WHITE PAPER

Select the Right Transformer for Your Application

Transformers of various types are needed for most automated machinery, so it is important to understand the selection and sizing basics.

By Bill Sonnenthal, AutomationDirect

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Power transformers play a key role in any electrical distribution system, and also for end-use equipment like industrial control panels. Although many engineers, designers, and installers encounter transformers during the course of their professional lives, sufficient knowledge to apply them correctly is often lacking.

A transformer's principal function is to "transform" alternating current (AC) from one voltage to another voltage. A good example is the use of control transformers to reduce higher line voltages to lower and safer control voltages.

This white paper covers what power transformers are, why they are used, their various styles, and how to select them for industrial applications.

What is a Power Transformer?

In basic terms, the amount of electrical power delivered by a circuit is a function of the operating current and voltage. Higher voltages and currents transmit more power overall. There is also an inverse relationship whereby a given amount of power can be transmitted by increasing the voltage, resulting in lower current.

For major transmission lines, higher voltages are used because the associated current is lower, which allows the use of relatively smaller conductors. But within industrial control panels, it is usually desirable to use voltages of 120 VAC or less for safety reasons, and reducing the current is less of an issue because the total amount of power required is usually minimal.

Transformers are built with input (primary) and output (secondary) windings of wire called coils assembled over an iron core (Figure 1). The AC voltages are transformed by inductively coupling the primary and secondary coils. As the voltage rises and falls in the primary coil, it creates a matching magnetic field that induces a corresponding voltage in the secondary coil.

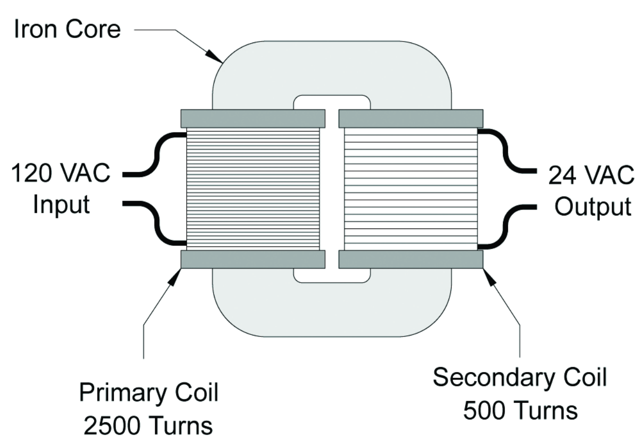

Figure 1: Basic transformer components.
This figure illustrates the turn ratios and voltage transformation of a transformer with a 2500:500 (or 5:1) turns ratio, transforming a 120 VAC input to a 24 VAC output.

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To manipulate the transformation between input and output voltages, the number of turns in each coil is adjusted to produce a "ratio" between the primary and secondary coils of the transformer, known as the "turns ratio,", with voltage transformation proportional to this turns ratio.

Thus, if a transformer has 100 turns on the primary and 50 turns on the secondary, then it has a 2 to 1 ratio. Therefore, when 240 VAC is applied to the primary, the secondary will produce 120 VAC. This is a "step-down" transformer.

Note that we are using the terms input/primary and output/secondary, but a transformer may be supplied with voltage to either coil (note: this is not always recommended or allowable). With the example transformer, if the roles of the coils are reversed and 240 VAC is applied to the secondary, then the primary will produce 480 VAC. This is a "step-up" transformer.

The currents involved go through an inverse transformation during this process. For the example step down transformer (and ignoring losses), if the primary is fed at 240 VAC with a current of 2.5A, the secondary will deliver 120 VAC @ 5 Amps. Because losses are ignored, the power in equals the power out.

Transformer Types

Two major types of transformers are isolation transformers and autotransformers. The following section describe each type and the advantages of using one or the other.

Isolation Transformers
Most transformers are isolation type, where the primary and secondary coils are physically and therefore electrically separate and isolated from one another, although they are magnetically coupled. An isolation transformer provides two distinct features desirable for most applications.

- The secondary circuit is electrically isolated from the higher, and more dangerous, input voltage. This provides a level of safety essential for most circuits.
- An isolation transformer will naturally filter high voltage transients and high frequency noise. In an environment with a high level of electrical noise this feature can play an important role in protecting delicate electronics and downstream equipment.

The following are two specific types of isolation transformer construction, along with an additional feature found in some transformers.

Isolation Transformers: "C Core" Type

Figure 2 shows an exploded view of a typical "C core" isolation transformer, also known as a "C-frame" type. Note that the two coils are completely separate from one another, both physically and electrically. The only coupling between the two coils is magnetically through the core

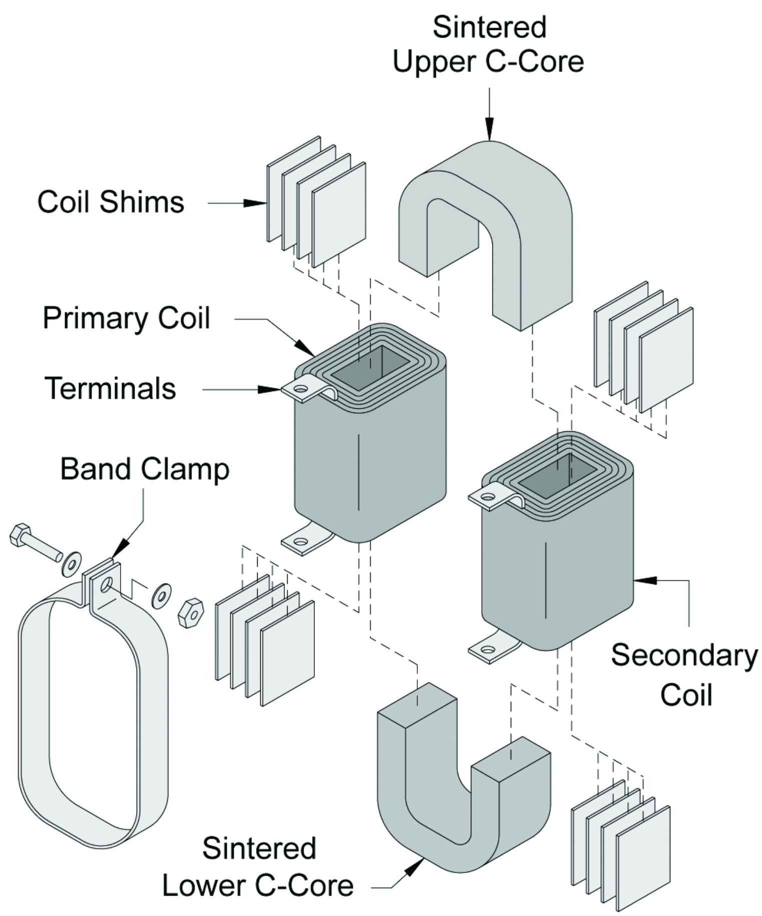

Figure 2: C-frame transformer..
This figure illustrates the completely isolated coils and "C"-shaped cores of a C-frame transformer.

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Isolation Transformers: "E Core" Type

Figure 3 shows a typical "E core" transformer. In this case the primary and secondary coils are placed around a common post in the center of the core. This arrangement produces a more compact unit with higher efficiencies. For these reasons, "E core" designs are the preferred construction for control and general-purpose transformers.

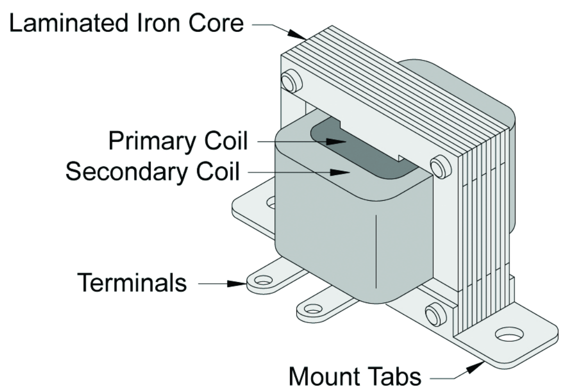

Figure 3: E-frame transformer. This figure illustrates how the coils are electrically separate but arranged around a common post of the "E"-shaped core in an E-frame transformer.

Isolation Transformers: Multiple Taps

Figure 4 shows a schematic representation of a three-phase distribution transformer, effectively three single-phase transformers built into one unit. The transformer is an isolation design, which helps protect downstream equipment from high voltage transients and electrical noise.

However, the output coils have multiple connections, or taps, so the designer can use one unit for more applications because different output voltages are available at each tap..

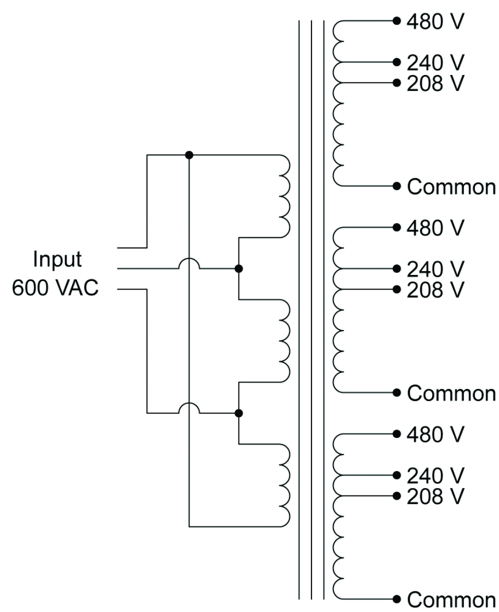

Figure 4: Three phase tapped power distribution transformer. This figure illustrates the isolated coils and multiple output taps of a three-phase power distribution transformer.

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Autotransformers

For applications where isolation is not desired or required, an autotransformer may be specified (Figure 5). These transformers are commonly used for voltage matching. In cases where supplied equipment may require a different voltage than what is available as standard at the install site, a voltage matching autotransformer provides an economical solution.

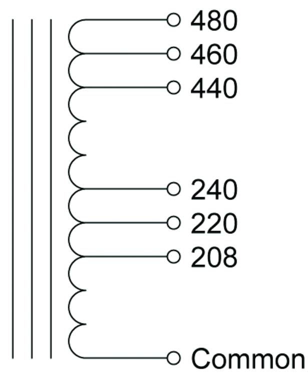

Figure 5: Auto-transformer. This figure depicts an autotransformer with no electrical isolation between the primary and secondary coils.

Autotransformers: Voltage Matching

A common voltage-matching example is when equipment is designed for a 240 VAC supply, but it is being installed in a building with only a 208 VAC service. In this case an autotransformer can boost the voltage and solve the problem quickly. Figure 5 shows a schematic representation of a voltage matching autotransformer. In this case the line voltage is connected to the appropriate input terminals and the adjusted voltages are available at the various output terminals.

Transformer Construction

In addition to electrical characteristics, transformers are designed with consideration for thermal properties. Heat is one of the worst enemies of transformers, so the thermal characteristics of most transformers are designed specifically so the unit can operate in air at full capacity by dissipating heat.

During operation, losses within transformers result in heat dissipation. The core of any transformer heats up because of eddy currents that form in the conductive material making up the core. An eddy current is a complete electrical circuit contained entirely within a conductor. Any conductive material placed in close proximity to rising and falling magnetic fields is subject to the formation of eddy currents and associated heat rise.

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To mitigate eddy currents, transformer cores are typically constructed by stacking laminations together. This stacked core provides an excellent magnetic mass while limiting the electrical path where eddy currents can form. Higher efficiency transformers commonly use very thin laminations to achieve good performance. Lower efficiency units use thicker laminations and are generally of a lower quality and cost. These lower efficiency units can typically be identified by their size-to-VA ratio. Higher efficiency transformers will be significantly smaller than a low efficiency unit carrying the same electrical rating.

Some transformers may be oil-filled for improved heat dissipation, but for purposes of this white paper we are only considering dry-type transformers. Two approaches to dry-type transformer construction are enclosed and encapsulated type.

Open Core Transformers

These transformers are the least expensive design and are unprotected (open core) therefore, they must be installed in some sort of housing to physically protect the transformer from the environment, and to also protect personnel working close to the unit. Larger transformers can be problematic because providing adequate safety, protection from the elements, and sufficient cooling usually results in a rather large and expensive enclosure.

Encapsulated Transformers

Encapsulated transformers address many of the issues associated with an open core transformer. For these transformers, the manufacturer places the transformer into a compact enclosure and fills the gaps with a thermally-efficient potting compound. This arrangement provides a number of distinct advantages including compactness, improved operator safety, superior cooling, better resistance to shock and vibration, available conduit connections, provisions for convenient mounting, low purchase cost, and extended life.

When considering installation and service life, encapsulated transformers are typically the best choice for general purpose, marine, and building distribution applications. Encapsulated transformers are generally available in common sizes such as 25kVA and less.

Ventilated Transformers

Ventilated transformers feature higher efficiency, which translates into increased profitability due to lower operating costs, decreased cost of ownership over the lifetime of the transformer, and reduced air conditioning costs due to lower heat emissions. Common models (i.e., HPS Sentinel G Ventilated Transformers) are rated for up to 75kVA with a standard 10kV BIL rating that provides increased reliability and protection against critical equipment failure (including protection against voltage spikes and other line transients).

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Control Transformers

Control transformers are designed for voltage conversion applications with high inrush that require reliable output voltage stability, such as where electromagnetic switching devices are used. Common models include 1-phase open core control transformers that support a variety of primary / secondary voltage configurations in a range of VA ratings.

Transformer Efficiency

As of January 1, 2016, the federal government has mandated, through the Department of Energy (DOE), 10 CFR-Part 431, that all low voltage, dry-type distribution transformers must have higher minimum efficiency ratings as shown in the Figure 6 Tables.

Single-phase

kVA	DOE Efficiency Level (%)
15	97.7
25	98.0
37.5	98.2
50	98.3
75	98.5
100	98.6
167	98.7
250	98.8
333	98.9

Three-phase

kVA	DOE Efficiency Level (%)
15	97.0
30	97.5
45	97.7
75	98.0
112.5	98.2
150	98.3
225	98.5
300	98.6
500	98.7
750	98.8
1000	98.9

Figure 6: Efficiency tables. These tables indicate the minimum efficiency ratings mandated by the DOE for dry-type transformers.

When selecting and sizing transformers, designers need to choose units with the required efficiency. They may also want to do a cost/benefit analysis to see when even higher efficiency units are warranted.

Transformer Applications

Although there are literally thousands of uses for transformers, the bulk of these applications fall into three basic categories.

Utility Transformers

The most visible application for utility transformers is power distribution throughout an electrical grid. One needs only to look up at the power poles and utility yards throughout a country's landscape to see a pole- or pad-mounted transformer.

Distribution Transformers

A second common transformer application is for building power distribution, where it is commonly necessary for a higher grid voltage to be stepped down into a suitable voltage for use within the building. Single-phase and three-phase power distribution transformers, each with multiple taps, are designed to provide the required standard voltages.

Control Transformers

The third application is for the control transformers commonly incorporated into a machine or other equipment. Control transformers are a very broad category, supporting many voltage-matching conditions and power delivery requirements.

In this category, high efficiency transformers are quite desirable because they are considerably smaller and produce less heat than their standard counterparts. Figure 7 shows a typical encapsulated transformer appropriate for general purpose applications.

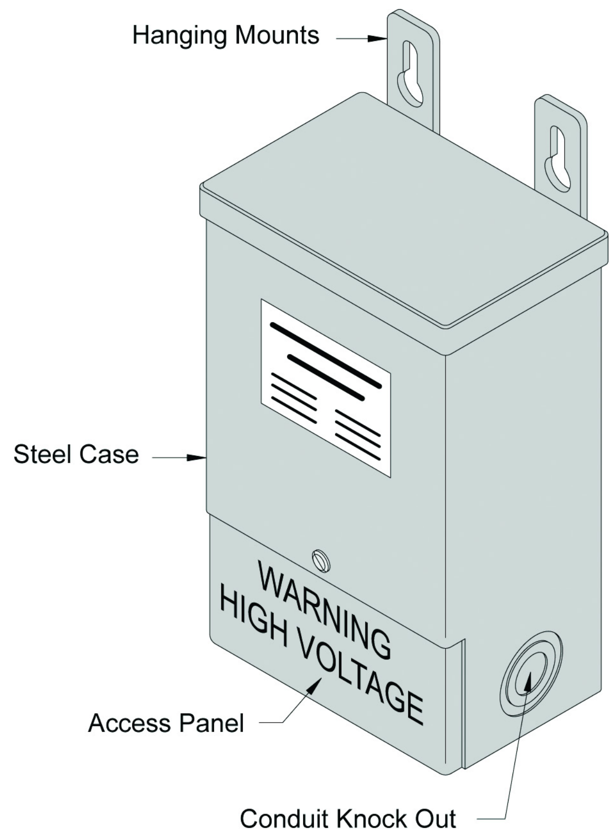

Figure 7: Encapsulated general-purpose transformer. Encapsulated general-purpose transformers are commonly used with industrial systems and equipment.

In most machine applications, AC control circuits operate at either 24 or 120 VAC. These lower voltages, especially 24 VAC, are significantly safer for users. Transformers keep these lower voltages completely isolated from the higher line voltages used to power the equipment.

Some control transformers are configured for use within a control panel. Figure 8 shows a typical high inrush "E" core control transformer, configured with a three-element fuse block on-board to save space. One fuse is used to protect the output and two are used to protect the input.

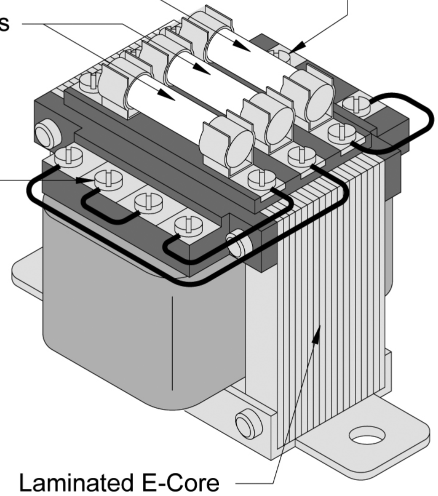

Figure 8: Control transformer with fuses. Control transformers for use within control panels may incorporate space-saving features like on-board fuses.

Transformer Electrical Considerations

The overall power rating of transformers is typically indicated in volt-amps (VA). To determine the VA rating required for any single-phase circuit, the total current load (in amps) must be added up, and the result multiplied by the required secondary voltage (in volts):

Current x Voltage = Volt Amps (VA)

To determine the VA rating for three-phase circuits, the following formula is used:

Current x Voltage x 1.732 = 3 PH VA

Therefore, if a 24 VAC circuit has six heating elements at 500 mA each, four indicators at 100 mA each and a panel lamp at 1 amp then the required power is:

[(6 x 0.5) + (4 x 0.1) + (1 x 1.0)] x 24 = 105.6 VA

This figure is referred to as the "total steady state", "holding", or "sealed" rating. This method is appropriate when sizing a transformer for resistive loads. However, when sizing for motors, solenoids and coils, the high inrush current of these inductive loads must be considered.

Inrush currents are the high momentary loads generated when power is first applied. For example, the inrush current for three-phase induction motors can be as high as seven to ten times the nameplate current. For solenoid valves, the holding VA rating may be 16, while the inrush VA may be 27. In these cases, the inrush current of the components must be used when calculating the required VA rating of the transformer. (See the transformer manufacturer's sizing charts for guidance).

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Most control transformers are specifically designed to provide the high inrush currents required by inductive circuits, with the duty cycle of the transformer sufficient to provide very high momentary currents, and then settle back to a steady state current. As components are switched on and off, surge currents will spike, but with no adverse effects on the transformer.

When considering circuit protection associated with transformers, delayed action or "slow-blow" fuses should be selected to accommodate the high inrush currents. Article 450.3 B of the National Electric Code provides requirements for protecting transformers with either fuses or circuit breakers. This code should be adhered to whenever specifying or installing a transformer.

Selecting a Control Transformer

Control transformer selection requires first-hand knowledge of the specific application, along with an understanding of some basic terms. To select the proper transformer, three characteristics of the load circuit must be determined: steady-state load (sealed VA), total inrush VA, and inrush load power factor.

Total steady-state "sealed" VA is the total amount of VA that the transformer must supply to the load circuit for an extended length of time. This is calculated by adding the total steady-state VA of all devices in the control circuit. The operating VA data for the devices should be available from the manufacturers.

The inrush VA is the amount of VA the transformer must supply for all components in the control circuit that may be energized at the same time, so consideration for the start-up sequence may be required. Inrush VA data should be obtained from the device manufacturers.

The inrush load power factor is difficult to determine without detailed vector analysis of all the control components. In the absence of such information, a 40% power factor may be utilized in most cases.

Once the three circuit variables have been determined, follow these five steps to select the proper transformer:

1. Determine the primary (supply) and secondary (output) voltage requirements, as well as the required frequency (i.e. 60 Hz), and whether the circuit is single-phase or three-phase. The transformer will be selected from products with suitable input and output voltage connections and VA ratings.

2. Calculate the total sealed VA of the load circuit.

3. Calculate the inrush VA by adding the inrush VA of all components being energized at the same time.

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4. Calculate the total inrush VA using one of two methods:
   a. If the nominal supply voltage does not fluctuate more than 5%, then reference the 90% secondary column in the manufacturer's Regulation Data Table for the correct VA rating.
   b. If the supply voltage varies up to 10%, the 95% secondary voltage column should be used to size the transformer.

5. Using the manufacturer's regulation data table, select the appropriate VA rated transformer:
   a. With a continuous VA rating equal to or greater than the value in Step 3.
   b. With a maximum inrush VA equal to or greater than the value obtained in Step 4.

Here are some additional considerations:

1. If the loads have nameplates in VA or kVA, those values can be totalized directly without requiring voltage and current calculation. Note that 1 kVA = 1,000 VA.
2. Single-phase loads are straightforward to calculate as VA = V x A. However, for three-phase loads the following relationships are useful:
   a. To determine 3-phase kVA when volts and amperes are known:

   $$\text{3–Phase kVA} = \frac{\text{Volts x Amps x 1.73}}{1000}$$

   b. To determine phase amperes with 3-phase kVA and volts are known:

   $$\text{Amps} = \frac{\text{3–Phase kVA x 1000}}{\text{Volts x 1.73}}$$

Transformer Sizing Example for a Mixed Three-Phase Load

Question:
Select a transformer so the available supply voltage of 480Y/277, three-phase, four-wire can provide power to the following two loads:

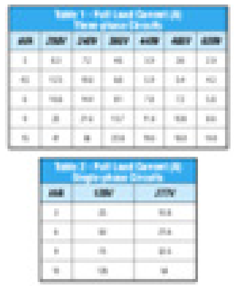
1. A three-phase induction motor, 25hp @ 240V, 60Hz
2. A one-phase resistive heater load of 4kW @ 240V

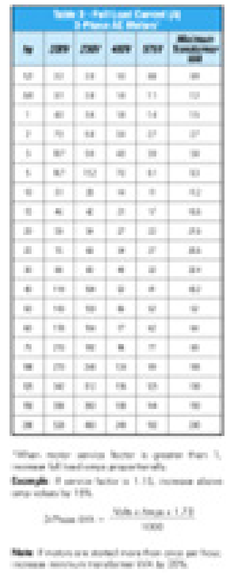
Answer:
Compute the kVA required.

1. Motor load from Example Table 2, the current is 68A.
   (240V x 68A x 1.73)/1000 = 28.2 kVA
   (or the kVA can also be obtained from Example Table 3)
2. Heater load — 4kVA

A three-phase transformer must be selected because of the motor load. For this case, each phase will have the additional 4kVA rating required by the heater, even though the heater will operate on one phase only. Therefore, the transformer should have a minimum kVA rating of 28.2 + 4 + 4 + 4 or 40.2 kVA.

Referring to the appropriate selection chart, a 480 delta primary-240 delta secondary transformer may be used on a four-wire, 480Y/277-volt supply. The fourth wire (neutral) is not connected to the transformer. To avoid overloading the transformer, a 45kVA transformer should be selected. Note: Any two wires of the 240V, three-phase developed by the secondary of the transformer may be used to supply the heater. Any two wires of a three-phase system will supply single-phase power.





Example Tables

Conclusion

Because transformers are a fundamental element of most electrical distribution systems, it is crucial for designers to have a solid understanding of what they are, how to use them, and the various styles available for common industrial applications. This white paper provides an introduction to these topics, with further information available from vendors and other sources.

SIDEBAR
Commonly Available Transformer Types

Buck-Boost Transformers:

Buck-boost transformers (Figure 9) are designed to maximize the performance and life of electrical equipment. They are typically used to power loads with specific voltage requirements differing from the available line voltage. The 2008 NEC Handbook Section 210.9 provides the following definition for a buck-boost transformer:

A buck-boost transformer is classified as an autotransformer. A buck-boost transformer provides a means of raising (boosting) or lowering (bucking) a supply line voltage by a small amount (usually no more than 20 percent).

A buck-boost transformer incorporates two primary windings (H1-H2 and H3-H4) and two secondary windings (X1-X2 and X3-X4). The primary and secondary windings may be isolated within the unit, and this type of transformer can be used as a standard step-down transformer. However, it is also possible to connect the windings together externally, creating an autotransformer configuration. As an autotransformer, connections can be made to buck (lower) or boost (raise) the output voltage compared to the input voltage, correcting voltage by anywhere from 5 to 20 percent.

Figure 9: Buck-boost transformers from Jefferson Electric. Buck-boost transformers can be used to adjust available voltage to whatever is required by utilization equipment.

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Energy Efficient Ventilated Distribution Transformers:

Ventilated stand-up distribution transformers (Figure 10) should meet the latest energy efficiency standards as outlined by the DOE, Natural Resources Canada (NRCan), and other regulatory agencies. These transformers offer significant energy savings as well as a variety of environmental benefits. Designed and manufactured using industry-leading design solutions, technology and materials, they feature higher efficiency which translates into increased profitability due to lower operating costs, decreased cost of ownership over the lifetime of the transformer, and reduced air conditioning costs due to lower heat emissions.

Figure 10: Ventilated distribution transformers from Hammond Power Solutions (HPS). Ventilated distribution transformers are often installed in the electrical rooms of buildings.

Dry-Type Encapsulated Distribution Transformers:

Ventilated stand-up distribution transformers (Figure 10) should meet the latest energy efficiency standards as outlined by the DOE, Natural Resources Canada (NRCan), and other regulatory agencies. These transformers offer significant energy savings as well as a variety of environmental benefits. Designed and manufactured using industry-leading design solutions, technology and materials, they feature higher efficiency which translates into increased profitability due to lower operating costs, decreased cost of ownership over the lifetime of the transformer, and reduced air conditioning costs due to lower heat emissions.

Figure 11: Dry-type encapsulated distribution transformers from Acme Electric. Dry-type encapsulated distribution transformers are suitable for use in dusty areas

Compact Industrial Control Transformers:

Compact industrial control transformers (Figure 12) work well in high inrush applications requiring reliable output voltage stability. Designed for industrial applications where electromagnetic devices such as relays, solenoids, etc. are used, they can accept high inrush currents, such as when electromagnetic devices are initially energized, while delivering good output voltage regulation.

Figure 12: Compact encapsulated industrial control transformers. Compact encapsulated 1-phase industrial control transformers are used in control panels to support the operation of electromagnetic devices like solenoids and relays.

Open Core Industrial Control Transformers:

Open core 1-phase industrial control transformers (Figure 13) are ideally suited for general purpose, industrial, and light duty loads. They are designed for applications with lower inrush and where less demanding environmental protection is required, with available models offering an efficient and economical solution.

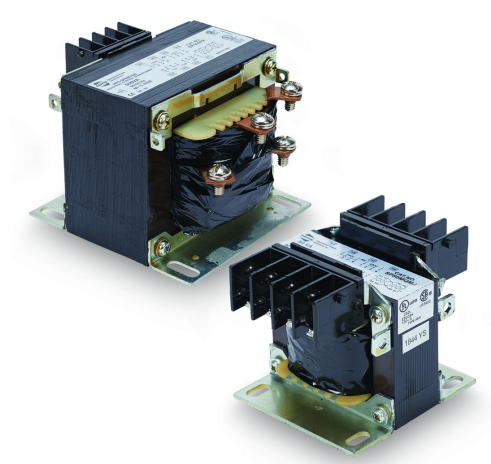

Figure 13: Open core industrial control transformers from Hammond Power Solutions (HPS). Open core 1-phase industrial control transformers are economical for light-duty applications but must be installed in properly protected enclosure.

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Commercial Encapsulated Transformers:

Commercial encapsulated transformers (Figure 14) provide a compact and innovative design for applications where quality, ease of installation, and low cost are key. Models encapsulated with electrical grade silica sand and resin compounds are available to completely enclose the core and coil to seal out moisture and airborne contaminants, eliminating corrosion and deterioration.

Figure 14: Commercial encapsulated transformers from Hammond Power Solutions (HPS). Commercial encapsulated 1-phase transformers are an economical alternative for many applications.

Ventilated Drive Isolation Transformers

Drive isolation transformers are specifically designed to withstand the mechanical, voltage distortion, and heating stresses associated with supplying power to motor variable frequency drives (VFDs). They are available for 5 to 200HP VFDs and are recommended for these installations, providing the following advantages:

- ***Isolation between the power source and the VFD system.***
- ***Acts as a line reactor, reducing harmonics and the effects of voltage and current distortion caused by the VFD.***
- ***The wye-connected secondary can be grounded, preventing the transfer of common-mode noise and transients between the power source and the VFD system.***
- ***Localizes the effects of VFD-induced ground currents, preventing them from being passed upstream to the power system.***
- ***Typically designed to withstand overcurrent of 150% rated load for 60 seconds, and 200% rated load for 30 seconds.***