Specialty Transformers

26406-05

Steven F. Udvar-Hazy Center
National Air and Space Museum
Chantilly, Virginia
Mega-Projects Over $100 Million Award Winner
Hensel Phelps Construction Co.

26406-05

Specialty Transformers

Topics to be presented in this module include:

Overview

When a circuit is connected to the secondary winding of a transformer and an AC voltage is applied to the primary, induced current will flow through the secondary winding and any circuits connected to it. Specialty transformers apply the same basic fundamentals of transformer induction, but they use different coil arrangements and access points (taps) to obtain unique voltage levels at the transformer secondary.

The basic electrical frequency generated by power plants in the U.S. is sixty cycles per second (60 Hz), which graphically appears as a near perfect sinusoidal waveform on a scope meter. Most equipment or electrical loads are considered linear loads, meaning that they operate over the entire sine wave generated by sixty cycles. However, certain loads, such as fluorescent lamps and high-performance electronic equipment used in computers, operate on sharp, irregular pulses drawn from the sixty-cycle frequency. These types of loads are referred to as non-linear loads. The resulting effect on the sixty-cycle sinusoidal waveform caused by non-linear loads is a distorted wave, where distortion occurs in multiples of the basic sixty-cycle pattern. These harmonic currents can flow back to the source transformer, causing overheating and other problems. In installations where harmonics are a problem, the ampacity of the supply transformers must be derated, or a specially designed transformer must be used to avoid overheating.

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Objectives

When you have completed this module, you will be able to do the following:

1. Identify power transformer connections.
2. Identify specialty transformers.
3. Size and select buck-and-boost transformers.
4. Connect current and potential transformers.
5. Calculate and install overcurrent protection for specialty transformers.
6. Ground specialty transformers in accordance with *National Electrical Code®* (*NEC®*) requirements.
7. Size, install, and connect control, shielded, constant-current, and other specialty transformers.
8. Derate transformers to account for the effects of harmonics.

Trade Terms

Ampere turn
Autotransformer
Bank
Core loss
Eddy currents
Harmonic
Hysteresis
Impedance
Isolation transformer
Reactance

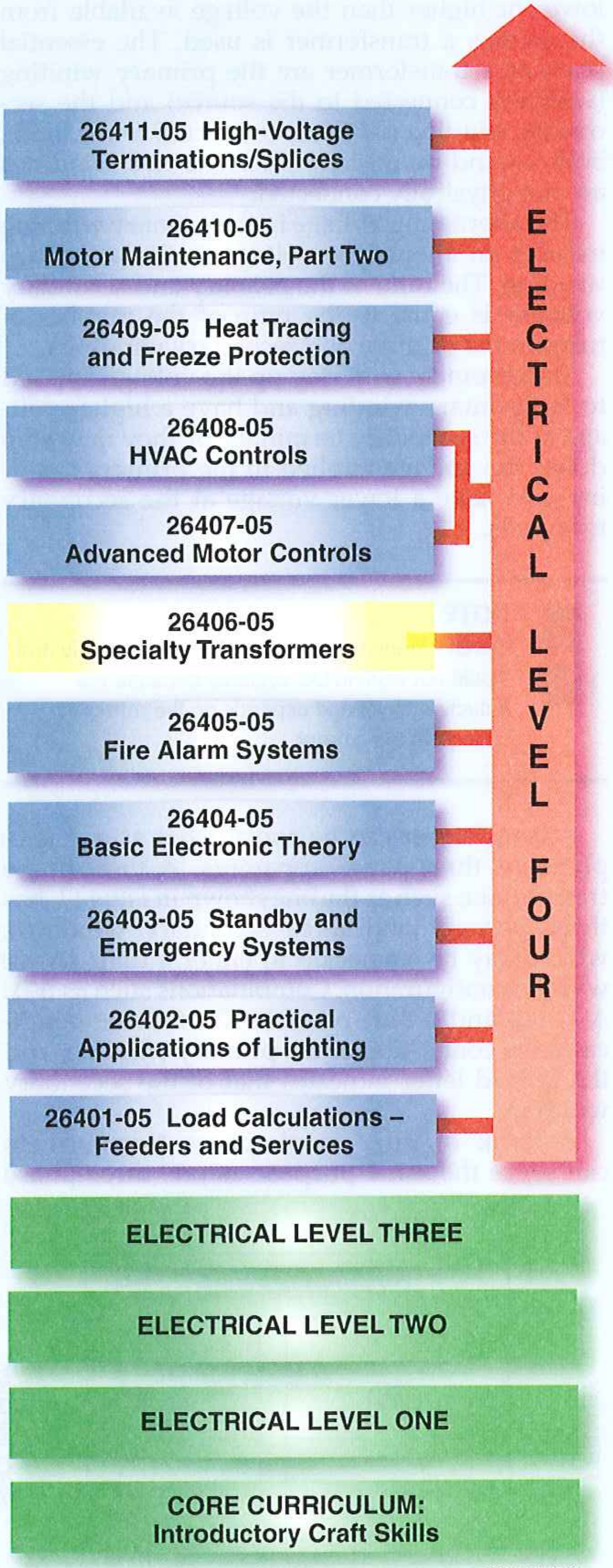
Required Trainee Materials

1. Pencil and paper
2. Appropriate personal protective equipment
3. Copy of the latest edition of the *National Electrical Code®*

Prerequisites

Before you begin this module, it is recommended that you successfully complete *Core Curriculum; Electrical Level One; Electrical Level Two; Electrical Level Three; Electrical Level Four,* Modules 26401-05 through 26405-05.

This course map shows all of the modules in *Electrical Level Four.* The suggested training order begins at the bottom and proceeds up. Skill levels increase as you advance on the course map. The local Training Program Sponsor may adjust the training order.



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1.0.0 ◆ INTRODUCTION

When the AC voltage needed for an application is lower or higher than the voltage available from the source, a transformer is used. The essential parts of a transformer are the primary winding (which is connected to the source) and the secondary winding (which is connected to the load), both wound on an iron core. The two windings are not physically connected.

The alternating voltage in the primary winding induces an alternating voltage in the secondary winding. The ratio of the primary and secondary voltages is equal to the ratio of the number of turns in the primary and secondary windings.

Transformers may step up the voltage applied to the primary winding and have a higher voltage at the secondary terminals, or they may step down the voltage applied to the primary winding and have a lower voltage at the secondary terminals.

NOTE

Transformers are applied in AC systems only and would not work in DC systems because the induction of voltage depends on the rate of change in the current.

A transformer can be constructed as a single-phase or three-phase apparatus. A three-phase transformer, such as the one shown in *Figure 1*, has three primary and three secondary windings, which may be connected in either a delta (Δ) or wye (Y) configuration. Combinations such as Δ-Δ, Δ-Y, Y-Δ, and Y-Y are possible. The first letter indicates the connection of the primary winding, and the second letter indicates that of the secondary winding.

A **bank** of three single-phase transformers can serve the same purpose as one three-phase transformer. The connections between the three primary windings and the three secondary windings are again Δ or Y, and they are available in all combinations.

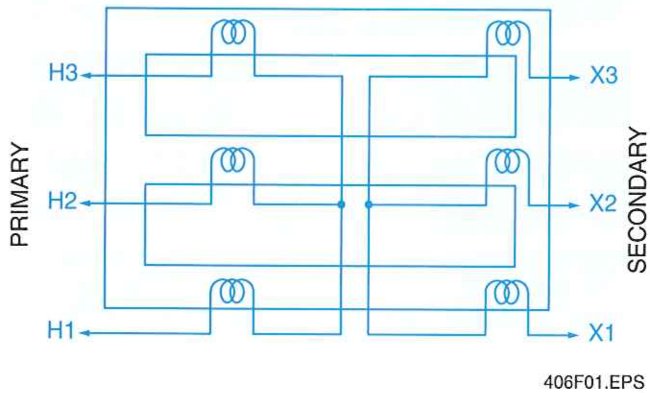

Figure 1 ◆ Typical three-phase transformer.

1.1.0 Types of Transformers

Large transformers used in transmission systems are called power transformers. They may step up the voltage produced in the generator to make it suitable for commercial transmission, or they may step down the voltage in a transmission line to make it practical for distribution. Power transformers are usually installed outdoors in generating stations and substations. The transformer shown in *Figure 2* is a liquid-filled power transformer with radiators that disperse the heat from the transformer.

Another type of transformer is the distribution transformer, which steps down the voltage at various points of a power distribution system for better utilization.

An **autotransformer** is a transformer with only one winding, which serves as both a primary and a secondary. Autotransformers are economical, space saving, and especially practical if the difference between the primary and secondary voltages is relatively small.

Three-winding, single-phase transformers have two secondary windings so that they can deliver two different secondary voltages.

In many applications of electrical measuring instruments, the voltage or current in the circuit to be measured is too high for the instruments. In such situations, instrument transformers are used to ensure safe operation of the instruments. An instrument transformer is either a current transformer, as

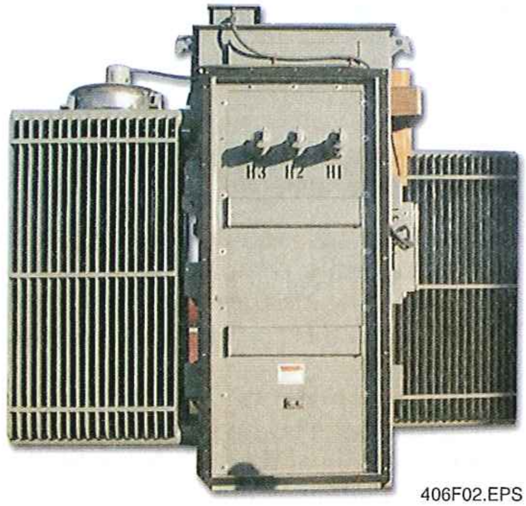

Figure 2 ◆ Typical liquid-filled, three-phase power transformer.

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Transformer Management Systems

Some manufacturers provide monitoring and diagnostic systems for large liquid-filled power transformers used in substations or in large industrial applications. These systems are used to obtain warnings of impending faults and as a predictor for scheduling maintenance shutdowns. The systems use data from sensors incorporated in the transformers. The sensors monitor the following conditions:

- Dissolved gas-in-oil
- Top and bottom oil temperature
- Gas pressure
- Ambient temperature
- Oil level
- Winding temperature
- Load and meter values
- Bushing activity

This data is transmitted via a network to a computer and used with IEEE or IEC analytical modeling software offline to access the condition of the equipment and diagnose impending failures. This includes moisture-in-insulation modeling, predictive insulation aging rate, cumulative aging, partial discharge activity, overflux (overvoltage), fault event recording, harmonic monitoring, cooling system efficiency, and other trending information.

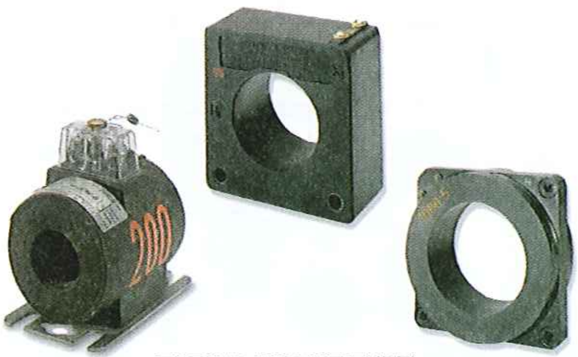
shown in *Figure 3*, or a potential (voltage) transformer, as shown in *Figure 4*. For example, if the current in a line is approximately 100A and the ammeter is rated at 5A, a bar-type current transformer with a current ratio of 100:5 can be connected in series with the line. The secondary winding is then connected to the ammeter. The current in the secondary is proportional to the current in the line. With the toroid current transformer, an insulated line passes through the center, and proportional current is induced in the toroid winding for application to the meter.

Similarly, the potential transformer reduces the voltage in a high-voltage line to the 120V for which the voltmeter is normally rated. The potential transformer is always connected across the line to be measured. Sometimes it is important to indicate the polarity of the current in both the instrument and the transformer. The polarity is the instantaneous direction of current at a specific moment. Wires with the same polarity usually contain a small black block or cross in electrical diagrams, as shown in *Figure 4*.

1.2.0 Internal Connections in Three-Phase Transformers

Various combinations of primary and secondary three-phase voltages are possible with the proper combination of delta and wye internal connections

BAR-TYPE CURRENT TRANSFORMER



TOROID (DONUT-TYPE)
CURRENT TRANSFORMERS

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Figure 3 ◆ Two types of current transformers.

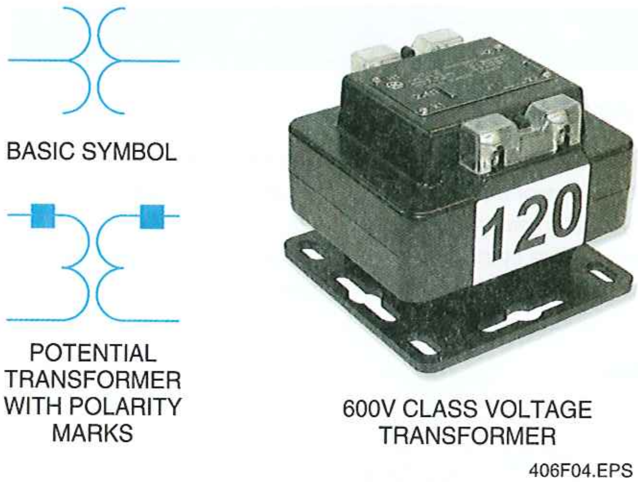

Figure 4 ◆ Voltage (potential) transformer.

of three-phase transformers or with banks of single-phase transformers.

See *Figure 5*. In all examples, it is assumed that the primary line voltages between lines A, B, and C are all 1,000V and that the transformation ratio is 10:1. The primary connections are shown by the upper three windings, and the Δ or Y next to the winding indicates how the winding is connected.

In the Δ connections, as in *Figure 5(A)* and *Figure 5(D)*, the phase voltages of the primaries are the same as the line voltage or 1,000V. In the Y connections of the primaries, as in *Figure 5(B)* and *Figure 5(C)*, the phase voltages are 0.577 times the line voltages or 577V. The wye point (N) is indicated as a common point if the windings are wye connected.

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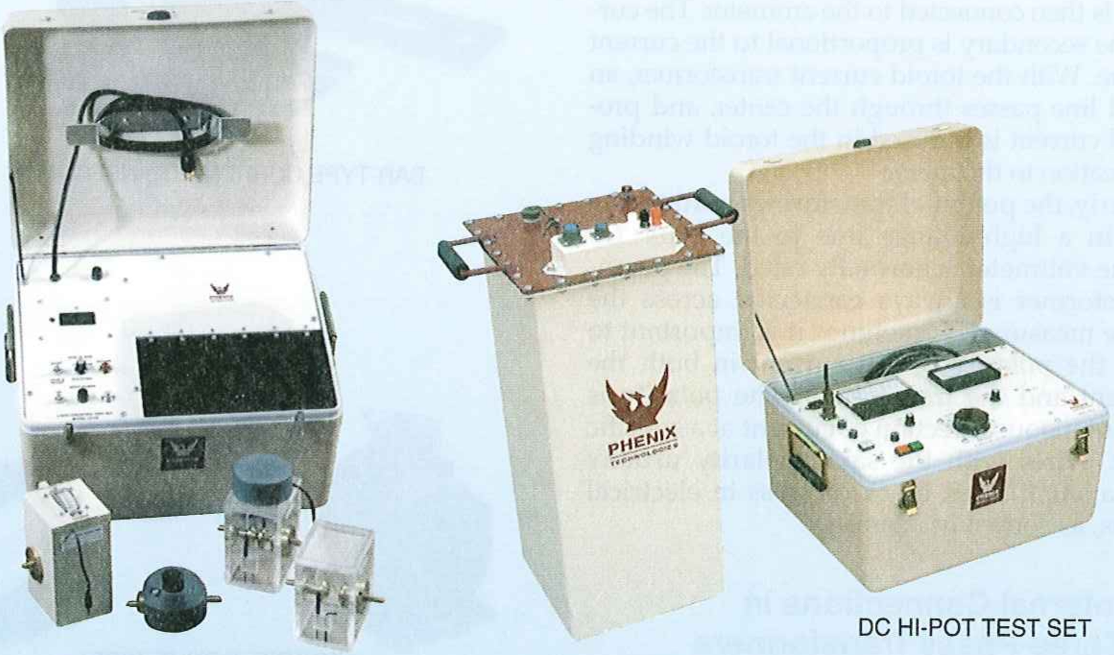
Maintenance Testing of Transformers

In commercial or industrial applications involving a number of large liquid-filled or dry transformers that are not automatically monitored, manual periodic preventive maintenance testing and performance trending is normally instituted in a manner similar to that for large motors. These tests include liquid dielectric tests to measure the breakdown voltage of samples of insulating fluids from transformers and DC hi-pot tests of transformer winding insulation. Some DC hi-pot testers are also available with a test pot for high-voltage components. The test sets shown here are capable of performing tests ranging up to 160kV.



LIQUID DIELECTRIC TEST SET

COMPONENT TEST POT

DC HI-POT TEST SET

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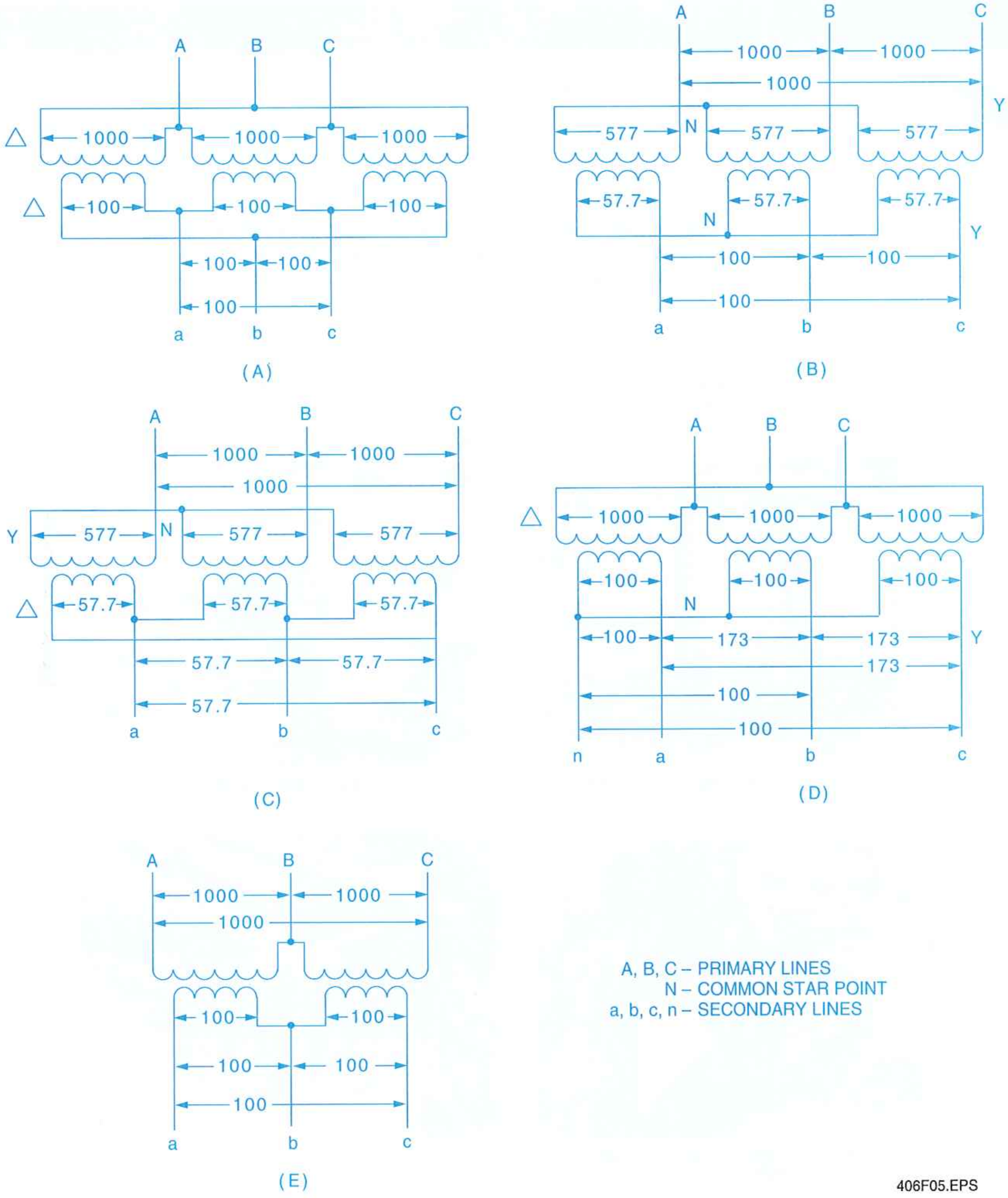

Figure 5 ◆ Common power transformer connections.

The secondaries are shown in the lower row of windings, and their connections are also indicated by the symbol Δ or Y. Each secondary phase winding has only ⅒ of the turns used in the corresponding primary phase winding and therefore supplies a phase voltage that is ⅒ of the primary phase voltage. In *Figure 5(A)* and *Figure 5(D)*, the secondary phase voltages are 1,000 ÷ 10 = 100V, and in *Figure 5(B)* and *Figure 5(C)*, they are 577 ÷ 10 = 57.7V. The secondaries are delta connected in *Figure 5(A)* and *Figure 5(C)*, and their line voltages or the voltages between the secondary line wires (a, b, and c) are the same as the secondary phase windings. When the secondaries are wye

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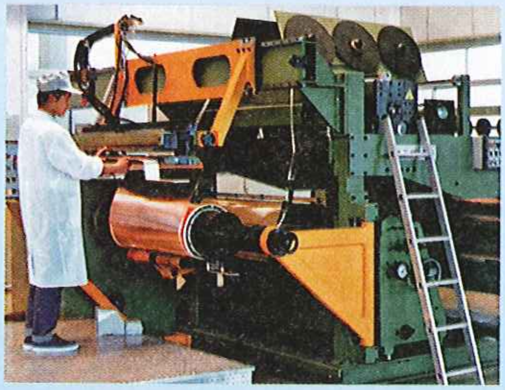
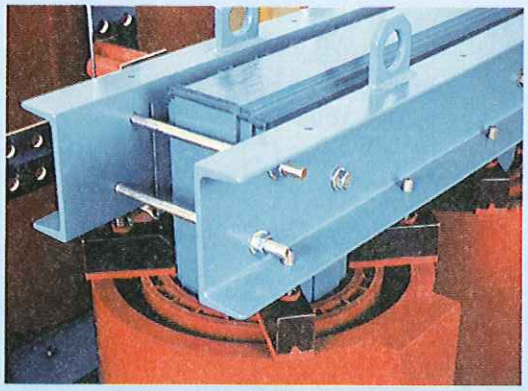
Cast-Coil Transformers

Some newer types of power transformers are made without using wire to wind the coils of the transformer. In the three-phase, step-down transformer shown here, strip foil technology is used to wind each of the primary coils. The primary coils are then placed in molds and encased with a mixture of epoxy resin and quartz powder under a high vacuum to remove any moisture. After heat curing, the coils are placed on the legs of the transformer core. Then, concentric secondary coils are wound using a sheet conductor. These secondary coils are encased in the same way as the primary coils. After curing, they are placed over the primary coils. Transformers made in this manner are capable of operating at temperatures ranging from −40°C to +180°C. They do not require liquid cooling or vaults and can be placed in NEMA Type 1 indoor or NEMA Type 3R outdoor enclosures. The epoxy-encased coils are highly resistant to caustic and humid environments.


CAST-COIL THREE-PHASE TRANSFORMER


STRIP-FOIL WINDING OF A PRIMARY COIL


SHEET-CONDUCTOR WINDING OF A SECONDARY COIL


CONCENTRIC PRIMARY AND SECONDARY CAST COILS

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connected, as in *Figure 5(B)* and *Figure 5(D)*, they have a common wye point (N) and the secondary line voltages are 1.732 times the phase voltage. In *Figure 5(B)*, the voltages between lines a, b, and c are 1.732 × 57.7 = 100V, and in *Figure 5(D)*, they are 1.732 × 100 = 173V. In addition, a fourth secondary wire (n) is brought out from the wye point (N) in *Figure 5(D)*, and the secondary voltage between any of the lines (a, b, or c and n) is equal to the secondary phase voltage or 100V.

As you become more experienced in reading electrical diagrams, you should be able to immediately recognize the differences between delta and wye connections in any three-phase system.

If the three windings have a common point, it is a Y connection, and the line voltages are 1.732 times higher than the individual phase voltages. If the three windings build a closed path, it is a delta connection, and the line voltages are the same as the phase voltages.

A connection using two single-phase transformers for a three-phase system is shown in *Figure 5(E)*. This is an open delta connection that provides a three-phase secondary with only two transformers.

2.0.0 ◆ SPECIALTY TRANSFORMERS

A transformer may be specially designed for a specific purpose. The principle of operation is the same for all transformers, but the forms, connections, and auxiliary devices differ widely. Among the many transformers designed for a specific purpose are single-phase transformers with two secondaries, single-phase transformers with three windings, autotransformers, constant-current transformers, series transformers, rectifier transformers, network transformers, and step-voltage regulators.

2.1.0 Transformers with Multiple Secondaries

One common type of transformer is a single-phase transformer with two secondaries (*Figure 6*). The first secondary has terminals X_1 and X_2 and is connected internally in series with the other secondary, which has terminals X_3 and X_4. Terminals X_1 and X_4 are connected to outside leads, and terminals X_2 and X_3 are connected together, with the junction point connected to a third outside lead. Such transformers are commonly used as distribution transformers where three-wire service is needed from a two-wire, single-phase supply. The rated secondary voltage (120V in *Figure 6*) is obtained between either outside lead and the middle lead or neutral. In addition, double voltage (240V in *Figure 6*) is available between the two outside leads. This higher voltage is usually needed for HVAC equipment, electric ranges, and dryers, while lamps and small appliances are operated on 120V.

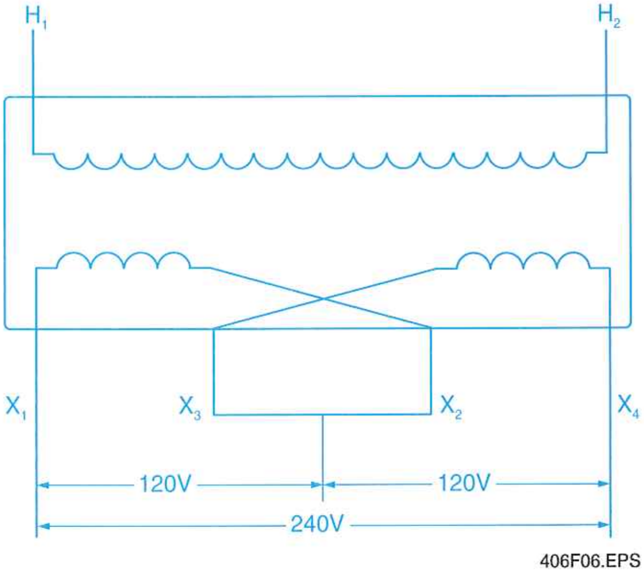

Figure 6 ◆ Single-phase transformer with two secondaries.

2.1.1 Three-Winding Transformers

Another widely used type of transformer is a three-winding, single-phase transformer. A third winding can be added to a transformer, and voltages will be induced in this winding proportional to the number of turns, the same as in the other windings. As a matter of fact, there is theoretically no limit to the number of windings that may be provided in a transformer. Practically, however, there is a limit because of the greater complexity, and transformers are seldom provided with more than four windings.

Three-winding transformers are used when a third voltage is desired at a given point. For example, a transformation may be desired from 132kV down to 66kV, with provision for supplying a 12kV circuit for local power distribution. Instead of using two transformers, one transforming from 13kV to 66kV and the other transforming from 66kV to 12kV, all three voltages may be obtained from one three-winding transformer.

A three-winding transformer, with the third winding connected in a delta configuration, may be used for Y-Y-connected banks for the suppression of third **harmonic** voltages. The third harmonic voltages and currents are induced in windings and superimposed on the normal voltages and currents. They have a frequency three times that of the rated frequency. Three-winding transformers are also sometimes used to tie together three transmission systems; they permit the flow of power in any direction with good voltage regulation.

Three-winding transformers are built in the same way as two-winding transformers, and they may be either the core or shell types. In the core construction, the additional winding is usually arranged so that it is concentric with the other two. In a shell transformer, the third winding is interleaved with the other two, which makes it more flexible than the core form.

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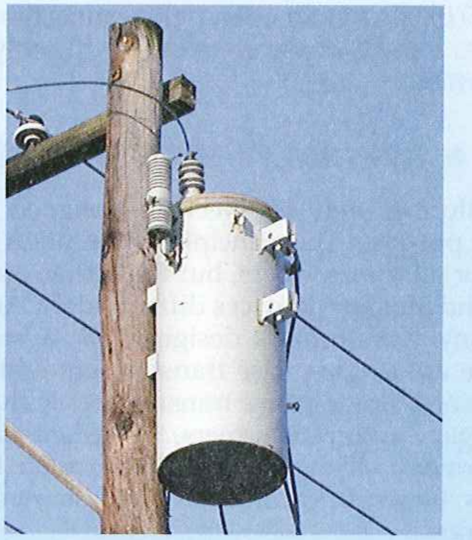
Multiple-Secondary Transformers

The two multiple-secondary transformers shown here are liquid-filled for cooling and insulation purposes and have internal, manually switched voltage taps. They are used for single-phase residential 120V/240V service.

PAD-MOUNTED TRANSFORMER



POLE-MOUNTED TRANSFORMER

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2.2.0 Autotransformers

The usual transformer has two windings that are not physically connected. In an autotransformer, one of the windings is connected in series with the other, thereby forming the equivalent of a single winding, as shown in *Figure 7*. This illustration represents a step-up autotransformer, so called because the secondary voltage is higher than the voltage supplied to the primary.

The primary voltage (E_P) is applied to the primary or common winding. The secondary or series winding is connected in series with the primary at the junction terminal. This point may be obtained by a tap, which will divide a single winding into a primary and a secondary.

A voltage induced in the secondary winding adds to the voltage in the primary winding, and the secondary voltage (E_s) is higher than the applied voltage. The ratio of transformation depends on the turns ratio, as in a two-winding transformer.

The primary current (I_p) branches into current I_c through the common winding and the current I_s through the series winding, as indicated by the arrows in *Figure 7*. The values of currents I_c and I_s

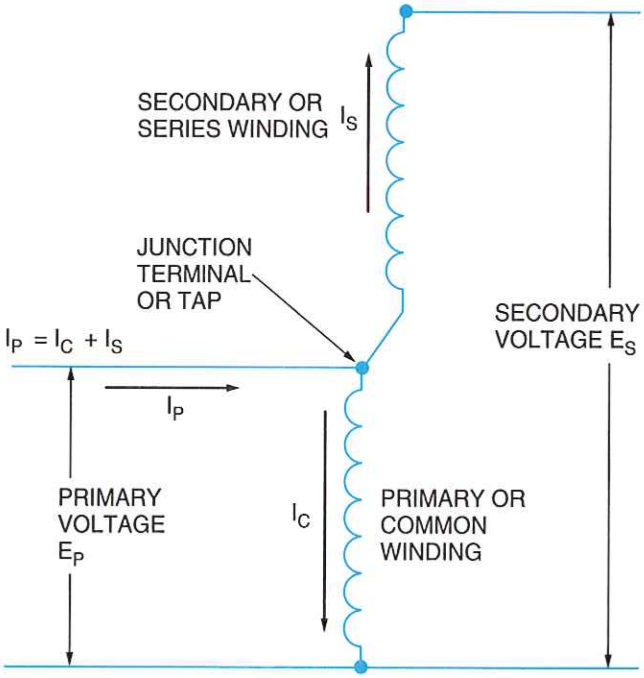

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Figure 7 ◆ Wiring diagram of a typical autotransformer.

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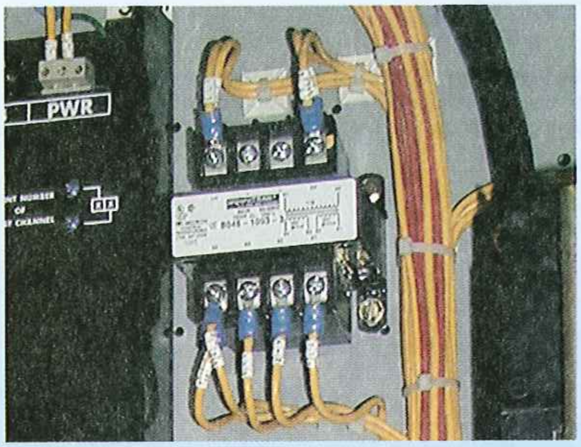
Three-Winding Control Transformers

Small three-winding transformers may be used in control systems. The one shown here has separate 24V and 26V secondary windings and a 120V primary winding.



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Advantages of Autotransformers

Autotransformers are less costly than conventional two-winding transformers and have better voltage regulation and a better ratio of energy output to input (efficiency). They are used in motor starters so that a voltage lower than the line voltage may be applied during the starting period.

are inversely proportional to the ratio of turns in the two windings and the primary current ($I_p = I_s + I_c$). Since the currents I_s and I_c oppose each other, the secondary current is lower than the primary current.

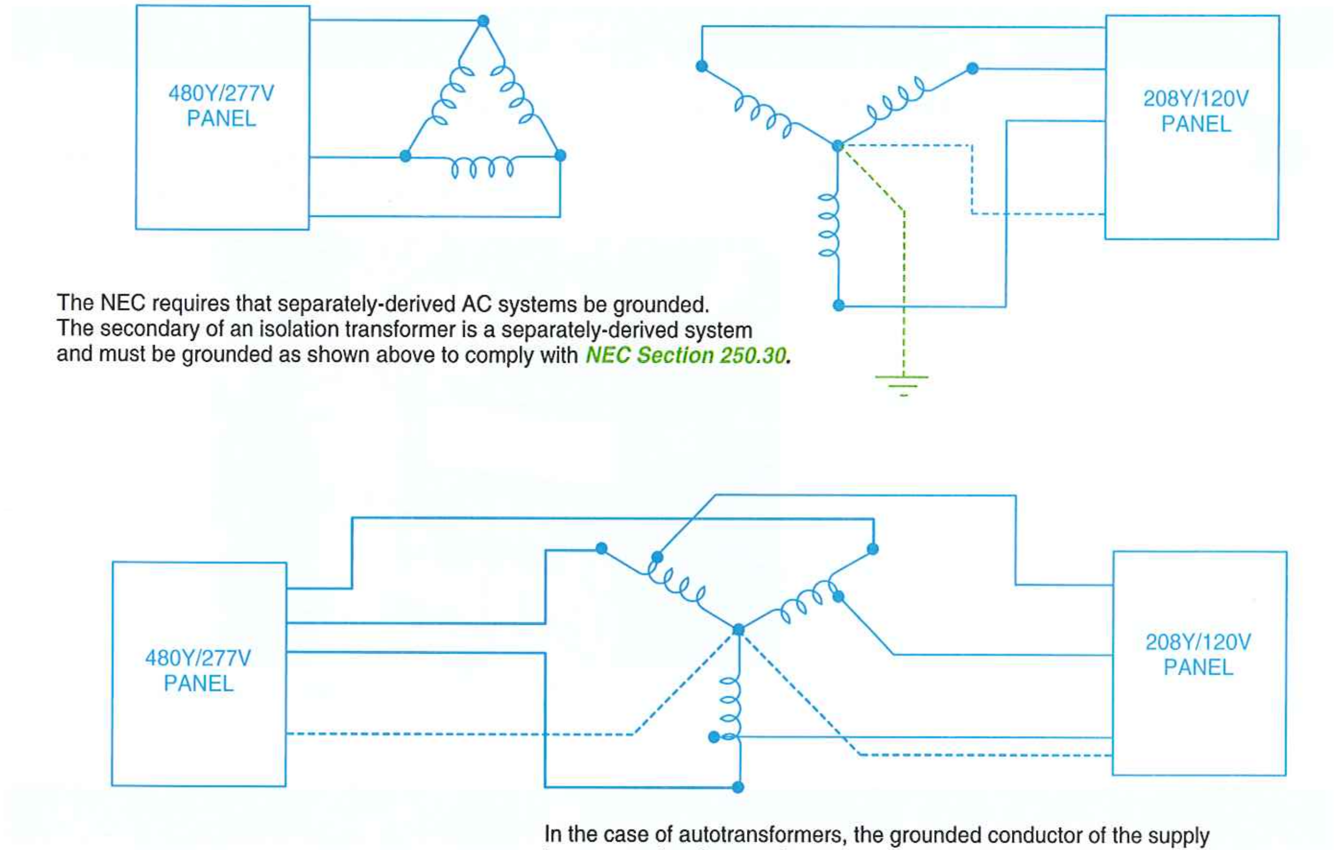
Autotransformers may be used economically to connect individual loads requiring voltages other than those available in the distribution system. An example would be increasing the voltage on a branch circuit from a 120V/208V panel to 240V for more effective utilization of a motor or resistive load.

An autotransformer, however, cannot be used on a 240V or 480V, three-phase, three-wire delta system. A grounded neutral phase conductor must be available in accordance with *NEC Section 210.9*, which states that branch circuits shall not be supplied by autotransformers unless the system supplied has a grounded conductor that is electrically connected to a grounded conductor of the system supplying the autotransformer.

In general, the *NEC®* requires that separately derived alternating current systems be grounded. The secondary of an **isolation transformer** is a separately derived system. Therefore, it must be grounded in accordance with *NEC Section 250.30.* See *Figure 8*. In the case of an autotransformer, the grounded conductor of the supply is brought into the transformer to the common terminal and the ground is established to satisfy the *NEC®*.

2.3.0 Constant-Current Transformers

Constant-current transformers are used to supply series airport lighting and street lighting circuits in which the current must remain constant while the number of lamps in series varies because of burnout or bypass switching. This type of transformer has a stationary primary coil connected to a source of alternating voltage and a movable secondary coil connected to the lamp circuit. To allow it to move freely, the secondary coil is suspended



The NEC requires that separately-derived AC systems be grounded. The secondary of an isolation transformer is a separately-derived system and must be grounded as shown above to comply with ***NEC Section 250.30.***

In the case of autotransformers, the grounded conductor of the supply is connected to the transformer common terminal and the ground is established to satisfy ***NEC Section 210.9.***

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Figure 8 ◆ *NEC*® grounding requirements for isolation and autotransformers.

from a shaft and rod attached to a rocker arm on which hinges are attached. The tendency of the secondary coil to move downward due to gravity is opposed by both the counterweight and the magnetic repulsion between the coils caused by the current in them.

The constant secondary current is usually between 4A and 7.5A, depending on the current rating of the lamps. In order to maintain a constant secondary current, the voltage of the secondary must vary directly with the number of lamps in series. If the resistance of the secondary is reduced by decreasing the number of lamps in series because of burnout or bypass switching, the current in the transformer will momentarily increase. This will increase the force of repulsion between the coils, which will move apart. The increase in distance between the coils increases the leakage **reactance** of the transformer and causes a greater voltage drop in the transformer, with a consequent decrease in the secondary voltage. The coil will continue to move until the current in the secondary winding reaches its original value, at which position the mechanical forces acting on the secondary coil are again balanced. Incandescent lamps used in series lighting circuits have a film cutout in the socket. When a lamp burns out, the full transformer secondary voltage appears between two spring contacts separated by a thin insulation film in the socket. The voltage punctures the film, causing the series circuit to be re-established.

2.4.0 Control Transformers

Control transformers and their connections were covered in your Level Three training. However, due to the number of control transformers used in industrial establishments (both in new construction and in existing installations), and the importance of having a basic knowledge of how to size these transformers for any given application, we will review the process briefly.

In general, the selection of a proper control circuit transformer must be made from a determination of the maximum inrush VA and the maximum continuous VA to which it is subjected. This data can be determined as follows:

Step 1 Determine the inrush and sealed VA of all coils to be used.

Step 2 Determine the maximum sealed VA load on the transformer.

Step 3 Determine the maximum inrush VA load on the transformer at 100% of the secondary voltage. Add this value to any sealed VA present at the time inrush occurs.

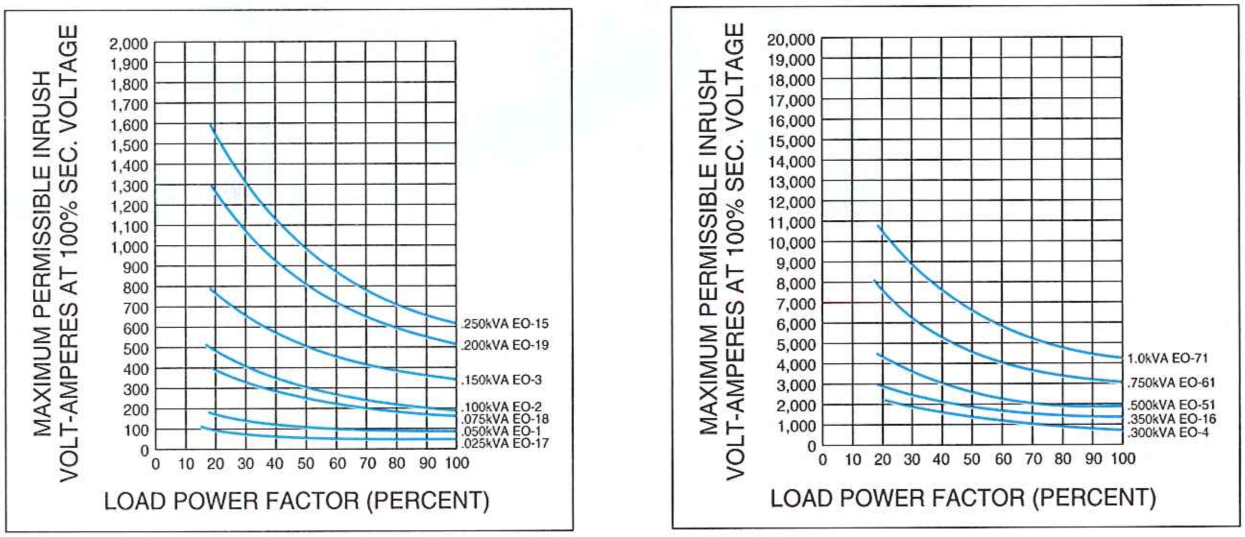
Step 4 Calculate the power factor of the VA load obtained in Step 3. The actual coil power factor should be used. If this value is unknown, an inrush power factor of 35% may be assumed.

Step 5 Select a transformer with a continuous VA rating equal to or greater than the value obtained in Step 2 and whose maximum inrush VA from Step 3 at the calculated load power factor falls on or below the corresponding curve in *Figure 9*.

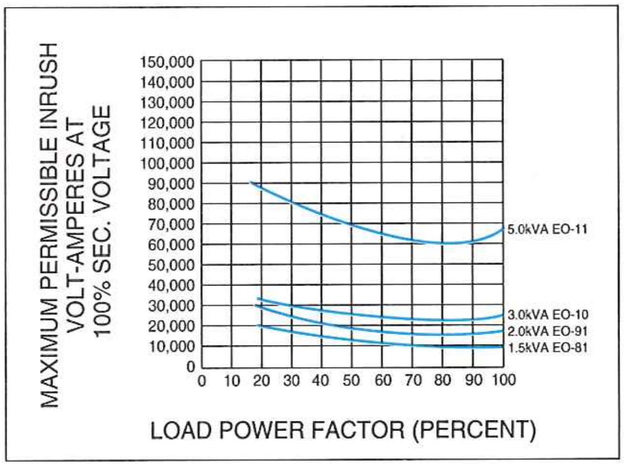
The regulation curves in *Figure 9* indicate the maximum permissible inrush loads (volt-amperes at 100% of the secondary voltage), which, if applied to the transformer secondary, will not cause the secondary voltage to drop below 85% of the rated voltage when the primary voltage has been reduced to 90% of the rated voltage.

2.5.0 Series Transformers

A power or distribution transformer is normally used with each of its primary terminals connected across the line. When a transformer is used in series with the main line, the term series transformer is applied.



(A) 60/50 HERTZ **(B) 60/50 HERTZ**



(C) 60/50 HERTZ

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Figure 9 ◆ Regulation curves.

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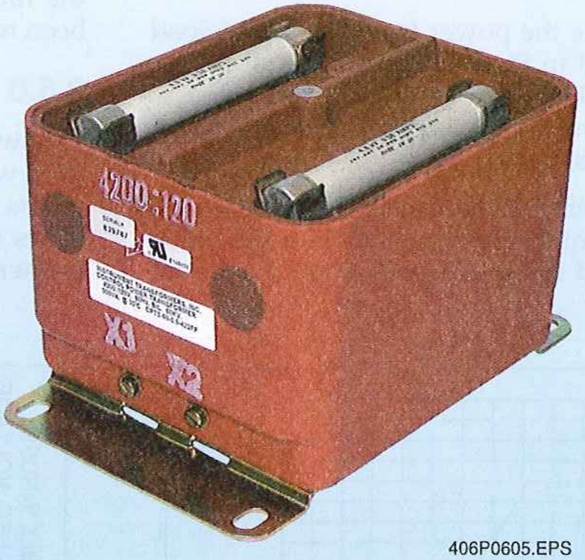
Control Power Transformers

The control power transformer shown here is rated for use in medium-voltage applications, including switchgear, with primary voltage ranges from 5kV to 34kV. Standard output voltages are 120V/240V for single-phase units and 208V/120V for three-phase units. Some versions can be mounted vertically to conserve space.



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A common application of a series transformer is its use in an airport system that has runway lamps connected in series. A small transformer is used with one or more lamp(s). The primary is connected in series with the line, and the secondary is connected across the lamp(s). The secondary winding is automatically short-circuited if a lamp burns out. The short circuit is obtained by a film cutout. When the circuit opens and the voltage across the secondary rises, it punctures the film, thereby short-circuiting the transformer secondary.

Series transformers are used in load tap changing circuits and with step-voltage regulators to reduce the operating voltage to ground when it is too high for the tap changes or to reduce the current in the tap changer contacts when the current exceeds the tap changer rating. These series transformers usually serve the purpose of an auxiliary transformer mounted in the main transformer tank.

2.6.0 Step-Voltage Regulators

Regulators of the step-voltage type are transformers provided with load tap changers. They are used to raise or lower the voltage of a circuit in response to a voltage-regulating relay or other control device. Regulators are usually designed to provide secondary voltages ranging from 10% below the supply voltage to 10% above it, or a total change of 20% in 32 steps of ⅝% each.

2.7.0 Other Specialty Transformers

Specialty transformers make up a large class of transformers and autotransformers used for changing a line voltage to some particular value best adapted to the load device. The primary voltage is generally 600V or less. Examples of specialty transformers are sign lighting transformers in which 120V is stepped down to 25V for low-voltage tungsten sign lamps; arc-lamp autotransformers in which 240V is stepped down to the voltage required for best operation of the arc; and transformers used to change 240V power to 120V for operating portable tools, fans, welders, and other devices. Also included in this specialty class are neon sign transformers that step 120V up to between 2,000V and 15,000V for the operation of neon signs. Many special step-down transformers are used for small work, such as doorbells or other signaling systems, battery-charging rectifiers, and individual low-voltage lamps. Practically all specialty transformers are self-cooled and air-insulated. Sometimes the cases are filled with a special compound to prevent moisture absorption and to conduct heat to the enclosing structure.

3.0.0 ◆ INSTRUMENT TRANSFORMERS

Instrument transformers are so named because they are usually connected to an electrical instrument, such as an ammeter, voltmeter, wattmeter, or relay. As mentioned earlier, instrument transformers are of two types: current and potential (voltage).

The primary winding of a current transformer is connected in series in a line connecting the power source and the load, and it carries the full-load current. The turns ratio is designed to produce a rated current of 5A (or some other specified value) in the secondary winding when the rated current flows in the primary winding. The current transformer provides a small current suitable for the current coil of standard instruments and

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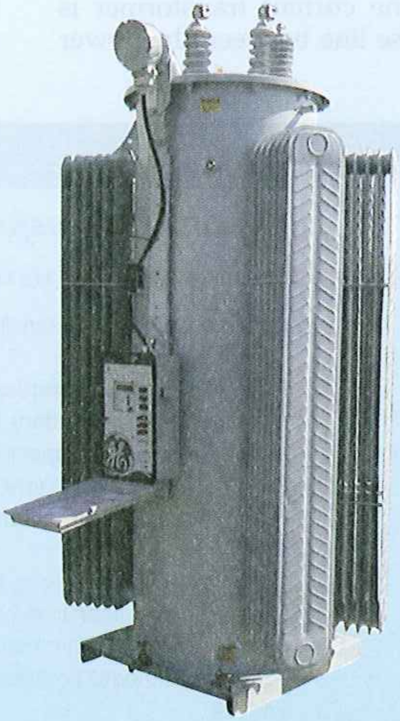
Voltage Regulators

Depending on size, individual single-phase step-voltage regulators can be pole- or pad-mounted and are available in sizes up to 830kVA at voltages from 2,500V to 19,920V. The step-voltage regulator shown here is liquid-filled and has both remote and local digital switching control for tap changing. It uses a switching reactor with equalizer windings to balance reactor voltage. An internal voltage supply furnishes power to the switching motor and control devices. Another type of voltage-adjusting transformer is the automatic voltage regulator. It continuously senses and self-adjusts to maintain a selected output voltage level at ±1% for critical loads including computer, medical, communications, and industrial process equipment. These are dry-type units with a variable-ratio autotransformer consisting of a rotor and stator. The rotor only turns 180° to add or subtract from the supply voltage and is driven by a reversible motor. Because these units regulate by transformer action instead of impedance change, no waveform distortion occurs. The regulators are available in single- and three-phase versions in sizes up to 1,000kVA at voltages from 120V to 480V.



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proportional to the load current. The low-voltage, low-current secondary winding providing the current may be grounded for safety and economy in the secondary wiring and instruments.

A potential transformer is connected from one power line to another. Its secondary winding provides a low voltage, usually up to 120V, that is proportional to the line voltage. This low voltage is suitable for the voltage coil of standard instruments. The low-voltage secondary winding may be grounded for the safety of the secondary wiring and the instrument, regardless of the power line voltage.

When connecting instrument transformers to wattmeters, watt-hour meters, power factor meters, etc., it is necessary to know the polarity of the leads. One primary lead and one secondary lead of the same polarity are clearly marked on all instrument transformers, usually by a white spot or white marker on the leads.

The direction of current in the two leads of the same polarity is such that, if it is toward the transformer in the marked primary lead, it is away from the transformer in the marked secondary lead.

In diagrams, the polarity mark is usually indicated in one of three ways, as shown in *Figure 10*.

3.1.0 Current Transformers

A current transformer is always a single-phase transformer. If current transformers are used in a three-phase system, one current transformer is inserted into each phase line between the power supply and the instrument. A connection of a current transformer into a single-phase, two-wire line is shown in *Figure 11*.

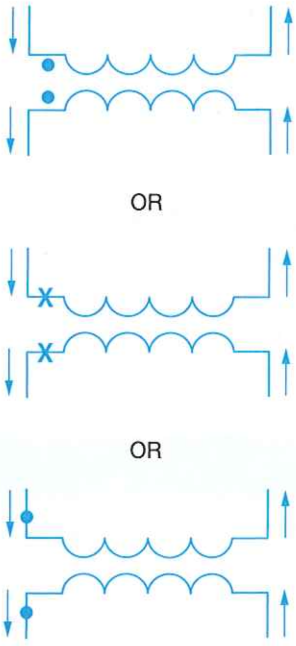

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Figure 10 ◆ Polarity marks on transformers.

The primary winding of a current transformer must be connected in series with one of the main power lines; thus, the main line load current flows through the primary winding. The secondary winding at the current transformer is connected to a current-responsive instrument. The secondary

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Instrument Transformers

Instrument transformers are classified according to the following factors:

- *Service* – Instrument transformers are designated for either metering or relaying service.
- *Burden* – The burden represents the size and characteristics of the load connected to the transformer secondary. For potential (voltage) transformers, the burden is expressed in VA at a specified power factor and voltage. For current transformers, the burden is expressed in total impedance at specified values of resistance and inductance. Generally, a transformer must perform as rated within the limits of its burden.
- *Accuracy* – For a metering transformer, an accuracy rating representing the amount of uncertainty (inaccuracy) is assigned for each rated burden of the transformer. For example, a transformer may have an accuracy rating of 0.3 at burden X and 0.6 at burden Y. Standard accuracy classes for instrument transformers are 0.3, 0.6, 1.2, and 2.4.

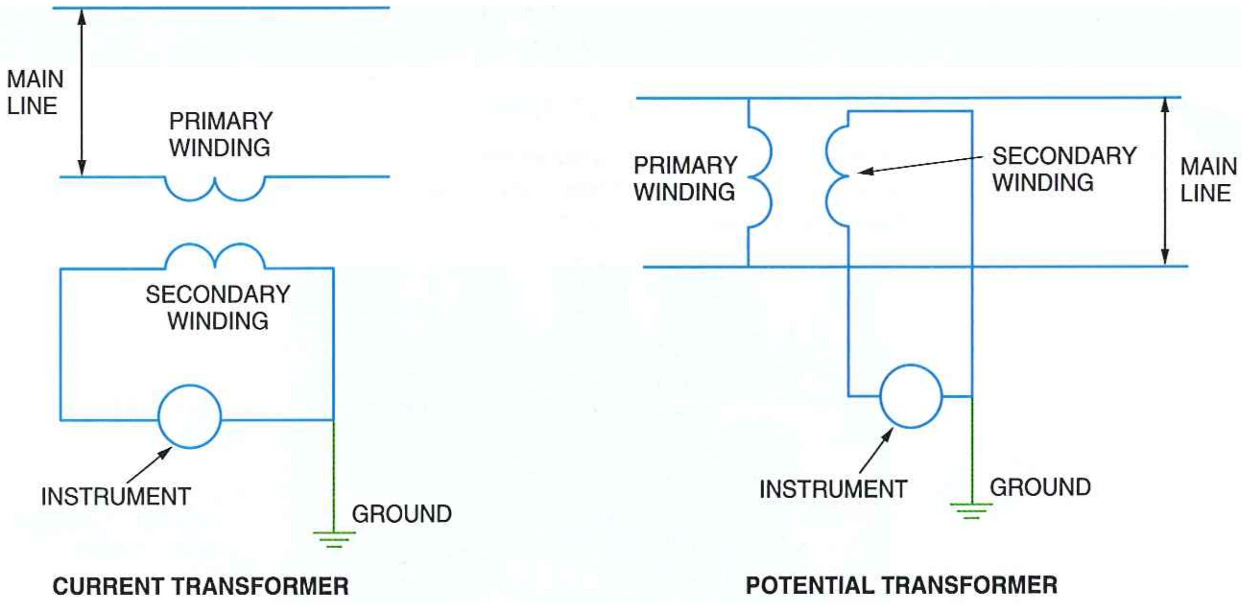

Figure 11 ◆ Connection of instrument transformers.

current is grounded for safety. Instruments that require a current transformer may include ammeters, wattmeters, watt-hour meters, power factor meters, some forms of relays, and trip coils of circuit breakers. One current transformer can be used to operate several instruments.

The current transformer is designed for a certain rated apparent power or VA rating. The volt-amperes of the secondary circuit are theoretically equal to the volt-amperes of the primary circuit. The value of the secondary voltage is obtained as the product of the secondary current and the **impedance** of the secondary circuit. This impedance, measured in ohms, consists of the impedances of all the instruments connected to the secondary terminals of the current transformer. When no instruments are connected to the current transformer, a short circuit connection must be placed across the secondary terminals; this results in a secondary voltage of 0V.

3.1.1 Using Current Transformers

Before disconnecting an instrument, the secondary of the current transformer must be short-circuited. If the secondary circuit is opened while the primary winding is carrying current, there will be no secondary **ampere turns** to balance the primary ampere turns. Therefore, the total primary current will become exciting current and magnetize the core to a high flux density, which will produce a high voltage across both the primary and secondary windings.

WARNING!

The secondary circuit of a current transformer should never be opened while the primary is carrying current.

Because current transformers are designed for accuracy, the normal exciting current is only a small percentage of the full-load current. The voltage produced with the secondary open circuited is high enough to endanger the life of anyone coming in contact with the meters or leads. The high secondary voltage may also overstress the secondary insulation and cause a breakdown. Still other damage may be caused by operation with the secondary open circuited—the transformer core may become permanently magnetized, impairing the accuracy of the transformer. If this occurs, the core may be demagnetized by passing about 50% excess current through the primary, with the secondary connected to an adjustable high resistance that is gradually reduced to zero.

3.2.0 Potential Transformers

Potential or voltage transformers are single-phase transformers. If used on three-phase circuits, sets of two or three potential transformers are applied. The primary winding of a potential transformer is always connected across the main power lines.

A connection to a single-phase, two-wire circuit is shown in *Figure 11*. The primary of the potential

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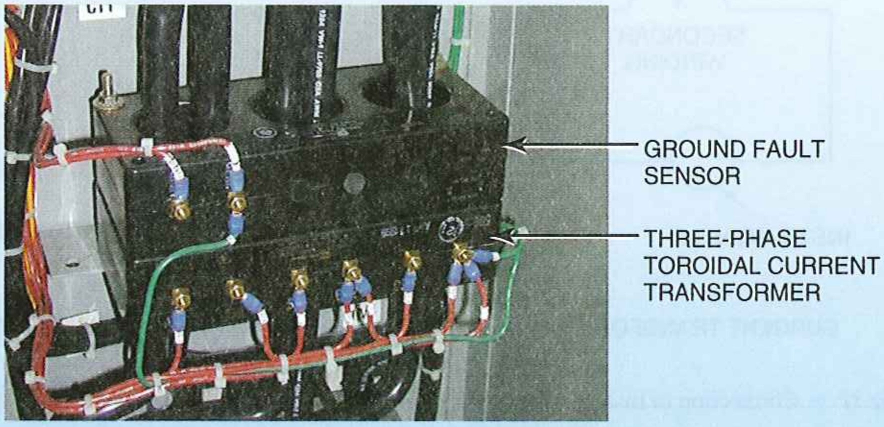
Three-Phase Current Transformers

A three-phase toroidal current transformer unit with the leads to a motor contactor passing through the center holes is shown here. The ground fault sensor is a similar type of transformer.



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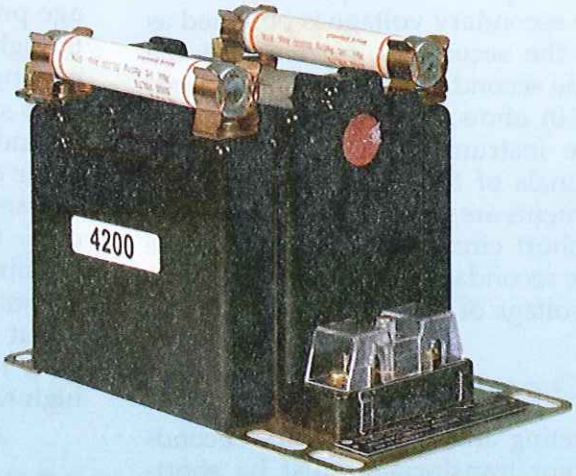
Voltage Transformers

This voltage transformer has a fused input and a primary rated for medium-voltage applications up to 34.5kV.



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transformer is connected across the main line, and the secondary is connected to an instrument. For safety, the secondary circuit is grounded.

The main circuit voltage exists across the primary winding. The secondary of the potential transformer is connected to one or more voltage-responsive devices, such as voltmeters, wattmeters, watt-hour meters, power factor meters, or some forms of relays or trip coils. The voltage across the secondary terminals of the potential transformer is always lower than the primary voltage and is rated at 120V. For example, if a potential transformer with a turns ratio of 12:1 is connected to a 1,380V main line, the voltage in the instrument connected across the secondary terminals will be about 120V.

3.2.1 Types of Potential Transformers

All potential transformers have a wound primary and a wound secondary. Mechanically, their construction is similar to that of wound current transformers. Their secondary thermal kVA rating seldom exceeds 1.5kVA.

Potential transformers are available in both oil-filled and dry types. In both types, the primary high-voltage leads are terminated at bushings and the housing contains the secondary low-voltage terminations. When supplied as part of a switchgear assembly, they occupy dedicated spaces.

In certain small services, both current and potential transformers are packaged into a metering unit that is a single enclosure. This reduces the assembly time in field installations.

4.0.0 ◆ SIZING BUCK-AND-BOOST TRANSFORMERS

Manufacturers of buck-and-boost transformers normally offer easy-to-use selector charts that allow you to quickly select a buck-and-boost transformer for practically any application. These charts may be obtained from electrical equipment suppliers or ordered directly from the manufacturer—often at no charge. Instructions accompanying these charts will enable anyone familiar with transformers and electrical circuits to use them. An overview of the principles involved in using buck-and-boost transformers is given here.

When reviewing the selector charts, it may surprise you to discover that these transformers can handle loads that are much greater than their nameplate ratings. For example, a typical 1kVA buck-and-boost transformer can easily handle an 11kVA load when the voltage boost is only 10%. We will see how this is possible. First, we will examine an isolation transformer that will be incorporated as part of an autotransformer to form a buck-and-boost transformer.

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Buck-and-Boost Transformers

A small buck-and-boost transformer is shown here. It is a single-phase compound-filled unit rated at 0.05kVA. However, depending on the percentage of voltage buck or boost required, it can be used in circuits with much higher loads.

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Assume that we have a 1kVA (1,000VA) isolation transformer that is designed to transform 208V to 20.8V (see *Figure 12*). This results in a transformer winding ratio of 10:1. The primary current may be found using the following equation:

$$\text{Primary current} = \frac{1{,}000\text{VA}}{208\text{V}} = 4.8\text{A}$$

Because the transformation ratio is 10 to 1, the secondary amperes will be 48A (4.8A × 10 = 48A), or the amperage may be determined using the following equation:

$$\text{Secondary current} = \frac{1{,}000\text{VA}}{20.8\text{V}} = 48\text{A}$$

Figure 13 shows how the windings are connected in series to form an autotransformer. Because we started with 208V at the source and now add 20.8V to it, the load is now 208V + 20.8V = 228.8V. To find the kVA rating of the system at the load, use the following equation:

$$\begin{aligned} \text{kVA} &= \frac{\text{volts}}{1{,}000} \times \text{amps} \\ &= \frac{228.8\text{V}}{1{,}000} \times 48\text{A} \\ &= 11\text{kVA} \end{aligned}$$

Ten kVA is conducted from the source, and 1kVA is transformed from the source. The total kVA rating is 10kVA + 1kVA = 11kVA.

The H_1H_2 winding is rated at 4.8A, and the X_1X_2 winding is rated at 48A. Therefore, the line current at 208V would be 4.8A + 48A = 52.8A. The input kVA rating is as follows:

$$\begin{aligned} \text{kVA} &= \frac{\text{volts}}{1{,}000} \times \text{I} \\ &= \frac{208\text{V}}{1{,}000} \times 52.8\text{A} \\ &= 11\text{kVA} \end{aligned}$$

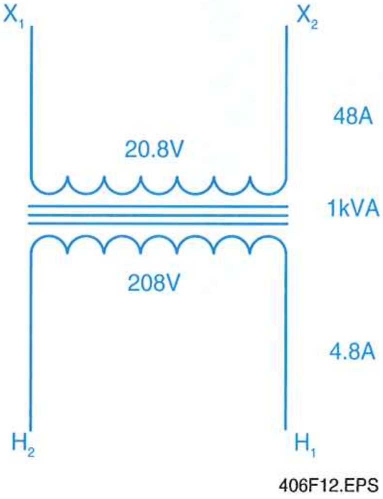


Figure 12 ◆ Isolation transformer.

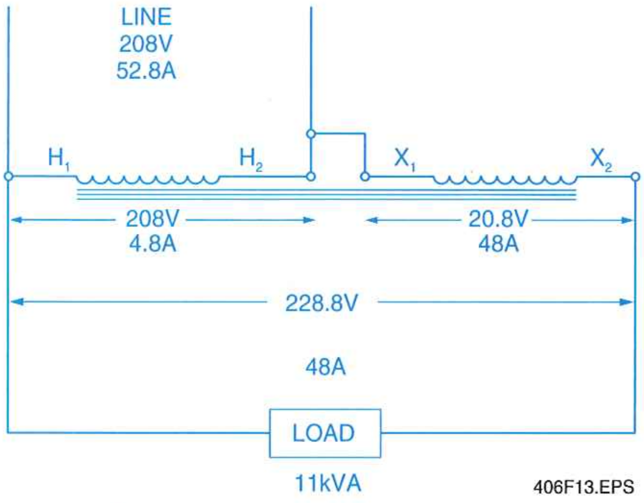


Figure 13 ◆ Boost transformer connection.

The diagrams shown in *Figures 12* and *13* are usually simplified even more in a line diagram, as shown in *Figure 14*. Actually, all three wiring diagrams indicate the same thing, and following the connections on any of these drawings will produce the same results at the load. *Figure 14* shows the calculations for a 240V source.

It should now be evident how a 1kVA buck-and-boost transformer, when connected in the circuit as described previously, can actually carry 11kVA in its secondary winding.

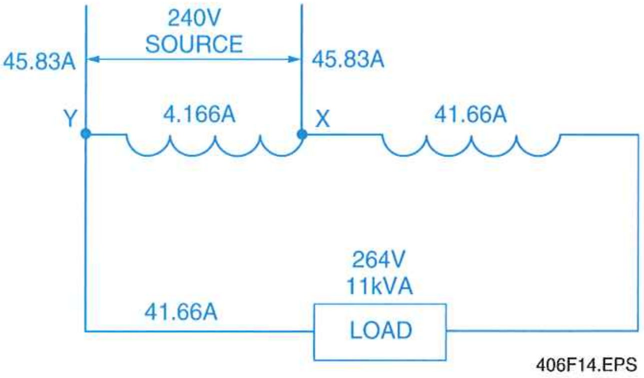


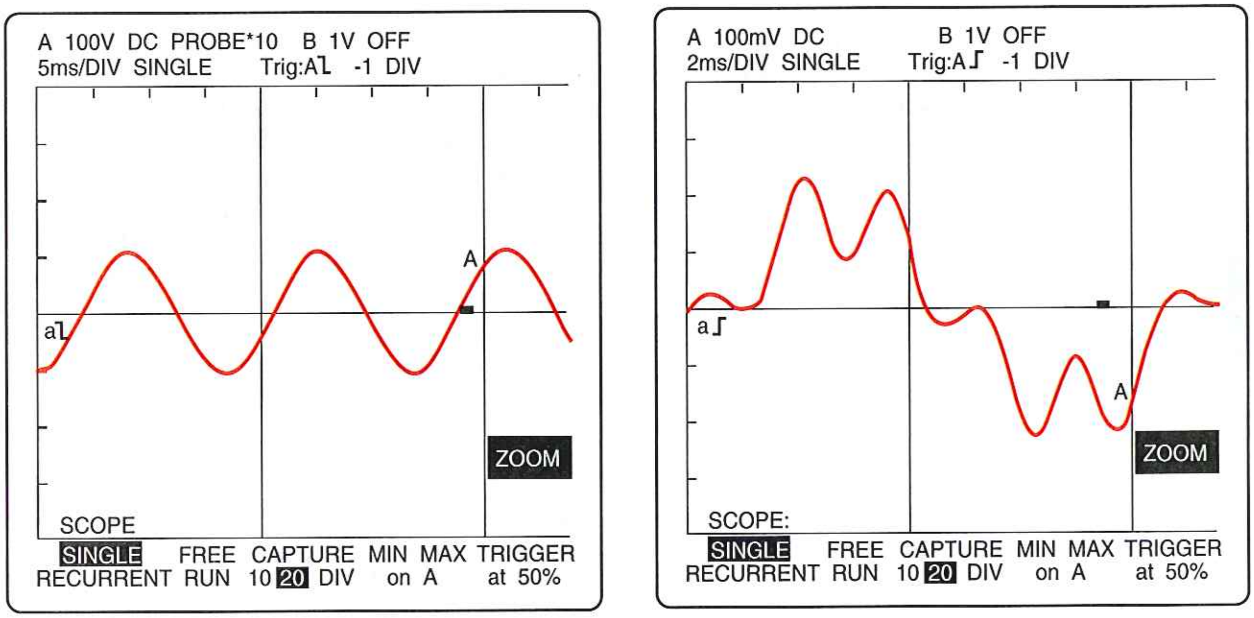
Figure 14 ◆ Typical line diagram of a transformer circuit.

5.0.0 ◆ HARMONICS

Harmonics are the byproducts of modern electronics. They are especially prevalent wherever there are large numbers of personal computers (PCs), adjustable-speed drives, and other types of equipment that draw current in short pulses.

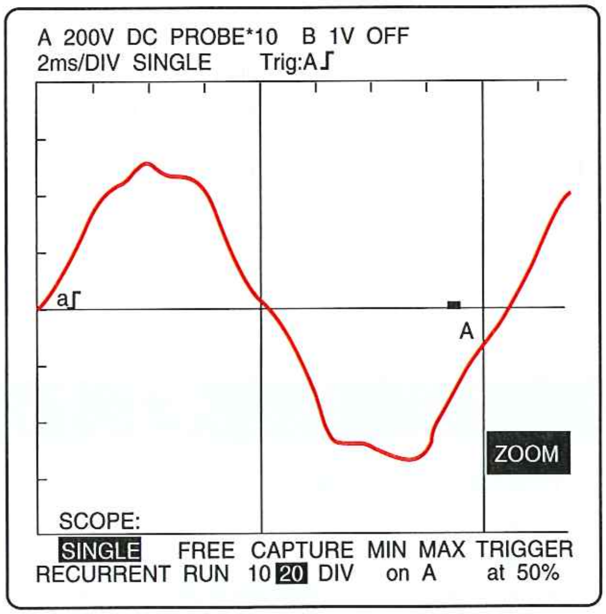
This equipment is designed to draw current only during a controlled portion of the incoming voltage waveform. Although this dramatically improves efficiency, it causes harmonics in the load current. This results in overheated transformers and neutrals, as well as tripped circuit breakers.

The problem is evident when you look at a waveform. A normal 60-cycle power line voltage appears on the oscilloscope as a near sine wave, as shown in *Figure 15(A)*. When harmonics are present, the waveform is distorted, as shown in *Figure 15(B)* and *Figure 15(C)*. These waves are described as non-sinusoidal. The voltage and current waveforms are no longer simply related—hence the term nonlinear.



(A) NEAR SINE WAVE

(B) DISTORTED WAVEFORM



(C) DISTORTED WAVEFORM

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Figure 15 ◆ Voltage waveforms.

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Harmonics

If you were to listen to an ordinary 60-cycle power line, you would hear a monotone hum or buzz. When harmonics are present, you hear a different tune, rich with high notes.

Finding the problem is relatively easy once you know what to look for and where to look. Harmonics are usually anything but subtle. This section will give you some basic pointers on how to find harmonics and some suggested ways to address the problem. However, in many cases, consultants must be called in to analyze the operation and design a plan for correcting the problem.

CAUTION

As part of a regular maintenance program, pay careful attention to overheating of the neutral conductors in distribution systems. Harmonics may cause deterioration of the insulation.

5.1.0 Defining the Problem

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. For example, if the fundamental frequency is 60Hz, then the second harmonic is 120Hz, the third is 180Hz, and so on.

Harmonics are created by nonlinear loads that draw current in abrupt pulses rather than in a smooth sinusoidal manner. These pulses cause distorted current waveshapes, which in turn cause harmonic currents to flow back into other parts of the power system. This phenomenon is especially prevalent with equipment that contains diode/capacitor input or solid-state switched power supplies, such as personal computers, printers, and medical test equipment.

In a diode/capacitor, the incoming AC voltage is diode rectified and is then used to charge a large capacitor. After a few cycles, the capacitor is charged to the peak voltage of the sine wave (for example, 168V for a 120V line). The electronic equipment then draws current from this high DC voltage to power the rest of the circuit.

The equipment can draw the current down to a regulated lower limit. Typically, before reaching that limit, the capacitor is recharged to the peak in the next half cycle of the sine wave. This process is repeated over and over. The capacitor basically draws a pulse of current only during the peak of the wave. During the rest of the wave, when the voltage is below the capacitor residual, the capacitor draws no current.

5.1.1 Voltage Harmonics

The power line itself can be an indirect source of voltage harmonics. The harmonic current drawn by nonlinear loads acts in an Ohm's law relationship with the source impedance of the supplying transformer to produce the voltage harmonics. The source impedance includes both the supplying transformer and the branch circuit components. For example, a 10A harmonic current being drawn for a source impedance of 0.1Ω will generate a harmonic voltage of 1.0V. Any loads sharing a transformer or branch circuit with a heavy harmonic load can be affected by the voltage harmonics generated.

Many types of devices are very susceptible to voltage harmonics. The performance of the diode/capacitor power supply is critically dependent on

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Nonlinear Loads

The diode/capacitor or solid-state switched power supplies found in office equipment typically consist of single-phase, nonlinear loads. In industrial plants, the most common causes of harmonic currents are three-phase, nonlinear loads. These include electronic motor drives, uninterruptible power supplies (UPSs), HID lighting, and welding machines.

the magnitude of the peak voltage. Voltage harmonics can cause flat-topping of the voltage waveform, lowering the peak voltage. In severe cases, the computer may reset due to insufficient peak voltage.

In an industrial environment, the induction motor and power factor correction capacitors can also be seriously affected by voltage harmonics.

Power correction capacitors can form a resonant circuit with the inductive parts of a power distribution system. If the resonant frequency is near that of the harmonic voltage, the resultant harmonic current can increase substantially, overloading the capacitors and blowing the capacitor fuses. Fortunately, the capacitor failure detunes the circuit and the resonance disappears.

5.1.2 Classification of Harmonics

Each harmonic has a name, frequency, and sequence. The sequence refers to phasor rotation with respect to the fundamental (F); that is, in an induction motor, a positive sequence harmonic would generate a magnetic field that rotates in the same direction as the fundamental. A negative sequence harmonic would rotate in the reverse direction. The first nine harmonics, along with their effects, are shown in *Table 1*.

5.2.0 Office Buildings and Plants

Harmonics have a significant effect in office buildings and industrial establishments. Symptoms of harmonics usually show up in the power distribution equipment that supports the nonlinear loads. There are two basic types of nonlinear loads: single phase and three phase. Single-phase loads are prevalent in offices; three-phase loads are widespread in industrial plants.

Each component of the power distribution system manifests the effects of harmonics a little differently, but they are all subject to damage and inefficient performance.

5.2.1 Neutral Conductors

In a three-phase, four-wire system, the neutral conductor can be severely affected by nonlinear loads connected to the 120V branch circuits. Under normal conditions for a balanced linear load, the fundamental 60Hz portion of the phase currents will cancel in the neutral conductor.

In a four-wire system with single-phase, nonlinear loads, certain odd-numbered harmonics called triplens—odd multiples of the third harmonic: 3rd, 9th, 15th, etc.—do not cancel, but rather add together in the neutral conductor. In systems with many single-phase, nonlinear loads, the neutral current can actually exceed the phase current. The danger here is excessive overheating because there is no circuit breaker in the neutral conductor to limit the current as there are in the phase conductors.

Excessive current in the neutral conductor can also cause higher voltage drops between the neutral conductor and ground at the 120V outlet.

5.2.2 Circuit Breakers

Common thermal-magnetic circuit breakers use a bimetallic trip mechanism that responds to the heating effect of the circuit current. They are designed to respond to the true root-mean-square (rms) value of the current waveform and therefore will trip when they get too hot. This type of breaker has a better chance of protecting against harmonic current overloads.

A peak sensing electronic trip circuit breaker responds to the peak of the current waveform. As a result, it will not always respond properly to harmonic currents. Since the peak of the harmonic current is usually higher than normal, this type of circuit breaker may trip prematurely at a low current. If the peak is lower than normal, the breaker may fail to trip when it should.

Table 1 Harmonic Rates and Effects

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Frequency	60	120	180	240	300	360	420	480	540
Sequence	+	—	0	+	—	0	+	—	0

Sequence	**Rotation**	**Effects (skin effect, eddy currents, etc.)**
Positive	Forward	Heating of conductors and circuit breakers
Negative	Reverse	Heating as above, plus motor problems
Zero	None	Heating, plus add-in neutral of three-phase, four-wire system

5.2.3 Busbars and Connecting Lugs

Neutral busbars and connecting lugs are sized to carry the full value of the rated phase current. They can become overloaded when the neutral conductors are overloaded with the additional sum of the triplen harmonics.

5.2.4 Electrical Panels

Harmonics in electrical panels can be quite noisy. Panels that are designed to carry 60Hz current can become mechanically resonant to the magnetic fields generated by high-frequency harmonic currents. When this happens, the panel vibrates and emits a buzzing sound at the harmonic frequencies.

5.2.5 Telecommunications

Telecommunications cable is commonly run right next to power cables. To minimize the inductive interference from phase current, telecommunications cables are run closer to the neutral wire. Triplens in the neutral conductor commonly cause inductive interference that can be heard on a phone line. This is often the first indication of a harmonics problem and gives you a head start in detecting the problem before it causes major damage.

5.2.6 Transformers

Commercial buildings commonly have a 120V/208V transformer in a delta-wye configuration, as shown in *Figure 16*. These transformers commonly feed receptacles in a commercial building. Single-phase, nonlinear loads connected to the receptacles produce triplen harmonics that algebraically add up in the neutral. When this neutral current reaches the transformer, it is reflected into the delta primary winding, where it circulates and causes overheating and transformer failures.

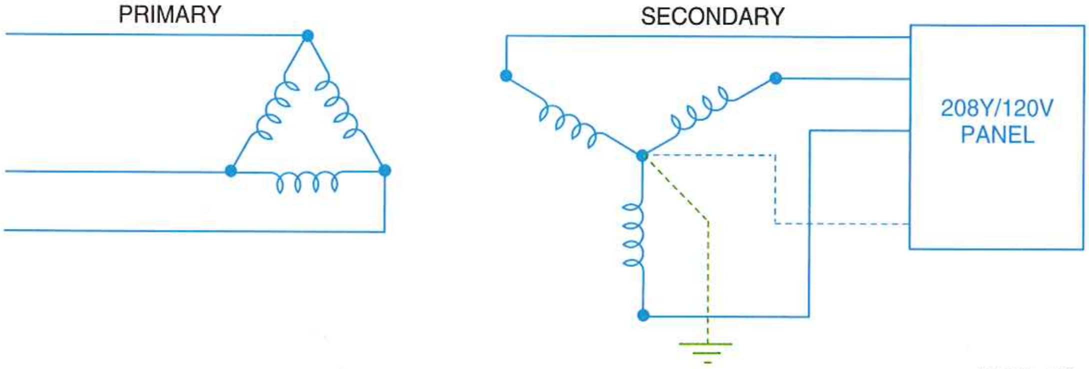

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Figure 16 ◆ Three-phase, delta-wye transformer configuration.

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K-Rated and Zig-Zag Transformers

Specially designed transformers that reduce or compensate for harmonic current include K-rated and zig-zag transformers. To prevent overheating, K-rated three-phase transformers for delta-to-wye connections are sized to handle 100% of the normal 60Hz load plus a specified nonlinear load defined by a K number. Manufacturers' specifications define the K numbers for various types of loads. If the various harmonics are known, a specific transformer can be custom built. The inherent phase shift of a K-rated transformer will cancel 5th and 7th harmonics but not the triplens. Because triplens are not cancelled, the neutral of the secondary is normally oversized at 200% of the maximum current rating of one of the phase connections. A zig-zag phase shift transformer cancels triplens and other harmonics at the load side of the transformer by using six windings in the secondary. An extra winding for each phase is connected in series with another phase to produce a phase shift. This type of transformer works well if the loads are balanced. A drawback is that zig-zag transformers use more material in the windings and are heavy. Other techniques such as active filters or ferroresonant transformers are also used for harmonic current suppression in certain applications.

Another transformer problem results from **core loss** and copper loss. Transformers are normally rated for a 60Hz phase current load only.

High-frequency harmonic currents cause increased core loss due to **eddy currents** and **hysteresis,** resulting in more heating than would occur at the same 60Hz current. These heating effects demand that transformers be derated for harmonic loads or replaced with specially designed transformers.

5.2.7 Generators

Standby generators are subject to the same types of overheating problems as transformers. Because they provide emergency backup for harmonics-producing loads such as data processing equipment, they are often even more vulnerable. In addition to overheating, certain types of harmonics produce distortion at the zero crossing of the current waveform, which causes interference and instability in the generator control circuits.

5.3.0 Survey the Situation

A quick survey will help to determine whether or not you have a harmonics problem and where it is located. The survey procedure should include the following:

Step 1 Take a walking tour of the facility and look at the types of equipment in use. If there are a lot of personal computers and printers, adjustable-speed motors, solid-state heater controls, and certain types of fluorescent lighting, there is a good chance that harmonics are present.

Step 2 Locate the transformers feeding the nonlinear loads and check for excess heating. Also, make sure that the cooling vents are unobstructed.

Step 3 Use a true rms meter to check transformer currents.

- Verify that the voltage ratings for the test equipment are adequate for the transformer being tested.
- Measure and record the transformer secondary currents in each phase and in the neutral (if used).
- Calculate the kVA delivered to the load, and compare it to the nameplate rating. If harmonic currents are present, the transformer can overheat, even if the kVA delivered is less than the nameplate rating.
- If the transformer secondary is a four-wire system, compare the measured neutral current to the value predicted from the imbalance in the phase currents. (The neutral current is the vector sum of the phase currents and is normally zero if the phase currents are balanced in both amplitude and phase.) If the neutral current is unexpectedly high, triple harmonics are likely, and the transformer may need to be derated.
- Measure the frequency of the neutral current. 180Hz would be a typical reading for a neutral current consisting of mostly third harmonics.

Step 4 Survey the subpanels that feed harmonic loads. Measure the current in each branch neutral, and compare the measured value to the rated capacity for the wire size used. Check the neutral busbar and feeder connections for heating or discoloration.

Step 5 Neutral overloading in receptacle branch circuits can sometimes be detected by measuring the neutral-to-ground voltage at the receptacle. Measure the voltage when the loads are on. A reading of 2V or less is normal. Higher voltages can indicate trouble, depending on the length of the run, quality of the connections, etc. Measure the frequency. 180Hz would suggest a strong presence of harmonics. 60Hz would suggest that the phases are out of balance. Pay special attention to under-carpet wiring and modular office panels with integrated wiring that use a neutral shared by three-phase conductors. Because the typical loads in these two areas are computer and office machines, they are often trouble spots for overloaded neutrals.

5.3.1 Meters

Having the proper equipment is crucial to diagnosing harmonics problems. The type of equipment used varies with the complexity of measurements required.

To determine whether you have a harmonics problem, you need to measure the true rms value and the instantaneous peak value of the waveshape. For this test, you need a true rms clamp-on multimeter or a handheld digital multimeter that makes true rms measurements and has a high-speed peak hold circuit.

The term true rms refers to the root-mean-square or equivalent heating value of a current or voltage waveshape. True distinguishes the measurement from those taken by average responding meters.

The vast majority of low-cost, portable clamp-on ammeters are average responding. These instruments give correct readings for pure sine waves only and will typically read low when confronted with a distorted current waveform. The result is a reading that can be up to 50% low.

True rms meters give correct readings for any waveshape within the instrument's crest factor and bandwidth specifications.

5.3.2 Crest Factor

The crest factor of a waveform is the ratio of the peak value to the rms value. For a sine wave, the crest factor is 1.414. A true rms meter will have a crest factor specification. This specification relates to the level of peaking that can be measured without errors.

A quality true rms handheld digital multimeter has a crest factor of 3.0 at full scale. This is more than adequate for most power distribution measurements. At half scale, the crest factor is double. For example, a meter may have a crest factor specification of 3.0 when measuring 400VAC and a crest factor of 6.0 when measuring 200VAC.

NOTE

Most true rms meters cannot be used for signals below 5% of scale because of the measurement noise problem. Use a lower range if it is available.

The crest factor can be easily calculated using a true rms meter with a peak function or a crest function. A crest factor other than 1.414 indicates the presence of harmonics. In typical single-phase cases, the greater the difference from 1.414, the greater the harmonics. For voltage harmonics, the typical crest factor is below 1.414 (i.e., a flat-top waveform). For single-phase current harmonics, the typical crest factor is well above 1.414. Three-phase current waveforms often exhibit the double-hump waveform; therefore, the crest factor comparison method should not be applied to three-phase load currents.

After you have determined that harmonics are present, you can make a more in-depth analysis of the situation using a harmonics analyzer.

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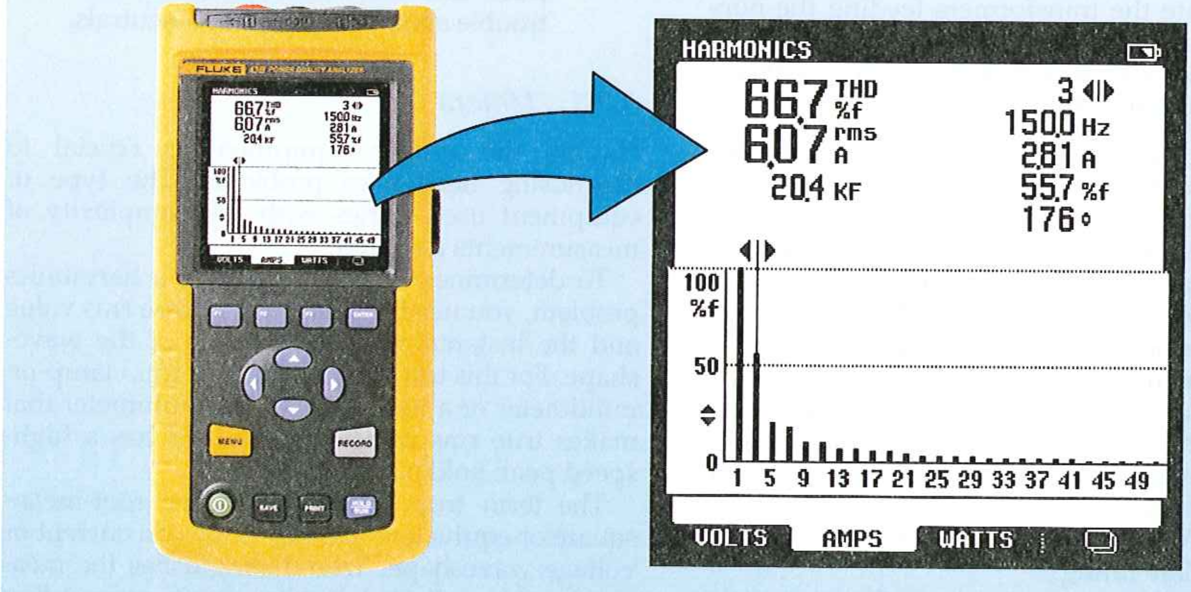
Power Quality Analyzers

Portable power quality analyzers like the one shown here can be used to determine harmonics, as well as to make power measurements (kW, VA, and VAR), power factor and displaced power factor measurements, voltage and current readouts and waveforms, inrush current and duration recording, transient measurements, and sag and swell recording. Extensive power quality measurements can be made continuously using the software provided with most energy management systems.



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THINK ABOUT IT

Four-Wire Systems

What condition might cause some conductors of a four-wire system to feel hot to the touch?

5.4.0 Solving the Problem

The following are some suggested ways of addressing some typical harmonics problems. Before taking any measures, you should consult a power quality expert to analyze the problem and design a plan tailored to your specific situation.

5.4.1 Harmonics in Overloaded Neutrals

In a three-phase, four-wire wye system, the 60Hz portion of the neutral current can be minimized by balancing the loads in each phase. *NEC Section 220.61* prohibits reduced sizing of neutral conductors serving nonlinear loads. The triplen harmonics neutral current can be reduced by adding harmonic filters at the load. If neither of these solutions is practical, you can pull in extra neutrals (ideally one neutral for each phase) or you can install an oversized neutral to be shared by the three conductors.

In new construction, under-carpet wiring and modular office partition wiring should be specified with individual neutrals and possibly an isolated ground separate from the safety ground.

5.4.2 Derating Transformers

One way to protect a transformer from harmonics is to limit the amount of load placed on it. This is called derating the transformer. The most rigorous derating method is described in *ANSI/IEEE Standard C57.110-1986*. This method is somewhat impractical because it requires extensive loss data from the transformer manufacturer, plus a complete harmonics spectrum of the load current.

The Computer and Business Equipment Manufacturers' Association (CBEMA) has recommended a second method that involves several straightforward measurements that you can get using common test equipment. It appears to give reasonable results for 208V/120Y receptacle transformers that supply the low-frequency odd harmonics (3rd, 5th, and 7th) commonly generated by computers and office machines.

The test equipment you use must be capable of taking both the true rms phase current and the instantaneous peak phase current for each phase of the secondary.

To determine the derating factor for the transformer, take the peak and true rms current measurements for the three-phase conductors. If the phases are not balanced, average the three measurements and plug that value into the following equation:

$$\text{Transformer harmonics derating factor (THDF)} = \frac{1.414 \times \text{true rms phase current}}{\text{instantaneous peak phase current}}$$

This equation generates a value between 0 and 1.0 (typically between 0.5 and 0.9). If the phase currents are purely sinusoidal (undistorted), the instantaneous current peaks at 1.414 times the true rms value and the derating factor is 1.0. If that is the case, no derating is required.

However, with harmonics present, the transformer rating is the product of the nameplate kVA rating times the THDF:

$$\text{Derated kVA} = \text{THDF} \times \text{nameplate kVA}$$

For example, a modern office building dedicated primarily to computer software development contains a large number of PCs and other electronic office equipment. These electronic loads are fed by a 120V/208V transformer configured with a delta primary and a wye secondary. The PCs are fairly well distributed throughout the building, except for one large room that contains several machines. The PCs in this room, used exclusively for testing, are served by several branch circuits.

The transformer and main switchgear are located in a ground floor electrical room. An inspection of this room immediately reveals two symptoms of high harmonic currents:

- The transformer is generating a substantial amount of heat.
- The main panel emits an audible buzzing sound. The sound is not the chatter commonly associated with a faulty circuit breaker, but rather a deep, resonant buzz that indicates the mechanical parts of the panel itself are vibrating.

Table 2 Current Measurements

Conductor Name	Multimeter (true rms)	Average Responding Multimeter	Instantaneous Peak Current
Phase 1	410A	328A	804A
Phase 2	445A	346A	892A
Phase 3	435A	355A	828A
Neutral	548A	537A	762A

The ductwork installed directly over the transformer to carry off some of the excess heat keeps the room temperature within reasonable limits.

Current measurements (see *Table 2*) are taken on the neutral and on each phase of the transformer secondary using both a true rms multimeter and an average responding unit.

A 600A, clamp-on current transformer accessory is connected to each meter to allow the meters to make high current readings.

The presence of harmonics is obvious by a comparison of the phase current and neutral current measurements. As *Table 2* shows, the neutral current is substantially higher than any of the phase currents, even though the phase currents are relatively well balanced. The average responding meter consistently shows readings that are approximately 20% low on all phases. Its neutral current readings are only 2% low.

The waveforms explain the discrepancy. The phase currents are badly distorted by large amounts of triplen harmonics, while the neutral current is not affected. The phase current readings listed in *Table 2* clearly demonstrate why true rms measurement capability is required to accurately determine the value of harmonic currents.

The next step is to calculate the transformer harmonic derating factor, or THDF, as explained previously.

The results indicate that, with the level of harmonics present, the transformer should be derated to 72.3% of its nameplate rating to prevent overheating. In this case, the transformer should be derated to 72.3% of its 225kVA rating, or 162.7kVA.

The actual load is calculated to be 151.3kVA. Although this figure is far less than the nameplate rating, the transformer is operating close to its derated capacity.

Next, a subpanel that supplies branch circuits for the 120V receptacles is also examined. The current in each neutral is measured and shown in *Table 3*.

Table 3 Neutral Loads

Neutral Conductor Number	Current (Amps)
01	5.0
02	11.3
03	5.0
04	13.1
05	12.4
06	15.0
07	1.8
08	11.7
09	4.5
10	11.8
11	9.6
12	11.5
13	11.3
14	6.7
15	7.0
16	2.3
17	2.6

THINK ABOUT IT

True RMS Meters

Why is it important to use a true rms meter?

When a marginal or overloaded conductor is identified, the associated phase currents and the neutral-to-ground voltage at the receptacle are also measured. When a check of neutral No. 6 reveals 15A in a conductor rated for 16A, the phase currents of the circuits (No. 25, No. 27, and No. 29) that share that neutral are also measured. See *Table 4*.

Note that each of the phase currents of these three branch circuits is substantially less than 15A and the same phase conductors have significant neutral-to-ground voltage drops.

In the branch circuits that have high neutral currents, the relationship between the neutral and the phase currents is similar to that of the transformer secondary. The neutral current is higher than any of the associated phase currents. The danger here is that the neutral conductors could become overloaded and not offer the warning signs of tripped circuit breakers.

Table 4 Phase Currents and Neutral-to-Ground Voltages

Circuit Number	Phase Current	Neutral-to-Ground Voltage Drop at Receptacle
25	7.8A	3.75V
27	9.7A	4.00V
29	13.5A	8.05V

The recommendations are:

- Refrain from adding additional loads to the receptacle transformer unless steps are taken to reduce the level of harmonics.
- Pull extra neutrals into the branch circuits that are heavily loaded.
- Monitor the load currents on a regular basis using true rms test equipment.

Summary

Transformers are used in numerous applications to alter the output voltage to serve various purposes. This module covered types of specialty transformers, including:

- Power transformers
- Buck-and-boost transformers
- Current and potential transformers
- Transformers with multiple secondaries
- Autotransformers
- Constant-current transformers
- Control transformers
- Series transformers
- Rectifier transformers
- Step-voltage regulators

It also discussed the problem of harmonics and its associated symptoms and possible solutions. A complete understanding of transformer selection, application, and troubleshooting techniques is essential to the proper installation and servicing of electrical systems.

Notes

Trade Terms Introduced in This Module

Ampere turn: The product of amperes times the number of turns in a coil.

Autotransformer: Any transformer in which the primary and secondary connections are made to a single winding. The application of an autotransformer is a good choice where a 480Y/277V or 208Y/120V, three-phase, four-wire distribution system is used.

Bank: An installed grouping of a number of units of the same type of electrical equipment, such as a bank of transformers, a bank of capacitors, or a meter bank.

Core loss: The electric loss that occurs in the core of an armature or transformer due to conditions such as the presence of eddy currents or hysteresis.

Eddy currents: The circulating currents that are induced in conductive materials by varying magnetic fields; they are usually considered undesirable because they represent a loss of energy and produce excess heat.

Harmonic: An oscillation whose frequency is an integral multiple of the fundamental frequency.

Hysteresis: The time lag exhibited by a body in reacting to changes in the forces affecting it; hysteresis is an internal friction.

Impedance: The opposition to current flow in an AC circuit; impedance includes resistance (R), capacitive reactance (X_C), and inductive reactance (X_L). It is measured in ohms (Ω).

Isolation transformer: A transformer that has no electrical metallic connection between the primary and secondary windings.

Reactance: The imaginary part of impedance; also, the opposition to alternating current due to capacitance (X_C) and/or inductance (X_L).

Additional Resources

This module is intended to present thorough resources for task training. The following reference works are suggested for further study. These are optional materials for continuing education rather than for task training.

American Electrician's Handbook, Terrell Croft and Wilfred I. Summers. New York, NY: McGraw-Hill, 1996.

National Electrical Code® Handbook, Latest Edition. Quincy, MA: National Fire Protection Association.