there is no ac voltage at the input of the circuit, or $E_{In} = 0$. At this time, only the dc emitter supply voltage less the base-emitter voltage is across R_E, the only component in this circuit that is outside of the transistor. This voltage is −1.5 volt minus 0.7 volt, or −0.8 volt. Thus, −0.8 volt is across R_E. Emitter current is now equal to −0.8 volt/100 ohms = −0.008 A. Because this is just about equal to the collector current, the voltage across R_C is (−0.008 A) (1000 ohms) = −8 volts. The polarity is as shown at the resistor. When this voltage is subtracted from E_{CC}, 20 volts minus 8 volts, or as much as 12 volts, is at the collector of transistor Q.

Now apply the ac signal voltage to the input. When it is at the crest of its cycle, the −1.5-volt dc is added to the −0.6 volt at the crest of the ac signal for a total of −1.4 volt. Since 0.7 volt is at the base-emitter junction, −1.4 volt is across R_E. At this instant, current in the collector and emitter circuits are −1.4 volt/100 ohms = −0.014 A. The voltage across R_C is (0.014 A) (1000 ohms) = 14 volts, so the voltage at the collector of Q is (20 volts) − (14 volts) = 6 volts.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

When the applied ac voltage is at its positive peak in the cycle, the +0.6 volt ac is added to the −1.5 = volt dc, for a total of 0.9 volt. Subtracting the 0.7 volt that is at the base-emitter junction, −0.2 volt is across R_E. I_E and I_C are at this instant equal to (−0.2 volt)/(100 ohms) = −0.002 A. The voltage across R_C is (0.002 A) (1000 ohms) = 2 volts. Now the voltage at the collector is 20 volts minus the 2 volts across R_C or 18 volts.

Voltage calculated to be at the collector must never drop below 0 volt or exceed the supply voltage—20 volts in this example. If either of these happen when ac voltage is at the input, the voltage across R_C or between the collector and base of the transistor would differ in shape from the voltage applied to the input. A good amplifier provides an output signal that looks exactly like the input. They differ only in that the output and input may have different overall magnitudes due to amplification by the transistor circuit.

Dc voltage at the collector is E_{CC} minus the voltage across R_C. If the collector current (current through R_C) were so high as to make the voltage across R_C greater than E_{CC}, our calculations would show that a negative voltage is at the collector of the transistor. But this cannot happen because collector voltage cannot drop below the zero volt at the base reference terminal under any circumstances.

Now let's see what happens when an ac signal is applied to the input. Assume that during a portion of the ac cycle, the sum of the ac voltage and dc bias voltage is sufficient to increase I_C to the level where calculations will show that the voltage across R_C exceeds E_{CC}. During this interval, the voltage at the collector of the transistor would theoretically drop below zero. But this cannot happen. It remains at its 0-volt minimum. The output will not follow the cyclic variation of the input in this portion of the cycle. It remains fixed at 0 volt. This portion of the waveform is distorted.

The same is true if during a portion of the cycle the sum of the ac input voltage and the dc bias voltage adds to a magnitude that is below zero volt. During this portion of the cycle, I_E and I_C would stay at zero, putting the voltage across R_C at zero volt. Now the collector voltage remains fixed at E_{CC}. During this interval, the output voltage is a distorted version of the input signal.

To avoid these problems or minimize the chances of this happening, the dc idling current is adjusted so that the collector bias voltage is at about one-half of E_{CC}. Now the output voltage can vary over its maximum range from zero to E_{CC} volts. R_E is also chosen so that the emitter and collector currents are limited to

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

values where the $I_C R_L$ voltage never exceeds E_{CC} even when the ac input voltage is at its peak. The total current must be less than E_{CC}/R_L or less than $(E_{EE} - 0.7)/E_E$.

Getting back to our example, note that the voltage across R_C varies from 14 volts to 2 volts, while the ac input signal varies from −0.6 volt to +0.6 volt. Therefore, the peak-to-peak output was 14 volts − 2 volts = 12 volts while the peak-to-peak input was 0.6 volt − (−0.6 volt) = 1.2 volt. The voltage gain of the circuit is the output voltage divided by the input voltage or 12 volts/1.2 volt = 10. But also note that the ratio of R_C to R_E is 1000 ohms/100 ohms = 10. You can therefore conclude that the ac voltage gain of the common-base circuit is equal to R_C/R_E.

Using Equation 3-5, you know that the power across the output circuit is $I_C^2 R_C$, and the power at the input circuit is $I_E^2 R_E$. Because I_E is just about equal to I_C, the power gain or ratio of the power at the output to the power at the input is $I_C^2 R_C / I_E^2 R_E = R_C/R_E$. Because this ratio is the same as the voltage gain, the power gain and voltage gain are identical.

When the ac voltage at the emitter is at its peak with respect to the base, the voltage at the collector is also at its peak with respect to the base. The crests of the ac signal also exist at the same time at the emitter and collector. You can therefore conclude that the ac output from a common-base circuit is in phase with the ac input to that circuit.

Common-Emitter Circuit

The common-base arrangement is used primarily as a high-frequency amplifier. Common-emitter circuits are used more frequently than are the common-base circuits. These arrangements are applied to most applications in the audio band. Common-emitter circuits are also used in some very high-frequency equipment.

The positive voltages applied to the base and collector in the common-emitter arrangement are with respect to the emitter. This is shown in Fig. 8-7 where the emitter terminal of the transistor is connected to ground. The base supply, E_{BB}, in conjunction with R_B, sets the idling current, I_B, in the base. It is equal to E_{BB} minus the 0.7 volt between the base and emitter divided by R_B, the only resistance in this portion of the circuit. This current, multiplied by beta, is equal to the idling collector current, I_C. Because I_C flows through R_C, voltage is developed across that resistor in the collector circuit. As was true in the common-base circuit, it is also desirable here to let the voltage at the collector terminal in this circuit

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

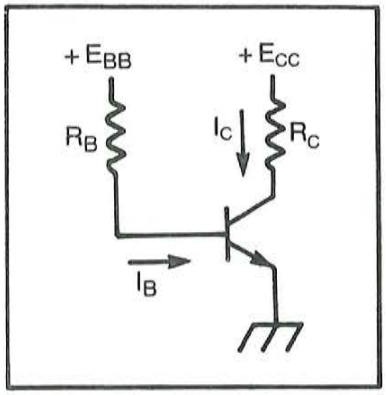


Fig. 8-7. Common-emitter circuit.

idle at $E_{CC}/2$ volts. To do this, the idling voltage across R_C must be equal to half of the supply voltage, or $I_C R_C = E_{CC}/2$. Because I_C is related to I_B, I_B is set by the designer of the circuit to equal the desired I_C divided by beta. I_B can, of course, be set by using the proper base resistor, R_B, in the circuit.

Ac signal voltage is usually fed through a capacitor to the base and applied between the base and emitter to the transistor. The input voltage varies the base and hence collector current in step with the cyclic variations of the ac. A magnified version of the ac input voltage is developed across the collector resistor by the ac collector current flowing through it. Output voltage is fed from the collector through a capacitor to a load of some type. This is shown in Fig. 8-8. The load is drawn here as a resistor. A resistor has also been added between the emitter and ground to simulate the usual circuit. Instead of having a separate supply for the base current,

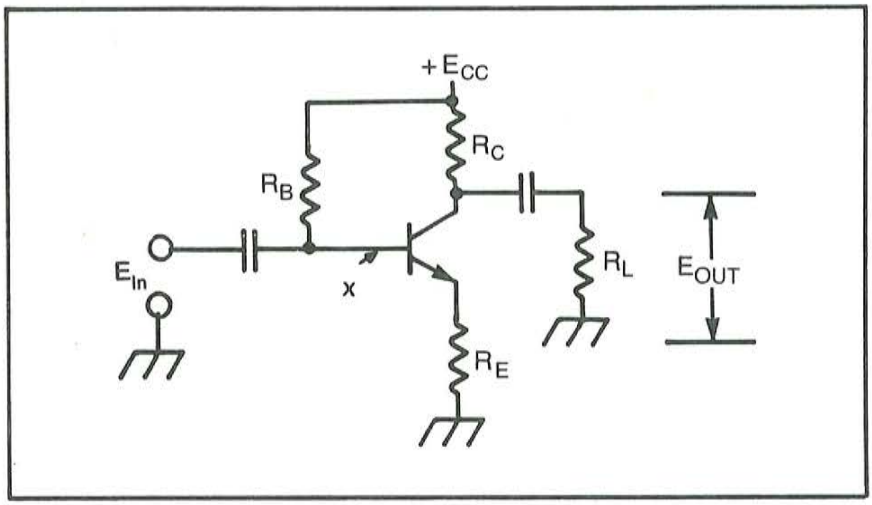


Fig. 8-8. Common-emitter ac amplifier. The beta of the transistor is an important factor in determining the operation of the circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

E_{CC} is used here as the supply for both the collector and base circuits.

Base idling current is established by the circuit involving E_{CC}, R_B, V_{BE}, and R_E. The voltage in this current is $E_{CC} - V_{BE}$, where $V_{BE} = 0.7$ volt. Current in R_B is I_B, while current in R_E is βI_B or I_E. In determining the base current, therefore, you can consider R_E as being in series with the base, replacing the lead at which arrow "x" is pointing. But before putting it there, R_E must be multiplied by beta. This is because the actual voltage developed across R_E is due to a current equal to beta multiplied by the current flowing in the base circuit. So in order for the same voltage to be developed across the resistor when moved to the base circuit as was developed across it in its original location, R_E must be multiplied by beta before being relocated. As a result, the total resistance in the base circuit is $R_B + \beta R_E$. Base idling current is $(E_{CC} - 0.7)\text{volts}/(R_B + \beta R_E)\text{ohms} = I_B$. Idling collector and emitter currents, I_C and I_E, are both about equal to beta times I_B.

As indicated, I_C should be of such magnitude as to establish a collector-emitter voltage and idling voltage at the collector equal to about one-half of E_{CC}. This is achieved when $I_C(R_C + R_E) = E_{CC}/2$.

The ac input signal adds a variable current to the dc idling current in the base. It is amplified by the transistor so that a magnified version of the ac input is across R_C. When the voltage at the base is at its peak in the cycle, the collector current is also at its peak. Because the voltage across R_C is the product of the collector current with R_C, this voltage is also at its maximum level. Subtracting the peak voltage across R_C from E_{CC}, you will find the voltage at the collector of the transistor at this instant. This is its minimum with respect to ground. Because the output voltage is at a minimum when the input voltage is at a maximum, you can conclude that the input and output voltages are 180° out of phase. This is the situation that exists with common-emitter circuits. Despite the fact that the input and output voltages are out of phase, the magnitude of the ac voltage at the output of the transistor is usually greater than it is at the input.

For example, let $R_C = 5000$ ohms, $R_L = \partial$ ohms, $R_E = 500$ ohms, $E_{CC} = 22$ volts, and the beta of the transistor be equal to 100. The total resistance in the collector-emitter circuit is $R_C + R_E = 5000$ ohms + 500 ohms = 5500 ohms. If the idling voltage across the transistor is to be one-half E_{CC} or 11 volts, I_C must be equal to 11 volts/5500 ohms = 0.002 ampere. Now 11 volts will

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

be across the total resistance in the collector-emitter circuit or 5500 ohms, as well as between the collector and emitter of the transistor.

If 0.002 A (or 2 mA) is to flow in the collector circuit, that current divided by beta must be in the base circuit. Because I_C = 0.002 A, I_B = 0.002 A/β = 0.002A/100 = 0.00002A = 2×10^{-5} A. Therefore, the resistance in the base circuit must be (E_{CC} – 0.7)/I_B = 21.3 volts/2×10^{-5}A = 10.65×10^{-5} ohms = 1,065,000 ohms. R_E appears in the base circuit as if it were beta times what it actually is or 100 × 500 ohms = 50,000 ohms. Because this resistance plus R_B is the total resistance in the base circuit, R_B must be equal to 1,065,000 ohms – 50,000 ohms or 1,010,000 ohms. A minor 1% error will occur if you let R_B equal 1,000,000 ohms or 1 megohm.

Current gain of this circuit is equal to the beta of the transistor. If 0.02 mA of current is fed to the base, beta times 0.02 mA is at the collector. In this example, with beta equal to 100, 100 × 0.02 mA = 2 mA flows through the collector (and emitter) circuit.

In order to determine the ac voltage gain, you must take into account the *ac emitter resistance* that is present inside the transistor. It is equal to 0.026/I_E, with I_E, the idling current, expressed in amperes. Thus, if I_E = I_C = 2 mA = 0.002A, the ac emitter resistance, r_e, in this example is 0.026/0.002 = 13 ohms. When ac flows in the circuit, this resistance is usually significant. As far as the ac is concerned, the total resistance in the emitter circuit is R_E + r_e. This is equal to 500 ohms + 13 ohms = 513 ohms. The dc resistance of the emitter circuit remains fixed at R_E. Here it is 500 ohms.

Using 513 ohms as the total ac resistance in the emitter circuit, lets determine the ac voltage gain of the circuit. Assuming E_{In} has a peak of 0.5 volt and a crest of –0.5 volt, the peak-to-peak variation of the input signal is 1 volt. This variation is applied to the series circuit consisting of the base-emitter junction, r_e and R_E. Because the input voltage is in the base circuit, it sees the 513 ohms in the emitter multiplied by the beta of the transistor or 51,300 ohms. The base current swing due to the E_{In} variation of 1 volt is 1 volt/51,300 ohms = 1.95×10^{-5}A. The transistor current is not cut off even when the swing of E_{In} is down to –0.5 volt at its crest because the base is biased by the dc to idle at 2×10^{-5} mA. The negative crest of the input signal tends to reduce the current at that instant of the cycle, but it will not counter the dc idling current enough to stop the transistor from conducting.

The ac collector current swing is beta multiplied by the base

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

current swing. Because beta is 100, the collector current swing is 1.9×10^{-5}A $\times$ 100 = 1.9×10^{-3}A. The peak-to-crest voltage developed across R_C due to the collector current swing is (1.95×10^{-3}A) (5000 ohms) = 9.75 volts. The ratio of the output voltage across R_C to the input voltage is 9.75 volts/1 volt = 9.75. This is the ac voltage gain, A_v, of the transistor circuit.

By looking at the circuit, you can find a very simple way of determining the voltage gain. It is approximately equal to $R_C/(R_E + r_e)$. Here, it is 5000 ohms/513 ohms = 9.75. This is the same gain number calculated using the longer procedure above.

The power at the input to the transistor is the rms base current multiplied by the applied voltage, or I_bE_{rms}. At the output, the ac power is the rms collector current multiplied by the rms voltage developed across R_C, or I_CE_{rms}. The power gain of the circuit is the ratio of the output power to the input power or I_CE_{OUT}/I_bE_{rms}. Because I_C/I_b is equal to beta and E_{OUT}/E_{rms} is equal to the voltage gain, the power gain, G, is beta times the voltage gain or βA_v. In this example, it is 100(9.75) = 975.

When dealing with practical circuits, three additional factors usually require some consideration. One is the signal source. Like the battery, the ac signal source is not perfect. It has some internal resistance. If this resistance is substantial, it must be take into account when calculating the gain of the overall circuit.

The second factor is the dc supply. In all circuits, whether the supply is a battery or a converted ac arrangement, a capacitor is connected across it. Because a capacitor passes ac and behaves as an open circuit for the dc, the supply is a short circuit for the ac. The negative terminal of the $+E_{CC}$ supply in Fig. 8-8, is at ac ground (unless shown otherwise). As far as the ac or signal voltage is concerned, the top terminal of R_C and R_B are both at ground.

A load resistor, R_L, is wired across R_C through a capacitor. The capacitor behaves as a short circuit for the ac, letting it pass freely. The end of R_C that is connected to $+E_{CC}$ is at ac ground. One end of R_L is also connected to ground. R_L is effectively in parallel with R_C through the coupling capacitor. The output load for the ac signal is the equivalent resistance of the parallel combination of R_L and R_C. R_L is usually so large as to be negligible when compared to R_C, but not always. The loading by R_L on the output circuit is the third factor of concern to us here.

So now let's modify Fig. 8-8 and change it to the circuit shown in Fig. 8-9. C1 conducts the ac from E_{In} to the base, and C2 con-

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

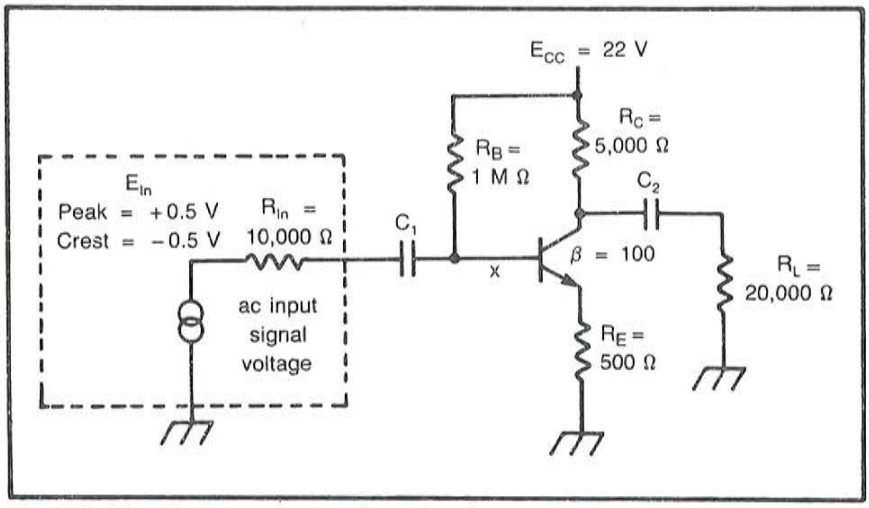


Fig. 8-9. Practical common-emitter circuit.

ducts the ac from the collector to R_L. These capacitors are again essentially short circuits for ac and open circuits for dc. Because of this, they do not let dc from the transistor circuit enter the E_{In} supply or the R_L load. They also do not let the resistance of the supply or load upset the dc bias and idling conditions established by E_{CC} and resistors R_B, R_E, and R_C.

In Fig. 8-9, all components in the dc circuit are identical to those used in the previous example. All idling currents are unchanged. $I_B = 2 \times 10^{-5}$A, and $I_C = 2 \times 10^{-3}$A. Because r_e is the ac emitter resistance of the transistor it does not affect dc currents or bias voltages.

The ac input "sees" resistor R_B between the base and ground. The resistance between the junction of R_B and the base is $\beta(R_E + r_e)$ = 51,300 ohms. The connection at the base is effectively at ground, for all resistors and resistances between the emitter and the ground, $R_E + r_e$, have been moved to the left side of the base. This leaves the emitter at ground. Therefore, E_{In} sees the 51,300 ohms as if it were a resistance between the R_B/C1 junction and ground. In the actual circuit, this resistance is shown as wired between the base terminal and ground.

The 51,300 ohms appears to shunt R_B, the 1 MΩ base resistor. Thus, the resistance at the input of the transistor is equal to the parallel combination of both items, or (1,000,000 ohms) (51,300 ohms)/(1,000,000 ohms + 51,300 ohms) = 48,797 ohms, or approximately 49,000 ohms. Considering this resistance in conjunction with the 10,000 ohm resistance of E_{In}, a voltage divider is formed and Equation 3-2 applies. This circuit is shown in Fig. 8-10A.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

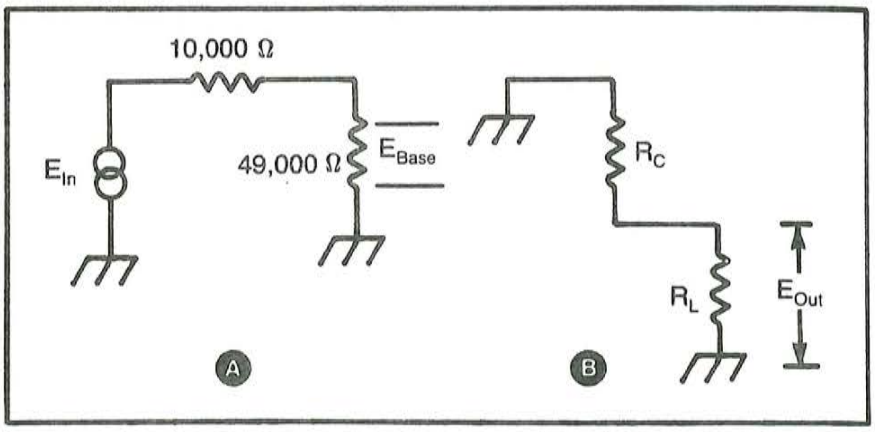


Fig. 8-10. Effects of the ac portion of the circuit in Fig. 8-9. A. Equivalent of input circuit. B. Equivalent of output circuit.

The total ac input voltage, E_{In}, is applied to the divider and base of the transistor through its internal 10,000 ohm resistance. The load presented to this circuit is 49,000 ohms. Using the voltage divider equation, E_{BASE} = 49,000 ohms/(49,000 ohms + 10,000 ohms) = 0.83 multiplied by E_{In}. If the peak and crest voltages supplied by E_{In} are 0.5 volt, the peak and crest voltages at the base are 0.83 × 0.5 volt = 0.415 volt for a peak-to-peak voltage swing of 2 × 0.415 volt or 0.83 volt.

The ac load resistance in the collector circuit consists of R_C in parallel with R_L. This is because the upper terminal of R_C is effectively at ac ground and C2 behaves as if it were a short circuit for the signal voltage. This is shown in Fig. 8-10B. The equivalent resistance of the combination is (5000 ohms) (20,000 ohms)/(5000 ohms + 20,000 ohms) = 4,000 ohms.

Gain is approximately equal to the ratio of the impedance in the collector circuit to the impedance in the emitter circuit. In this example, the gain of the transistor circuit is 4000 ohms/513 ohms = 7.8. So with peak-to-crest voltage of 0.83 at the base of the transistor, 7.8 × 0.83 volt = 6.5 volts is the peak-to-crest voltage across R_C and R_L. With this as the output voltage, the gain of the overall arrangement is 6.5 volts/1 volt = 6.5. This gain figure takes into account the resistors in the dc portion of the circuit as well as the input impedance of the supply and the ac load due to the presence of R_L. Note how much lower this gain is than the gain in the original example when R_{In} and R_L were not being considered. There, the gain was taken as being simply $R_C/(R_E + r_e)$ = 5000/513 = 9.75. This figure is 9.75/6.5 or 1.5 times the actual gain of the circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Common-Drain Circuit

There are times when voltage gain is not important and only the input and output impedance of a circuit are of concern. In Fig. 8-9, losses would be minimized if E_{In} saw a large load impedance and if R_C were much smaller than R_L. In the first case, the magnitude of R_{In} would be insignificant because practically all of the input voltage would be developed between the base and emitter. Only a very small voltage would be lost because of R_{In} if this situation existed. As for the output, all the voltage would be across R_C, while the shunting or loading effect of R_L would be negligible. But these conditions cannot be achieved solely through the use of the common-emitter circuit. A *common-drain* circuit would have to be added to help fulfill these goals. This arrangement is also known as an *emitter follower*. The circuit with ac inputs and outputs is shown in Fig. 8-11.

The collector is connected directly to the $+E_{CC}$ supply. As a result, the collector is at ac ground through the $+E_{CC}$ supply. Input from the ac source is therefore applied to the base-collector junction of the transistor. Output voltage is developed across R_E. Because the collector is at ac ground, the output voltage is between the emitter and collector. Ac input and output voltages are therefore considered here as being with respect to the collector.

The dc portion of this arrangement has requirements similar to those of the common-emitter circuit. Here, however, one-half of the E_{CC} supply voltage should be across R_E because there is no resistor in the collector circuit. In the diagram, I set R_E equal to 5000 ohms and E_{CC} equal to 20 volts. Therefore, $E_{CC}/2 = 10$ volts should be across R_E to satisfy the same idling current requirement

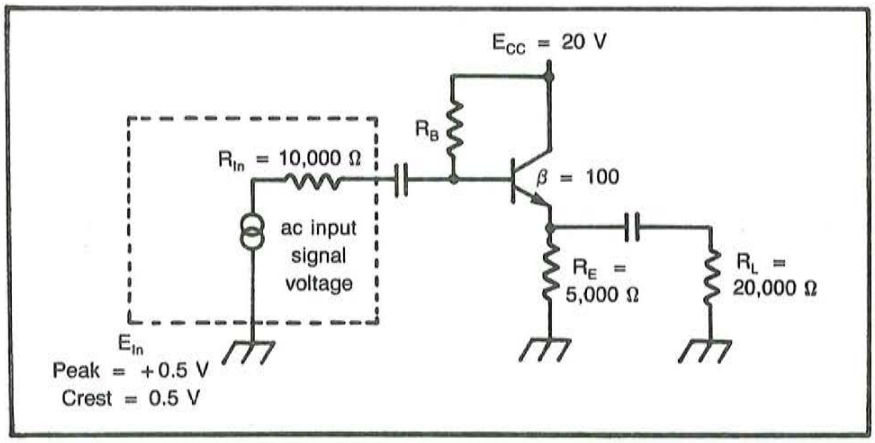


Fig. 8-11. Common-drain circuit with ac input and output.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

noted as in the common-emitter circuit. To accomplish this, the dc idling collector (or emitter) current must be 10 volts/5000 ohms = 0.002A = 2mA. If the beta of the transistor is equal to 100, the base current must be I_C/β = 2mA/100 = 2×10^{-5}A. This is the bias current that flows through R_B.

Idling voltage across R_B is equal to E_{CC} minus the 0.7 volt across the base-emitter junction, and that difference minus the voltage across R_E. This voltage is therefore equal to 20 volts − 0.7 volt − 10 volts = 9.3 volts. If the current through R_B is 2×10^{-5}A, that resistor must be equal to 9.3 volts/2.3×10^{-5}A or about 400,000 ohms.

In this circuit, R_E is larger than it was in the common-emitter arrangement. Because R_E = 5000 ohms and R_L = 20,000 ohms, the ac resistance in the emitter circuit is (5000 ohms) (20,000 ohms)/ (5000 ohms + 20,000 ohms) = 4000 ohms. This resistance, when reflected into the base portion of the circuit, is 100 × 4000 ohms = 400,000 ohms. It is much larger than the reflected resistance in the common-emitter circuit, because there only 500 ohms between the emitter and ground. Here, r_e is not important in determining the reflected resistance because it is usually negligible when compared to R_E. The ac and dc emitter resistance of the emitter-follower differ by only a small amount.

The resistance in the base circuit is due to the parallel combination of R_B and the reflected resistance from the emitter circuit. This is (400,000 ohms) (400,000 ohms)/ (400,000 ohms + 400,000 ohms) = 200,000 ohms. Using this as the resistance presented by the base circuit to the ac signal, the peak and crest voltages at the base can be determined from the equivalent circuit in Fig. 8-12A. From Equation 3-1, you will find these voltages are 0.5 volt(200,000 ohms)/(200,000 ohms + 10,000 ohms) = +0.476 volt and −0.476 volt. This is so close to E_{In} that the losses in this portion of the circuit are negligible.

In the output circuit, the resistance seen between the emitter and ground is R_E in parallel with the resistance reflected from the base circuit and divided by beta. This division by beta rule stems from the earlier demonstration that the resistance reflected from the emitter into the base circuit appears there as the resistance multiplied by beta. Therefore, the opposite is true when a resistance is reflected from the base circuit. It appears between the emitter and ground as the actual resistance in the base circuit but divided by beta. The resulting parallel combination is shown in Fig. 8-12B.

As far as the base circuit is concerned, the ac resistance is R_B

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

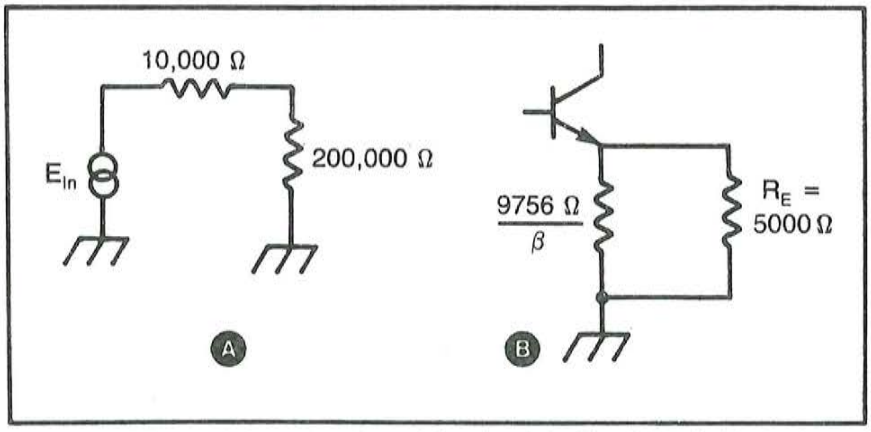


Fig. 8-12. Effects of the ac portion of the circuit in Fig. 8-11. A. Equivalent of input circuit. B. Equivalent of output circuit.

in parallel with R_{In}. It is obvious that R_B is between the base and ground because its upper terminal is at $+E_{CC}$. A 0-ohm ac resistance exists between $+E_{CC}$ and ground. As for R_{In}, it is the only resistance of the ac supply. Because it has one end at ground, the resistance is effectively connected between the base and ground. Thus, the total base-to-ground resistance of this parallel circuit is $(R_B)\ (R_{In})/(R_B + R_{In})$ = (400,000 ohms) (10,000 ohms)/(400,000 ohms + 10,000 ohms) = 9756 ohms. This resistance, divided by beta, is between the emitter and ground as shown in Fig. 8-12B. Because this circuit uses a transistor with a beta of 100, the resistance reflected into the emitter circuit is 9756 ohms/100 or 97.56 ohms. Since R_E = 5000 ohms, the actual resistance in the emitter circuit is (97.56) (5000)/(97.56 + 5000) or about 96 ohms.

Output voltage is developed across the 96-ohms located between the emitter and ground. This resistance feeds the output voltage developed across it to R_L. Because R_L is much larger than the 96 ohms, it has a negligible effect on the ac signal voltage developed in the dc portion of the emitter circuit and will not affect the gain of the circuit.

Voltage across R_E is slightly less than the voltage applied between the base and emitter. Therefore, the voltage gain of this circuit is just a trifle less than 1.

Current in the emitter circuit is just about equal to that in the base circuit multiplied by the beta of the transistor. Consequently, the power gain of this circuit, equal to the product of the current and voltage gains, is also just about equal to beta.

This circuit is very useful. Its high input impedance presents a negligible load to a signal source as well as to a resistor that is

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

in the collector circuit of a common-emitter stage that may be preceding this circuit.

In conventional circuits, one common-emitter stage will follow another. The second stage may excessively load the collector circuit of the first stage. To avoid this, a common-collector circuit can be inserted between the two stages. Not only is its high-input impedance important here, but its low output impedance is also of significance. This low impedance feeds the base circuit of the second stage. Because the output impedance of the emitter follower is low compared to the input resistance of the base circuit it is feeding, just about all signal present across the emitter resistor of the emitter-follower will be across the base-emitter circuit of the succeeding stage.

COUPLED STAGES

As I just mentioned, there can be more than one transistor in a single circuit. An arrangement showing a two stage amplifier using two common-emitter transistor circuits is in Fig. 8-13. Signal is fed to Q_1 and is amplified. Because the load in its collector circuit is R_1 in parallel with that presented by the base circuit of Q2, the voltage gain of Q_1 is the equivalent resistance of the parallel combination of these resistances divided by R_{E1}. Similarly, the load in the collector circuit of Q_2 is R_L in parallel with R_2. Gain of Q_2 is the resistance of this parallel combination divided by R_{E2}. The gain of the overall circuit is the product of the gains of the two transistors. This gain is reduced somewhat by the presence of R_{In}.

Note that a capacitor, C_2, is used between the two transistors. It lets the ac signal pass from the output of Q_1 to the input of Q_2,

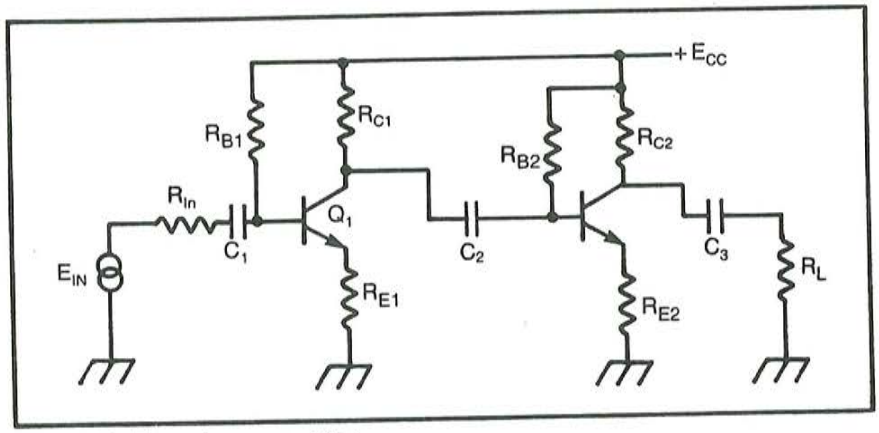


Fig. 8-13. Two-stage amplifier.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

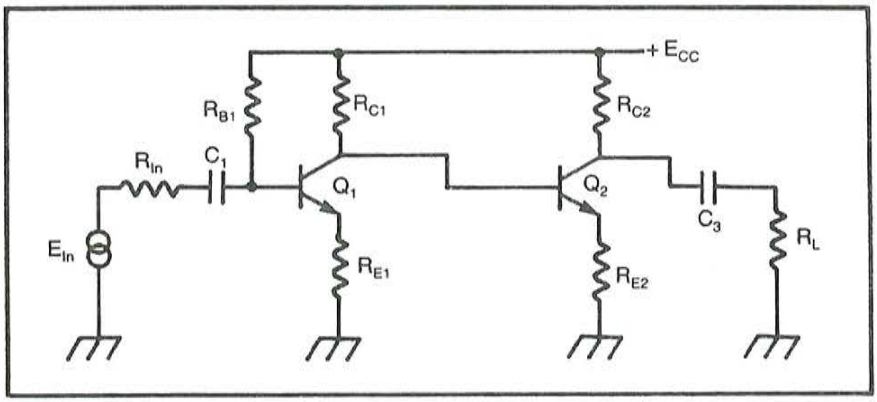


Fig. 8-14. Direct-coupled amplifier.

Note that a capacitor, C_2, is used between the two transistors. It lets the ac signal pass from the output of Q_1 to the input of Q_2, but it isolates the dc voltages of the two devices. In this way, both transistors can be biased independently. Capacitors, unfortunately, do not pass the low frequencies as well as they do the highs. Direct-coupling methods are therefore used where very low frequencies or even dc must be amplified. An arrangement showing this is shown in Fig. 8-14. Here, current flows through R_1 to the collector of Q_1 as well as to the base of Q_2.

Emitter followers were described as presenting a high impendance to the input signal and a low impendance to the load. They are shown as being used in this fashion in conjunction with a voltage amplifier in Fig. 8-15. Here, the ac input is fed to Q_1. Because it is an emitter follower, its high resistance in the base circuit is a negligible load on the ac input signal. The output from Q1 remains fixed at almost the magnitude of the ac input voltage. This voltage is fed to the base circuit of Q_2 and amplified by that stage.

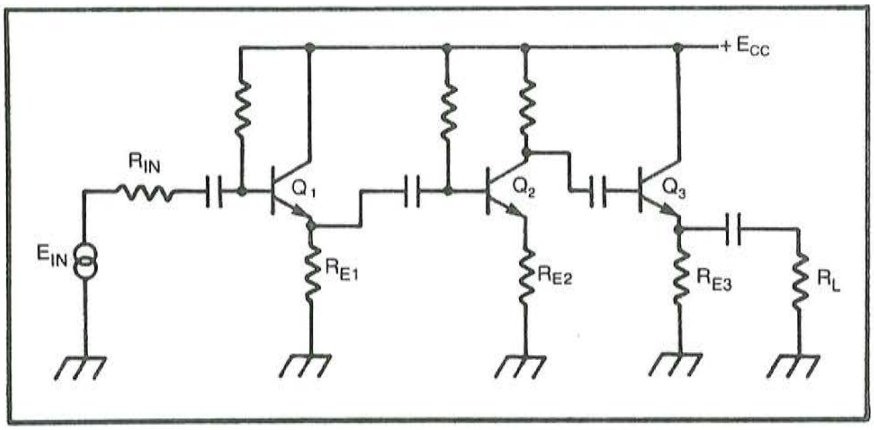


Fig. 8-15. Some methods of putting emitter followers to good use.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

Because of its high input impendance, emitter-follower Q_3 does not load the output of Q_2. It does present a low impendance to R_L. Consequently, R_L has little or no effect on the size of the voltage developed across this load.

DARLINGTON PAIRS

The common-collector arrangement produces a specific input impedance when a particular resistor is used in the emitter circuit. This impedance is usually quite high, but there are instances where an even higher input impedance is desirable. Two emitter followers can be used to accomplish this goal. A typical circuit is in Fig. 8-16 and it is referred to as a *Darlington pair* or *Darlington amplifier.*

The resistance seen between the base and ground at Q_2 is equal to the resistance between the emitter and ground of Q_2 multiplied by its beta. In a similar fashion, the base-to-ground resistance at Q_1 is its emitter-go-ground resistance multiplied by its beta. Since the emitter-to-ground resistance of Q_1 is equal to the beta of Q_2 times its emitter-to-ground resistance, the resistance presented at the base of Q_1 is the emitter-to-ground resistor at Q_2 multiplied by the product of the betas of the two transistors. This resistance is, of course, in parallel with R_B.

In a similar fashion, the resistance presented by the input circuit to R_L is equal to the equivalent resistance of R_{In} in parallel with R_B divided by the product of the betas of the two transistors.

NOISE

All amplifier circuits have problems with interference. In the

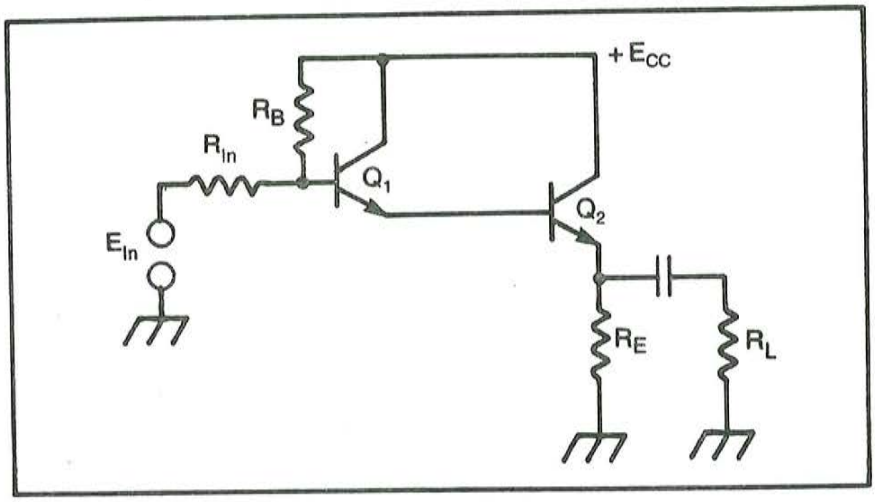


Fig. 8-16. Darlington circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

ideal case, only the input signal would be amplified and only this signal would appear at the output. But this aim is seldom achieved. There is a lot of random audio noise or radio frequency interference present in the air surrounding the amplifier. An amplifier will pick up some of the noise and amplify it. If the noise level is substantial, it will be heard in the background behind the amplified signal.

Transistors are not perfectly noise-free. Like others, they generate some background noise. The noise developed at the output of an amplifier is related to the quality of a particular transistor used in a circuit as well as to the quality of the passive components. This is in addition to the noise picked up in the air around the amplifier.

In order to determine the amount of signal at the output of a circuit with respect to the noise, a signal-to-noise ratio is used. First the output signal voltage is measured. Then the signal is shorted or removed from the input of the amplifier so that no signal is amplified. Only the noise voltage remains at the output and is measured. This relationship between the signal and noise voltages at the output is known as the *signal-to- noise ratio*. The voltage ratio is usually expressed in terms of *decibels* or dB where the larger number is the most desirable figure. Table 8-1 shows how decibels are related to voltage ratios.

For example, assume the two voltages measured at the output of an amplifier are 10 volts of signal and 1 volt of noise. The signal

Table 8-1. Decibel Notation for Voltage Ratios.

dB	Voltage Ratio
0	1:1
1	1.1:1
2	1.3:1
3	1.4:1
6	2:1
7	2.2:1
10	3.2:1
12	4:1
13	4.5:1
14	5:1
17	7:1
20	10:1
40	100:1
60	1000:1

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

to noise voltage ratio is 10:1. Checking this in Table 8-1, the ratio can be expressed as 20 dB.

Specifications of amplifiers usually list the signal-to-noise ratio in dB. Let us say the specification calls for 40 dB. By checking the numbers on the chart, you can see that the signal voltage is 100 times greater than the voltage of the noise.

But what are you to do if the ratio in dB is not listed on the chart? You can simply apply the rule that when you multiply numbers of voltage ratio; you must add the numbers in dB.

Assume that the specification calls for a signal-to-noise ratio of 65 dB. Looking at the table, you see only 60 dB. There is no 5 dB to add to it, for a total of 65 dB. But you can add 2 dB and 3 dB to the 60 dB for a total of 65 dB. The voltage ratio is the product of the ratios indicated by the dB numbers. Consequently, the signal to noise voltage ratio is (1.3/1) (1.4/1) (1000/1) = 1820/1 = 1820:1.

In a similar fashion, if you know the voltage ratio, you can divide it by other numbers to determine the ratio in dB. If this ratio happens to be 11,000:1, you can separate the number into the product of three numbers. These are 11,000 = 1000 × 10 × 1.1. The sum of the equivalent numbers in dB is 60 dB + 20 dB + 1 dB = 81 dB. If the original ratio cannot be divided into an exact number of terms, you can estimate the actual number of dB represented by that ratio, through use of approximations to the actual multipliers.

Db notation is not only useful only as an indicator of the signal-to-noise ratios. It is also useful in applications where gain of an amplifier must be different at different frequencies. For example, the frequency response of a phonograph amplifier which amplifies the output from a magnetic cartridge, is not flat. Its output should be about 14 dB less at 10,000 Hz than it is at 1000 Hz. To see if the amplifier is performing properly, you would feed 1000 Hz to its input and note the output voltage. Then you would feed 10,000 Hz to its input instead of the 1,000 Hz, and once again note the output voltage. The ratio of the two output voltages when expressed in decibels, should be 14 dB. Using Table 8-1, you can determine that the voltage ratio should be about 5:1. Filters are used to establish this gain-difference situation.

FILTERS

There are basically four types of filters used in different applications. One type, the *low pass*, is designed to reduce the output

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

voltage or amplifier gain of the high-frequency end of a band with respect to the low frequencies. An alternate type is referred to as a *high-pass* filter. It reduces gain at the low frequencies compared to the higher frequencies. There are also *bandpass* filters that permit a narrow group of frequencies to pass relatively easily through a circuit while all other frequencies are attenuated, and *band-rejection* filters that attenuate a narrow group of frequencies while letting all others pass freely. In this discussion, I will be discussing primarily high- and low-pass filters.

Modern high- and low-pass filters are constructed from resistors and capacitors. Circuits using these components are in Fig. 8-17. The basic filters are shown in Fig. 8-17A and B. If the *rolloff* or loss in gain at one end of the band with respect to the second end is not fast enough, then several of these filters can be used in the circuit. Arrangements of this type are shown in Fig. 8-17C and D.

In some applications, the rolloff will start at some low frequency and continue to a specific high frequency. The gain should remain fixed at that high frequency. A circuit doing this is shown in Fig. 8-17E. The way the gain varies in each of these arrangements is shown in Fig. 8-18. The letter associated with each graph is for the circuit with the same letter in Fig. 8-17.

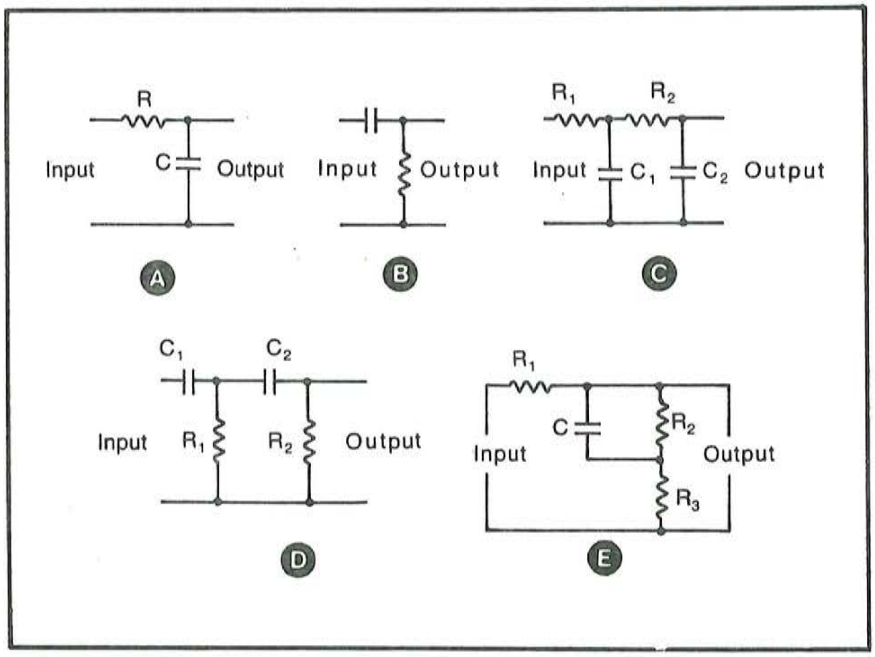


Fig. 8-17. Filter circuits. A. Low pass. B. High pass. C. Fast-rolloff low pass. D. Fast-rolloff high pass. E. Filter with rolloff over a limited frequency range.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

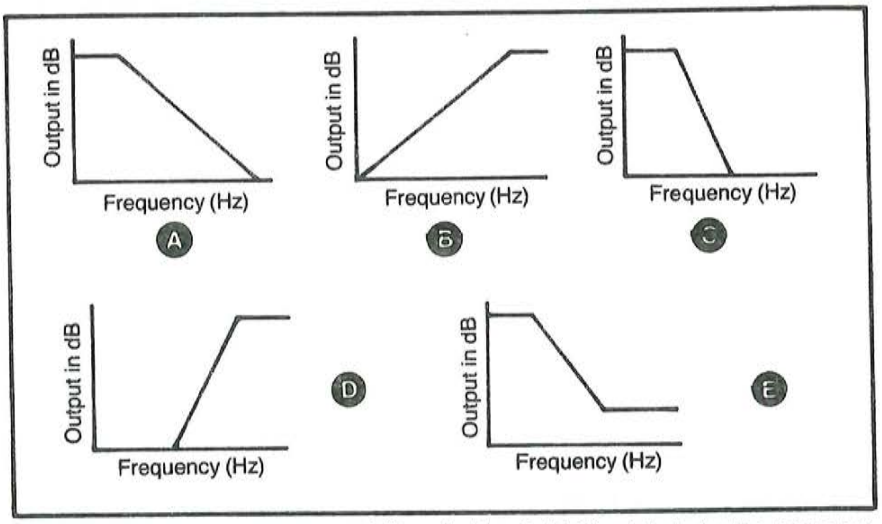


Fig. 8-18. Frequency response of filters in Fig. 8-17. The labels for the response curves are identical with the ones used for the filters.

Many different filter types and arrangements exist. To establish the frequency characteristic curve needed for a phonograph playback amplifier, the RC circuit in Fig. 8-17A can be placed between two amplifier stages. This is shown in Fig. 8-19A.

The required frequency-response curve for a phonograph record reproduction can be more accurately approximated through use of a filter network in a feedback loop. This is shown in Fig. 8-19B. Here, the signal is fed to the amplifier. All frequencies are amplified equally of Q_1 and Q_2 so that the gain over the entire band is the same. Ideally, you would be able to see this *linear* response (unchanging gain over the entire band) at the collector of Q_2 as a fixed output at all frequencies. However, the output does vary with frequency. If the R_1-R_2-C_1 network were not in the circuit, the response would be linear and gain would be the same at all frequencies. But it is there to reduce the gain of the overall circuit at the high frequencies.

Output from the collector of Q_2 is fed through a resistor/capacitor network back to the emitter of Q_1. Because of the capacitor in the feedback circuit, this network passes the high frequencies more readily from the output to Q_1 than the low frequencies. All frequencies passed by this network appear across R_{E1}. Because of C_1, there are more high frequencies here than low frequencies.

In Fig. 8-13, the input signal was applied between the base of Q_1 and ground. Only the portion of E_{In} that appeared across the input of the transistor between its base and emitter was amplified. Since a portion of the signal was across R_{E1}, R_{E1}, limited the

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

amount of signal that was between the base and emitter. Therefore, R_{E1} was an important factor in determining the gain of the transistor Q_1, which is equal to R_1/R_{E1}. The ac voltage developed across R_{E1} due to E_{In} affects the amount of signal appearing across R^{1}.

Now apply this to the circuit in Fig. 8-19B. A portion of the output is fed back and appears across R_{E1}. This voltage must be subtracted from E_{In} in order to determine the voltage that is between the base and emitter of Q_1 for amplification. The signal voltage left for application to the base-emitter circuit of Q_1 and amplified is E_{In} minus the voltage across R_{E1}. That difference is

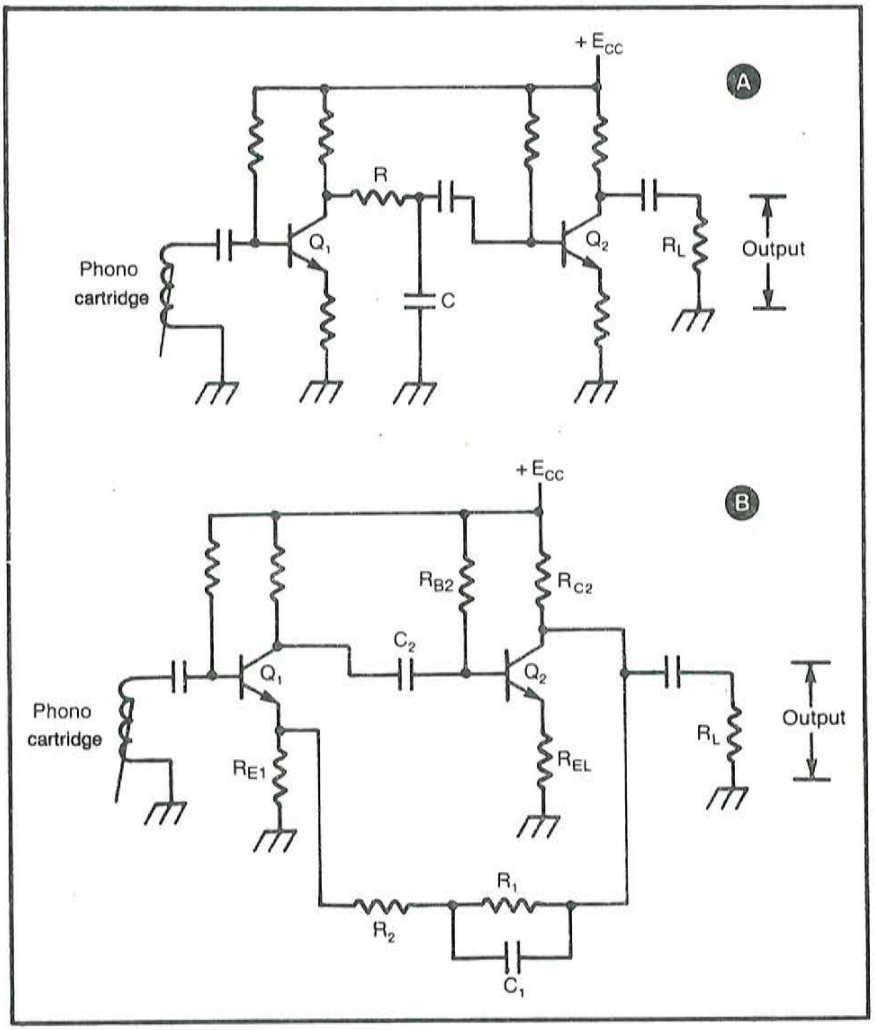


Fig. 8-19. Amplifier for signals from phono cartridge. A. Approximated response by using the circuit in Fig. 8-17A. B. More accurate response using a feedback circuit.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

across the base-emitter input terminals of the transistor. It is this difference voltage that is amplified by the circuit.

Because more high frequencies are fed back from the output than are low frequencies, fewer high frequencies remain between the base and emitter at the input terminals of Q_1 after the feedback voltage is subtracted from E_{In}. All frequencies are amplified linearly by the circuit. Thus, the same voltage ratio is at the output of the amplifier as was established at the input due to the presence of the $R_1/R_2/C_1$ filter network in the feedback circuit.

It is also desirable that the very low frequencies be attenuated for proper reproduction of the recorded signal. This is accomplished by the combination of C_2 with the resistance at the base of Q_2. This resistance is the parallel combination of R_{B2} with resistance reflected from the emitter circuit of that transistor. Together, C_2 and this parallel resistance combination, form the high-pass circuit shown in Fig. 8-17B.

The feedback and conventional filter arrangements shown here are used for phonograph preamplifiers, but they can be used equally well for tape recorder amplifiers playback amplifiers, rolloff of the signal on the fm band, and so on.

BIAS CIRCUITS

In the discussion of the circuit in Fig. 8-8, I noted that the base idling current is equal to $(E_{CC} - 0.7)$ volt/$(R_B + \beta R_E)$ ohms. This is true if the base-collector junction does not conduct any current from E_{CC} through R_C and the collector into the base. If this current should exist, (and there is always some current flowing here), it is known as the *leakage current*. The symbol for this is I_{CB0}. This leakage current has nowhere to go from the base but into the base-emitter junction. After passing through this junction, the current is multiplied by beta. This current is equal to βI_{CB0}, flows in R_E and R_C and has been assigned the symbol I_{CE0}.

The dc voltage developed across R_C is due primarily to βI_B, where I_B is the dc current flowing into the base through R_B. This collector current is used to set the quiescent voltage at the collector at about one-half of E_{CC}. If I_{CE0} is substantial, the collector current is equal to that leakage current added to βI_B. This added current upsets the quiescent voltage that is normally at the collector. The situation can be improved by using different circuits than the one shown in Fig. 8-8 to make I_{CE0} substantially less than βI_B. A number of different bias circuits have been developed. Some of these are shown in Fig. 8-20. These can be used to reduce I_{CE0} for

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

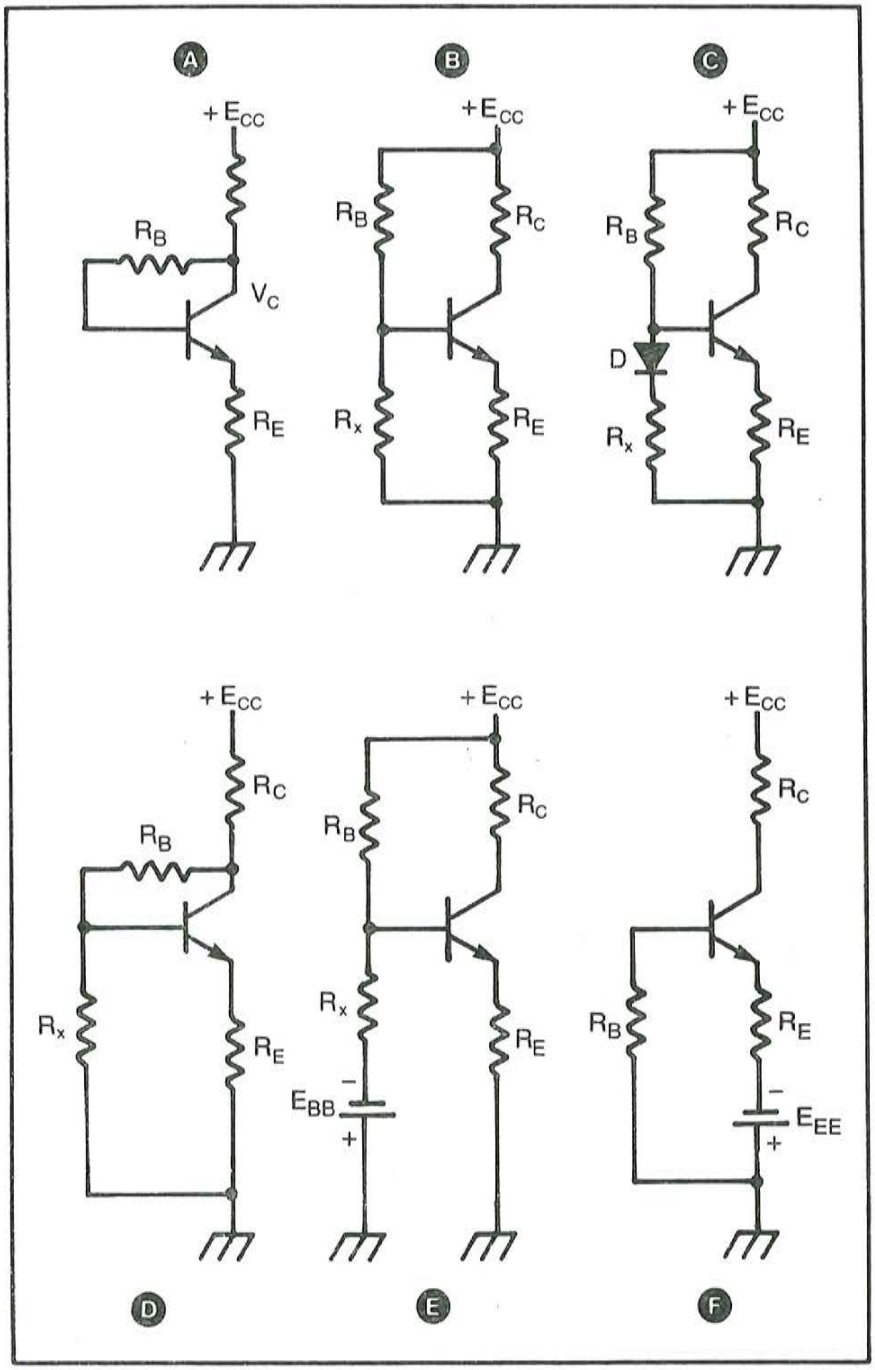


Fig. 8-20. Bias arrangements used in electronic equipment.

fixed values of I_{CB0}. The diagrams shown here are based on the common-emitter circuit, but the circuits can be used to provide equivalent characteristics in any of the other situations.

Transistor idling and leakage currents drift with temperature.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

In addition to helping reduce the effects of I_{CB0}, the circuits shown in Fig. 8-20 are also used to reduce I_C variations with temperature.

In Fig. 8-20A, R_B is connected to the collector of the transistor rather than to the power supply, E_{CC}. Base current is equal to the dc voltage at the collector, V_C, minus the 0.7 volt across the base-emitter junction. This difference is then divided by $R_B + \beta R_E$. The base current is determined using the same methods as in the original circuit, except now V_C is used as the voltage in the equation rather than E_{CC}. Ac voltage gain is slightly lower here than in the original circuit because some signal is fed back from the collector to the base through R_B.

Voltage E_{CC} is divided between R_B and R_x in Fig. 8-20B before being applied to the base. In Fig. 8-20C, a diode is added in series with R_x. This diode-resistor combination is in parallel with the series circuit consisting of the diode formed by the base-emitter junction of the transistor and resistor R_E. This circuit helps to compensate for changes in the base-emitter junction voltage with temperature. If the temperature change is such as to cause the base-emitter voltage of the transistor to change, the voltage across the diode should change by the same amount. Because these changes are alike, the voltages remaining across R_x and R_E remain fixed. This keeps the transistor bias current from varying with temperature.

In Fig. 8-20D, you see a combination of circuits A and B. Here, R_B is connected to the collector rather than to $+E_{CC}$, as it was in Fig. 8-20B.

Two voltage supplies are used in the circuits in Fig. 8-20E and F. In E, the voltage developed across R_x must be greater than E_{BB} if the transistor is to conduct. Otherwise, the base-emitter junction is reverse biased because the base is negative with respect to the emitter. In F, the V_{EE} source supplies voltage with the proper relative polarity to the base and emitter to turn on that junction.

There are many variations on these circuits. The most common ones have been described here.

POWER AMPLIFIERS

Power gain is one of the characteristics that I discussed earlier for the various transistor circuits and is an important factor. Power is frequently required at the output of an amplifier. Power is necessary to drive a loudspeaker, feed signal to a head on a tape recorder, light a bulb when an amplifier is turned on, and so on.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

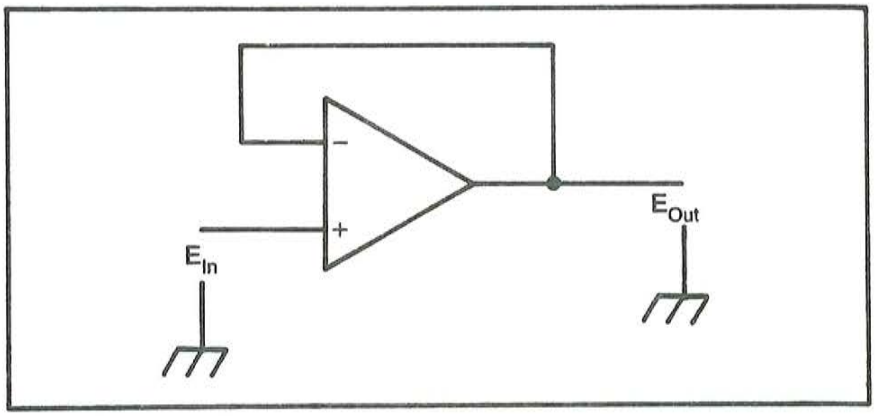


Fig. 10-14. Voltage follower.

and so on. Typical circuits for each of these applications are shown in Fig. 10-15. The relationships between the inputs and outputs are shown in the figure.

RADIOS

Oscillators are typically built into modern radios. These oscillators use positive feedback circuits. Feedback circuits are also involved when information about the signal strength is fed back from one section of the electronics in the radio to another section. This information is obtained at the audio portion of the circuit and is fed back to amplifiers nearer the input stage of the radio. The data fed back is in such form as to keep modifying the overall gain of the radio as the magnitude of the received radio signal changes. In this way, the audio output from the radio remains relatively constant despite changes in the strength of the received signal. There are also negative feedback circuits in the audio amplifier portion of the radio.

Amplitude Modulation

The frequency of radio signals varies from a low 20,000 Hz up to many billions of Hertz or gigahertz. Here, we are only concerned with the broadcast band which ranges from 535 kHz to 1605 kHz. A different radio frequency is transmitted in this range by each station. Due to the characteristics of the transmitted signal, an individual frequency is not sufficient for each radio station. Each station is therefore allotted a range of frequencies for its use. This range can be as low as plus and minus 5000 Hz around its assigned center frequency, or may be as high as plus and minus 10,000 Hz.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

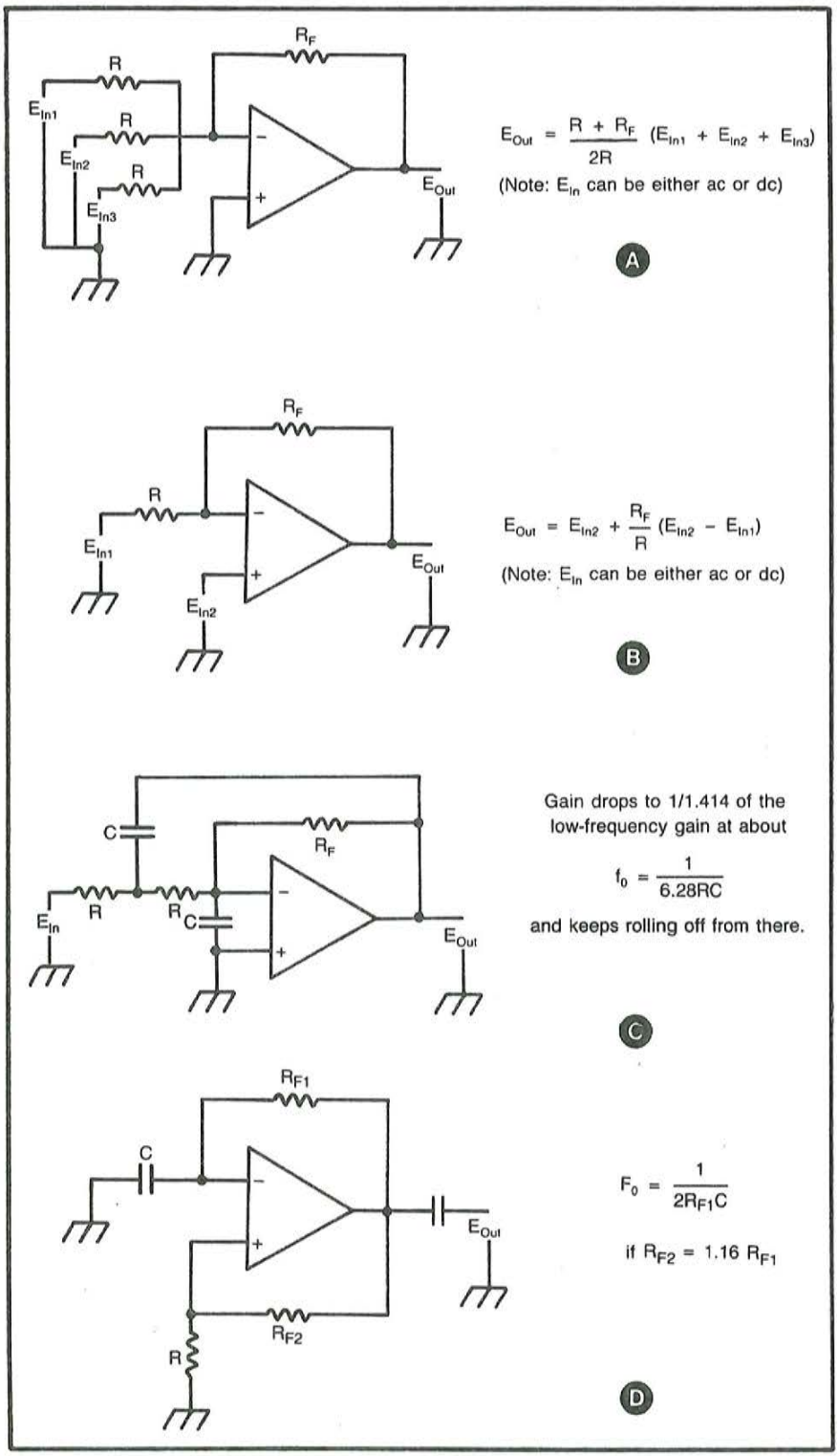


Fig. 10-15. Circuits using op amps. A. Adder. B. Subtractor. C. Low-pass filter. D. Oscillator.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

In a few isolated cases, it ranges up to plus and minus 15,000 Hz. This permitted range of frequencies or *bandwidth* minimizes changes of interference between stations broadcasting on frequencies that are close to each other.

Whatever radio or rf frequency is used, it serves no function by itself. It is not audible because it is about 20,000 Hz, the top of the audio band. And even if you could hear it, it wouldn't sound like much because there would be no music or speech if the station transmitted only the radio frequency or carrier wave. For the radio station to perform its function, intelligence must be transmitted along with the rf. This "intelligence" is speech or music. The radio frequency carries this information to the radio receiver. At the receiver the signal is separated from the rf, magnified by an audio amplifier, and fed to a loudspeaker.

The process of modifying the rf to carry the speech or music, is known as *modulation.* There is *amplitude modulation* or am where the amplitude of the carrier is changed by the size of audio applied to the modulating circuit. There is also *frequency modulation* or fm, where the carrier frequency changes with the amplitude of the applied audio. There is *phase modulation*where the phase of the carrier frequency is shifted in step with the magnitude of the applied audio. There are also *pulse modulation,* combinations of the different types of modulation, and so on. Here, I will concentrate on amplitude modulation as applied to the broadcast band.

An unmodulated rf transmitter broadcasts sine waves at its assigned carrier frequency. This is represented in the diagram marked rf in Fig. 10-16. A low frequency or audio signal is applied to the rf transmitter. This is shown by the sine wave designated as *audio* in the figure. When the two signals are combined, you have an rf with amplitude variations. The amplitude variations are in step with the applied audio, as shown in the section of the drawing labeled *rf modulated by audio.* Note the fluctuations of the modulated rf around the 0-volt level. If you add the plus and minus voltages present above and below zero, you will get a total of zero volts. But there is rms power in the signal just as there is rms power in an ordinary sine wave.

Modulated signal flows through the air. It is intercepted by a radio antenna or by a coil inside the radio. The received signal is processed by circuitry inside the radio, the audio is separated from the rf and applied to an amplifier and loudspeaker. But we are getting ahead of ourselves!

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

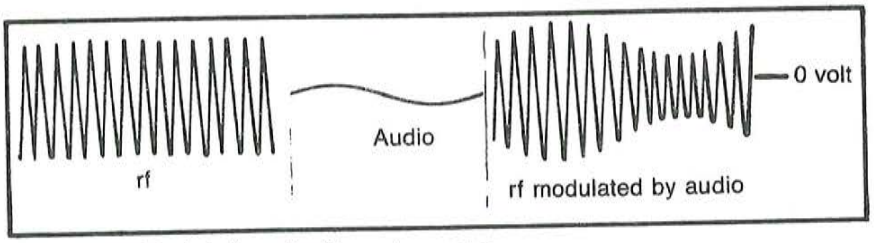


Fig. 10-16. Modulating rf with a sine wave.

Superheterodyne Radio

Modern radios utilize the *heterodyne* principle in their receive circuitry. Musically inclined readers have witnessed heterodyning when two different, very loud musical notes were played at the same time. You not only heard the two individual notes, but also two additional notes. The frequencies of the additional notes were equal to the sum and the difference of the two original notes. Superheterodyne radios utilize this heterodyne phenomenon in their circuits, but here the two rf signals that are combined produce frequencies other than audio tones.

A block diagram of a radio is shown in Fig. 10-17. Modulated rf is intercepted by the antenna, amplified in the *rf amp* and fed to a *mixer.* A local oscillator at the mixer is tuned to a frequency that is 455 kHz above that of the received rf. Output from the oscillator is fed to the mixer along with the amplified rf. The two signals are combined in the mixer. Just as in the case when the two audio notes were combined, four signals are at the output of the mixer. These are the received rf, the oscillator frequency, and the sum of the two frequencies and the difference of the two frequencies. For example, assume that a radio station broadcasting on 1000 kHz is being received. Because the local oscillator would be set to supply a frequency of 455 kHz above the frequency transmitted by the radio station, it oscillates at 1455 kHz. When the 1000 kHz is mixed ith the 1455 kHz, the heterodyned outputs from the circuit are at 1000 kHz, 1455 kHz, 1000 kHz + 1455 kHz = 2455 kHz and 1455 kHz − 1000 kHz = 455 kHz. Because the oscillator frequency is always 455 kHz above the frequency of the received rf, there is always a difference frequency of 455 kHz available. Because of this, all other frequencies at the output of the mixer are discarded. Only the 455 kHz is passed by the i-f or intermediate *frequency* amplifier to the balance of the i-f circuit. Because the rf used when forming this difference frequency is modulated by audio, the 455 kHz is modulated by the same audio.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

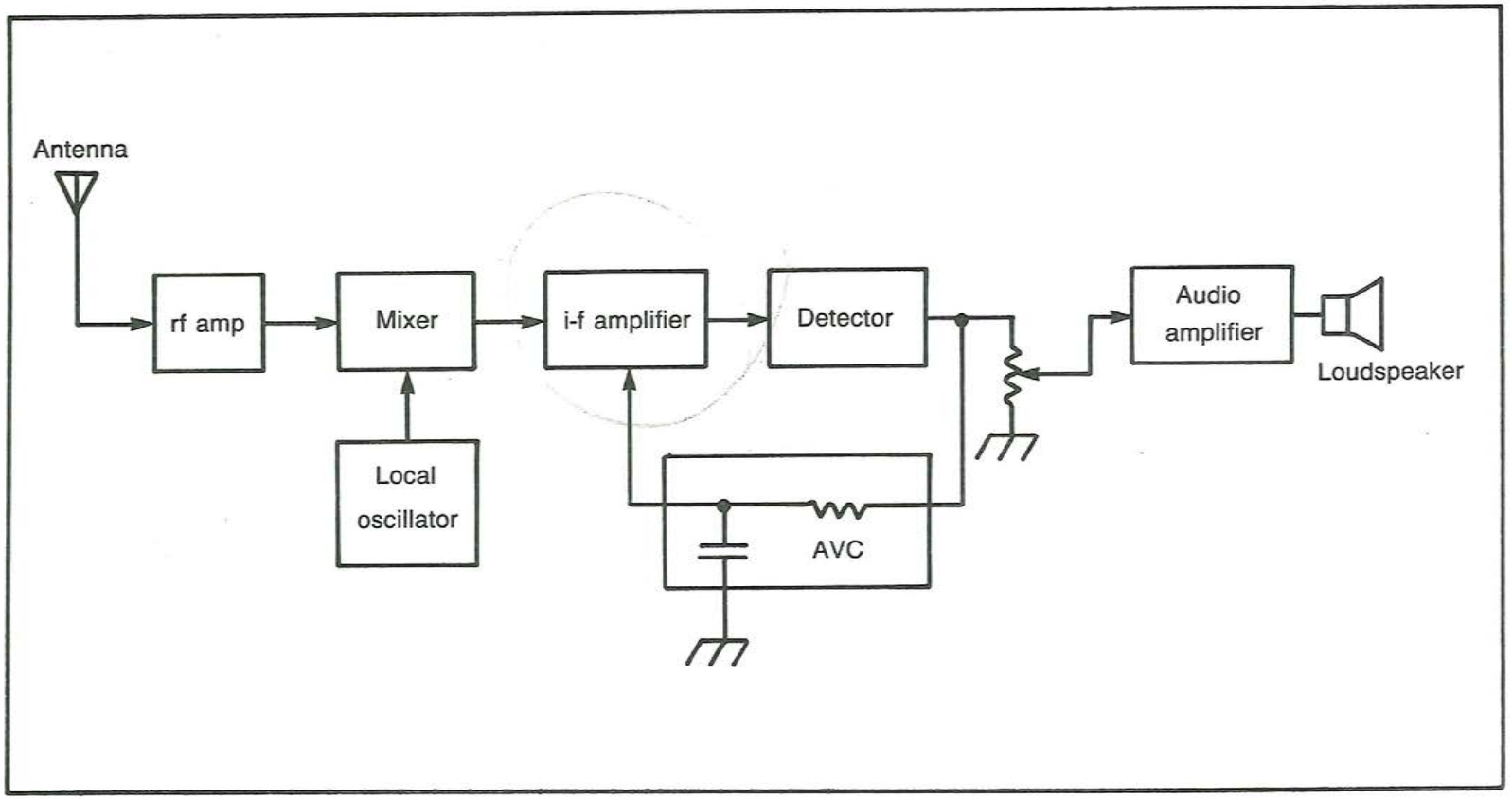


Fig. 10-17. Block diagram of a superheterodyne radio.

Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc. EX-1043

The modulated i-f signal is detected. Here the audio is separated from the rf, amplified in an audio amplifier, and applied to a loudspeaker.

The output from the detector is actually half of the modulated signal shown in Fig. 10-16, either the upper half of the signal above the 0-volt line or the lower half that is below the 0-volt line. When only one-half of the waveform is present as it is here, then the total voltage of the modulated signal is no longer equal to zero. The voltage of the upper or lower half of the modulated rf has an amplitude that varies in step with the audio that modulated it. If this signal were analyzed mathematically, you would find that there are actually rf and audio components present in the waveshape. To get only audio from the overall signal for application to the power amplifier and loudspeaker, the rf from the output of the detector is filtered and only audio remains. Audio is passed through a variable resistor or volume control and then applied to the input of the audio amplifier.

The magnitude of the rf output from the detector depends upon the size of the signal applied to the input of the radio circuit. To compensate for rf signal level variations, a circuit is provided which first passes the rf in the detected signal through a resistor and then applied to a filter capacitor. Because this signal is either above or below the 0-volt line, it has only one polarity and is an effectively pulsating dc. The pulses are eliminated through use of the filter capacitor in what is known as *avc circuit.* The magnitude of the filtered dc voltage is proportional to the strength of the received signal. The dc voltage is applied to the i-f amplifier to again bias the transistors in this circuit. This change of bias affects the gain. If the applied filtered voltage from the detector is relatively low, the overall gain of the rf amplifier is higher than it is when the filtered voltage is high. Because the gain is changed with changes in the rf output voltage from the detector, the output from the audio circuit remains at a fixed level regardless of the magnitude of the input rf signal. This *automatic volume control* (or *automatic gain control*) circuit is thus a type of feedback arrangement.

Circuit Description

No rf amplifier stage is included in the actual circuit of the radio shown in Fig. 10-18. Rf is fed directly from the secondary winding of the antenna coil to mixer Q_2. Q_1 is also in the local oscillator circuit. L_S, L_P, C_P, and Q_1 make up the oscillator. Signal developed across a portion of the oscillator tank circuit, C_P-L_P is fed to the

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

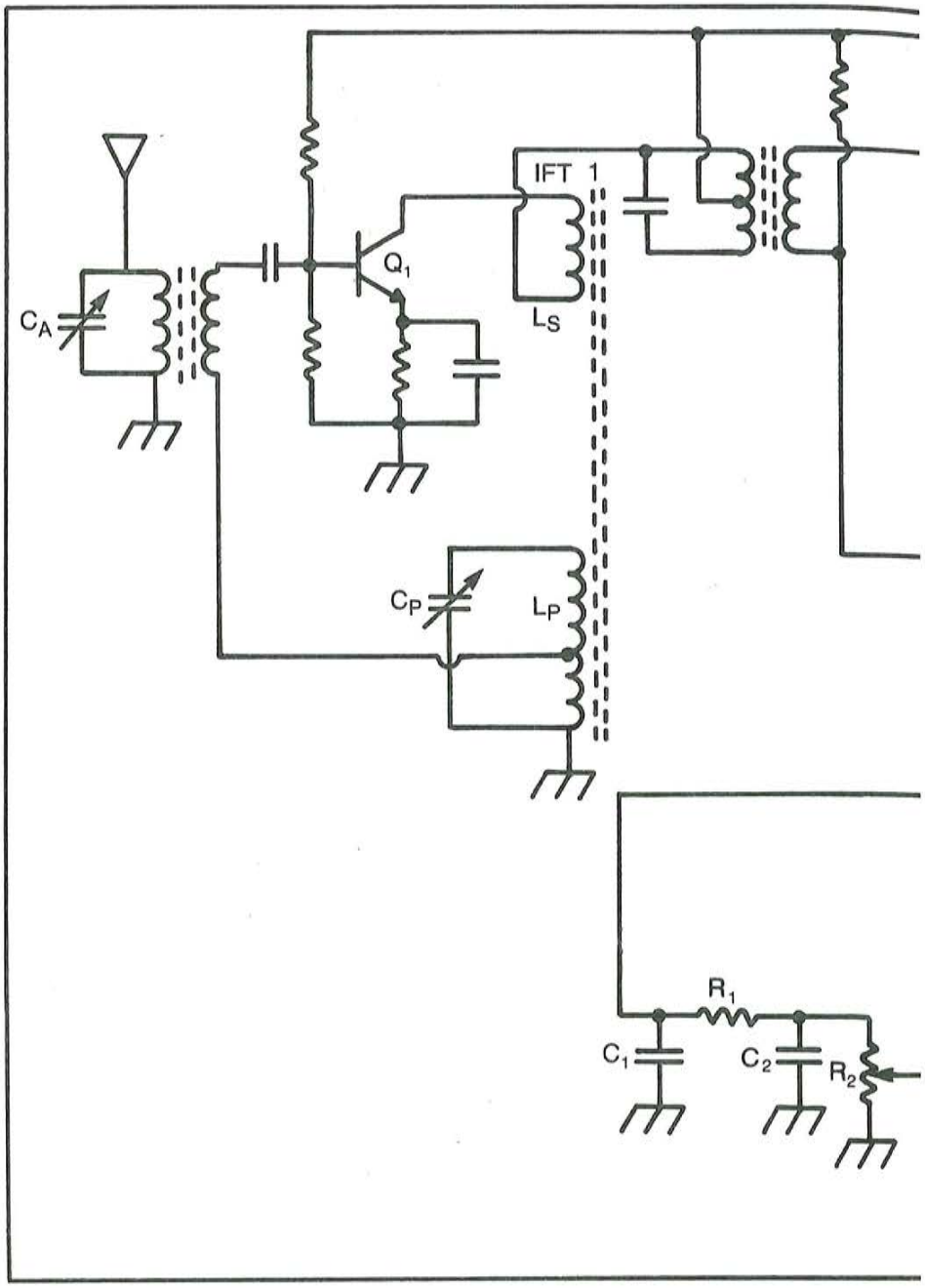
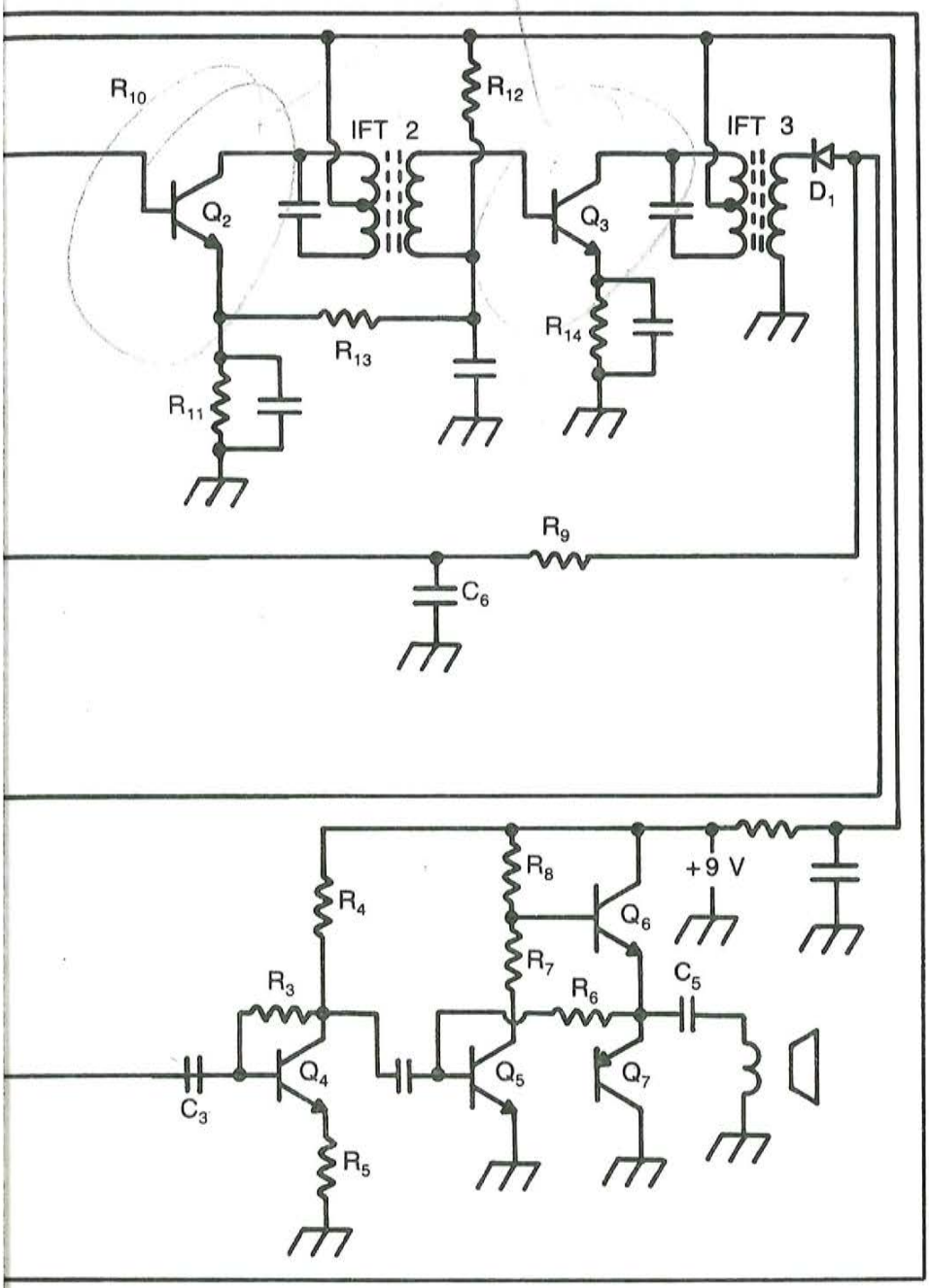


Fig. 10-18. Superheterodyne radio circuit.

secondary winding of the antenna coil. The total signal is amplified by Q_1 and applied through L_S to the primary of intermediate frequency transformer IFT-1 and is tuned to 455 kHz.

The local oscillator is in a feedback circuit extending from the input of Q_1 to its output. Signal from the output is fed back to the

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.



input. The local oscillator voltage at the input of Q_1 is amplified by this transistor. The amplified output is developed across L_S and is led from there into L_P in the resonant tank circuit. This circuit is used to set the oscillator frequency. A portion of the tank circuit voltage is fed back to the secondary of the antenna coil. From here

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

it is amplified by Q_1. The amplification and feedback sequence keeps repeating itself. Because of the wiring of the various windings, phases are adjusted so that this circuit oscillates.

Capacitor C_A is in a resonant circuit which involves the primary winding of the antenna coil. The resonant frequency of this circuit is that of the radio station being received. C_A is mounted on one shaft with C_P so that when C_A is adjusted to receive a particular station, C_P is simultaneously adjusted to tune the oscillator circuit (involving resonant circuit C_P - L_P) to a frequency that is 455 kHz above that of the received rf signal.

The modulated 455 kHz difference frequency is selected from the four available frequencies by the various IFTs at the output of Q_1 and amplified by i-f amplifiers Q_2 and Q_3. Diode D_1 is connected to the secondary winding of IFT-3. It detects the signal. The way it's shown here, only the negative or bottom half of the audio-modulated rf passes through the diode. The R_1-C_2 network filters the rf from this half of the signal, so only audio remains for application to the level control, R_2, and to the audio amplifier consisting of Q_4, Q_5, Q_6, and Q_7.

Q_4 is an ordinary voltage amplifier. R_5 is a feedback resistor in the emitter of the transistor, and R_3 feeds voltage back from the collector of Q_4 to its base.

Q_5 is also a voltage amplifier. Besides amplifying the voltage, it also drives output stages Q_6 and Q_7. This is similar to the power amplifier circuit shown in Fig. 8-25 except that the bootstrapping circuit there using C_1 is not required here. Transistors Q_4 and Q_5 in that circuit have been omitted here. For a portable radio, Q_2 and Q_3, in the circuit in Fig. 8-25, would supply sufficient drive for a small loudspeaker so that Q_4 and Q_5 are not needed. In Fig. 8-25, Q_2 and Q_3 are in a circuit that is identical to the one involving transistor Q_6 and Q_7 in Fig. 10-18. Note the feedback from the output load to the base of Q_5 through resistor R_6 in the radio circuit.

Getting back to the detector circuit, the modulated rf with negative polarity is fed from the detector through R_9 and applied to filter capacitor C_6. This dc is fed from there to the base of Q_2 through the secondary winding of IFT-1. Without the voltage that is across C_6, Q_2 is biased through the R_{10}-R_{11} resistors in the base-emitter circuit. This bias sets the maximum gain level of the stage, the gain is modified when the voltage developed across C_6 is applied to the bias circuit. The magnitude of this voltage affects the voltage gain of Q_2. Because this avc voltage varies with the strength of the received signal, it varies the gain of Q_2 in step with

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

the gain of the received rf. This is an attempt to keep the audio output at a fixed level regardless of the strength of the received rf.

The bias voltage for Q_3 is set by dc voltage at its base-emitter circuit due to the presence of resistors R_{11}, R_{12}, and R_{13}. But voltage across R_{11} varies with the avc voltage across C_6. Therefore, the voltage across R_{11}, and in turn the bias voltage for Q_3, is affected by the avc voltage. Thus, two transistors, Q_2 and Q_3, work together to maintain a fixed output level regardless of the variations in magnitude of the applied rf. Avc is accomplished through the feedback circuit using the rf that was originally converted to a specific negative dc voltage for this purpose.

EX-1043
Kangxi Communication Technologies (Shanghai) Co., Ltd. v. Skyworks Solutions, Inc.

