**PDHonline Course E162 (2 PDH)**

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# 240 V Motor Operation on 208 VAC

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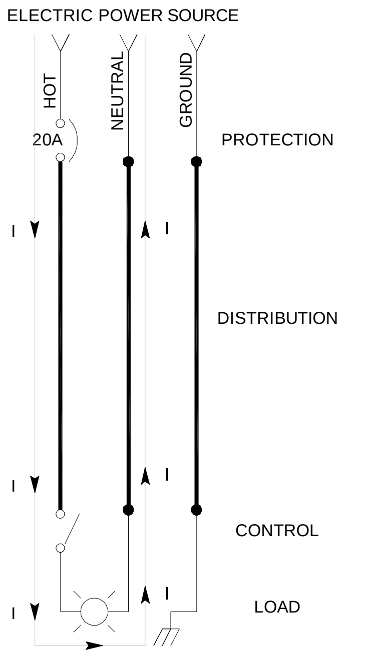
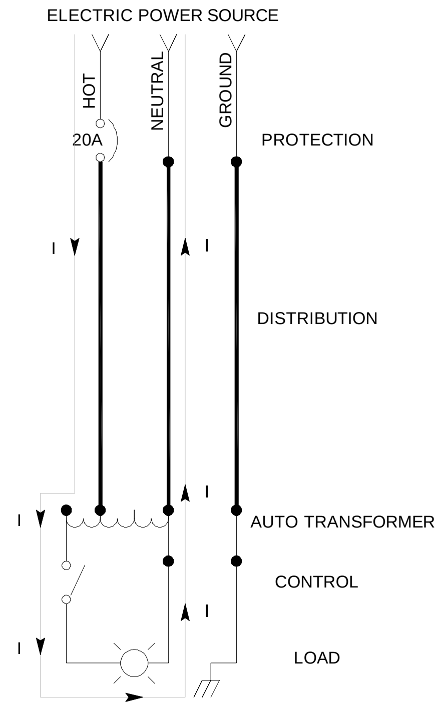
*Thomas Mason, P.E.*

## Course Content

The basic form of a motor circuit for a pump, fan or light is as follows:




GENERIC POWER CIRCUIT




GENERIC AUTO TRANSFORMER POWER CIRCUIT

On the left is the "as-found" electrical distribution system. The AC power comes from somewhere. We are not addressing the details of the source in this course. We must note, however, that there is a safety conductor, the Ground, a current return conductor, the Neutral, and one conductor trying to kill you or the next person who uses the device, this is the Hot. The Ground is supposed to be completely safe and the Neutral is supposed to be safe most of the time. The Hot must be watched closely.

There is a 20 A circuit breaker for protection. It is a thermal-magnetic circuit breaker. The thermal portion trips it off when 30 amps flows for 10 minutes or when 100 amps flows for 10 seconds. The magnetic portion trips it off when 1,000 amps tries to flow. For most circuit breakers, the 1,000 amps flows for about 3 cycles, or .048 seconds. Circuit protection is addressed in the PDHonline course, "Minimal Selective Coordination."

The three heavy lines are the distribution from the power panel to the load. Again, this course does not examine the power distribution system, but we will assume a long run, perhaps from the main building to a pump house at the edge of the property, or from a main distribution panel in the basement to an exhaust fan in the penthouse. Exactly the same effect is observed for a house with a long driveway and the utility transformer at the street.

The example demonstrates simple control, a switch. The switch may be part of the load or separate from the load. Our example does not involve the switch.

The load shown is a light bulb. This is nice because a light bulb very clearly demonstrates voltage problems. A mixer or drill could be used as the load, but you would have to listen for the slowing down instead of noticing the dimming. This example is single-phase, and shows an auto transformer “boost” solution for tool problems far from the electric source. The same circuit, with different transformer connections, is an auto transformer “buck” solution for rapid burn-out of incandescent light bulbs close to the electric source.

The ground connection between the supply and the load is a present day requirement but plays no part in normal circuit operation.

The light line with the arrows indicates that current flows when the protective device is closed and the switch is closed. (Switches are conventionally shown open because it is very difficult to show a closed switch that still looks like a switch. Also, open is safe.)

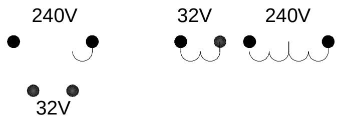
When the switch is closed and current is flowing, there are losses in the distribution system. If we measure the voltage at the source and at the switch with the switch off, we should see 120 volts in both places. With the switch closed, there are losses along the distribution. The source remains 120V, but the switch only sees 115V or 110V. You will NOT see a momentary brightness that dims down. Instead, you will see dim that slowly brightens. Incandescent lamps have an inrush characteristic that much current flows when they start up. The much current causes excessive voltage drop so that the first light is very dim. As the inrush subsides, the lamp brightens. [Parenthetical note: old auto brake lights and turn signals were incandescent lamps. New truck brake lights and turn signals are LED’s. LED’s do not have an inrush characteristic. Note the “sharp” switching of the turn signals on a commercial truck.]

This inrush current for the lamp is very similar to the inrush for a motor, but for a different reason. The motor functions by magnetic fields. Magnetic fields need extra current to form before the motor can spin. Typically, 6x normal current flows during the inductive inrush current portion of motor starting. In addition, motors must get some mass rotating before they can do any useful work, like pushing air or cutting sawdust. The starting inertial load adds to inrush current and takes longer to subside. Typically, an oscilloscope trace of a motor starting will show the 6x inductive inrush for about one cycle (.016sec) and inertial inrush for up to 10 seconds.

A very interesting, easy experiment is to watch the lights when you start your vacuum cleaner. You can also load down the vacuum by stepping on the case and grinding the brush into the carpet. Watch the lights dim. [Doesn’t work for fluorescent lights, though, the ballast compensates for voltage changes.]

The right-hand graphic just described is identical to the basic system just describes, with the addition of an auto transformer connected in “boost” or “buck” configuration.

Most auto transformers are very conventional two-winding transformers, with the windings connected together as an auto transformer. Compare the separate winding transformer below with the auto transformer in the introductory graphic.




SEPARATE WINDING TRANSFORMER

The way a transformer works is that you connect 240V to that side and you get 32V out of the other side. Common uses of small transformers are to provide safe, low voltage for doorbells, cell phone battery chargers and toys. [There are also switching power supplies that work differently on some cell phone chargers and toys.]

The transformer is very simple and reliable. Typical losses are less than 5%. They work exactly as they are graphically presented. Supply voltage goes around one set of windings. It creates magnetism which is connected to the other winding by an iron core which is not usually shown. The magnetism creates a voltage which will drive current through a load on the second winding. Hold firmly to this idea - the new voltage source is a separately derived source. Yes, the primary winding must be connected for it to work, but the secondary is a new and independent source.

The auto transformer connection, shown in the introductory graphic, connects one wire from the secondary to one wire of the primary. The load is connected from the other wire of the secondary to the return conductor. Depending upon which wires you connect, the voltages add or subtract. Adding voltage is called the “boost” connection and subtracting voltage is the “buck” connection. These are the three basic confusions associated with auto transformers. Everyone thinks that there is something special taking place between the primary and secondary. No. It is exactly the same as a 9V battery and a 1-1/2V battery. Connect them one way in series and get 10.5V. Connect them the other way and you get 7.5V.

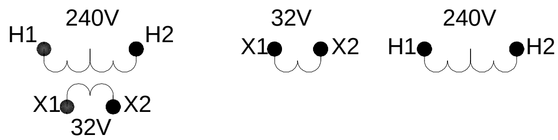
Our transformer can give us 240+32 = 272V or 240-32 = 208V.

The first confusion is that there is something special about auto transformers.

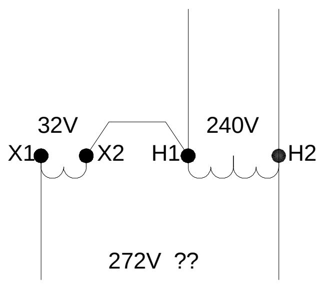
The second confusion is whether the voltages add or subtract.

In order to guess successfully whether a particular connection will add or subtract, the leads on both the primary and secondary are labeled. For the most simple 240-32V transformer, the high side (240V) leads are labeled H1 and H2. The low side (32V) leads are labeled X1 and X2. They are in order, so that X1-to-load, X2-to-H1, H1-to-source, H2-to-source, and H2-to-load provides addition. This is sometimes called a boost connection.

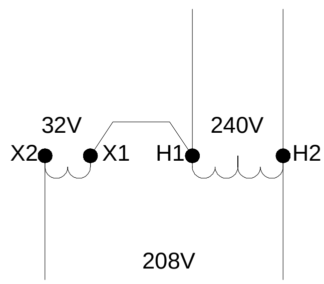
Similarly, X2-to-load, X1-to-H1, H1-to-source, H2-to-source, and H2-to-load provides subtraction. This is sometimes called a buck connection.



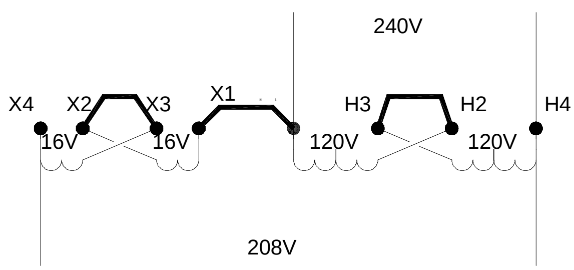

SEPARATE WINDING TRANSFORMER
(TERMINALS LABELED)




BOOST CONNECTION




BUCK CONNECTION




BUCK CONNECTION
USING 120x240-16x32 TERMINALS
(INDUSTRY STANDARD CONFIGURATION)

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The third confusion is sizing the auto transformer. Most persons look closely at the motor horsepower and want a transformer about that size - maybe a little bigger. Not good for the auto transformer task.

The auto transformer provides only 32V of the 240V for the motor. All of the motor would require a transformer the size of the motor (or a little larger). 32/240 of the motor requires a transformer only 32/240 of the motor (or a little larger).

For a 20HP, 240/3 motor, rated current is about 54A. All of the motor KVA = SRT(3)*V(l)*I(l) = 1.732*.240*54 = 22.45 KVA. This sounds right, because a HP is about a KVA. If you wanted a transformer for all of the motor, you should buy 30KVA.

Or, we could calculate 32/240 of 22.45 KVA and get 2.99 KVA for an auto transformer. Or, we could look at the manufacturer's application table for our voltage and our current. This is highlighted below:

| | | | | |
|---|---|---|---|---|
| Single Phase | | | | |
| Line Voltage (Available) | | | 208 | |
| Load Voltage (Output) | | | 240 | |
| Acme Cat No. | Conn. Diagram | | H | |
| | | | | |
| T-1-13073, 1.00KVA | Load KVA | | 7.5 | |
| | Load Amps | | 31.25 | |
| | Max Fuse or CB | | 50 | |
| | | | | |
| T-1-13074 1.50 KVA | Load KVA | | 11.25 | |
| | Load Amps | | 46.90 | |
| | Max Fuse or CB | | 70 | |
| | | | | |
| T-1-13075 2.00 KVA | Load KVA | | 15.00 | |
| | Load Amps | | 62.50 | ← No inrush |
| | Max Fuse or CB | | 90 | |
| | | | | |
| T-1-13076 3.00 KVA | Load KVA | | 22.50 | |
| | Load Amps | | 93.80 | ← W/ inrush |
| | Max Fuse or CB | | 350 | |
| | | | | |
| | | | | |

This is for a single phase load of 54A. To provide for a three phase load of 54A, two auto transformers are connected in open delta, as alluded to previously and discussed in more detail later.

The correct size of the transformer is 3.00KVA and two are required to handle running load and inrush. The manufacturer's table says that 350A is the maximum protection size, but the 2005 National Electric Code, Section 450.4, limits auto transformer protection to 1.25 the rated amps, 1.25 x 93.80 = 117A. Therefore, use a 125A circuit breaker (next larger standard size).

Please note that the controlling section of the National Electric Code is ARTICLE 450.4 and the requirement is protection to 1.25x the rated amps of the transformer low-voltage winding.

It is your instructor's recommendation to consider 1KVA the smallest practical auto transformer. Sizes are available down to .05KVA, but if you consider the design cost and the installation cost, there is very little savings below 1 KVA and substantial likelihood of overload from inrush or mis-sizing.

A 1KVA auto transformer will support three fractional horsepower motors (with individual motor protection), including inrush. Most often, we provide three phase 240 V using two auto transformers, because you get 3x capacity with only 2x materials cost and less than 1.5x labor cost. The open delta produces a "soft phase" and discussed previously, so it should be lightly loaded when you distribute the single phase loads. The transformers and motors are fully protected. If you accidentally get a heavy load on the soft phase, it will draw extra current and trip the motor protection if the motor is in danger of overload. [Motors are very sensitive to voltage imbalance and will trip standard motor protection overloads before the imbalance is large enough to measure.]

In the following portion of this course, we will discuss the following topics:

Voltage Names, 110V, 115V, 120V, 200V, 208V, 220V, 230V and 240V

Using an auto transformer to correct low or high voltage

Limitations of auto transformers

Use and protection of auto transformers per the National Electric Code

Motor inrush current and sizing the transformer and protective circuit breaker

Quick Summary of sizing an auto transformer and circuit breaker for a small single-phase electric motor

Quick Summary of sizing an auto transformer and circuit breaker for a small three-phase electric motor

Open-delta graphic

Below, each of these topics is discussed in some detail:

**Voltage Names, 110V, 115V, 120V, 200V, 208V, 220V, 230V and 240V -** The rule for 2005 is that power is supplied at a voltage which is an even multiple of 120V. In the odd way that electrical engineers think, 208V is an even multiple of 120V. 240V is an even multiple of 120V. Until recently, 208V was used for multi-wire receptacle circuits, 120/208, and 240V was used for HVAC equipment, 240-delta 3-phase. Today, 240/3 is considered unnecessary and almost all HVAC equipment is sold for 208/3 or 208-240/3.

The present names for the "source" voltage are 120V, 208V, 240V, 480V or 600V. (480V and 600V equipment tend to blow up catastrophically when abused and are not part of this course and not normally considered for auto transformer application.) The values 120V, 208V, 240V, 480V and 600V are part of your contract with the Utility and, in theory, enforceable via the State Utilities Commission.

The international standards expect a 5% loss of voltage between the utility service and the point of utilization. 120 --> 114.0V, 208 --> 197.6V, 240 --> 228V, 480 --> 456V and 600V --> 570V. For this reason, utilization voltage is often considered 115V, 200V, 230V, 460V and 575V.

In fact, electric loads are rated for normal operation at the utilization voltage, with a range of +5% to –10%. Therefore, a 120V motor is really a 115V motor, with a within-warranty range of 105-120V. A 208V motor is really a 200V motor, with a within-warranty range of 180-210V. A 240V motor is really a 230V motor, with a within-warranty range of 210-240V. In addition, some especially forgiving motors are available with both 200V and 230V operation permitted. These are 200-230V motors.

110V and 220V are remnants of earlier days with slightly lower supply voltages or slightly higher acceptable system losses. They are not meaningful today.

There are three very valuable learnings from this discussion. First, “120V” is imaginary. Your utility may give you 130V, 125V, 115V, 110V or 105V. Most of their customers get something near 120V, but some do get 130V and many do get 105V. (This was the original application of auto transformers, to correct stable utility off-voltages.)

Second, utilization voltage is dependent upon system losses within your facility, system losses on the Utility side of the service and really weird things that Utilities do because they can get away with it. Almost all business and commercial customers experience high voltage in the morning, lower voltage at mid-day and higher voltage in the evening. Around midnight, things stabilize to the rated value. Auto transformers will not correct for unstable voltages. If the supply voltage is low and your boost it, then the supply rises, the utilization voltage becomes very high. High voltage pops light bulbs. If the supply voltage is high and you buck it, then the supply drops, the utilization voltage becomes very low. Very low voltage burns out motors.

Third, slightly high voltage is good for motors, fluorescent lights and HID lights. Less current is drawn, more available capacity remains and everything operates at higher efficiency. For this reason, it is almost universal for factories, with the ability to select voltage taps, to choose slightly high voltages. It is good to give a 240V motor 240V, even if the nameplate says 230V. It starts better and runs better.

**Using an auto transformer to correct low or high voltage -** All discussion up to this point has been of the form 208V + 32V = 240V. It would be easy to conclude that auto transformers are available only in 240V-32V form. The table reproduced in the sizing example had only one column.

In fact there are two standard forms of auto transformers, 120x240-16x32 and 120x240-12x24. Using the second form, 120V nominal can be raised or lowered by 12V or 24V. Thus, 96V or 108V can be brought up to 120V. Using the first form, 88V or 104V can be brought up to 120V. Similarly, four over voltage corrections are available. Application of all the various forms at many, many available supply voltages are illustrated in the complete table provided by the manufacturer. This, of course, adds to the confusion which introduced the course.

**Limitations of auto transformers -** There are three problems with auto transformers. First, they are inherently high impedance devices. They disproportionately reduce the voltage at the motor during starting inrush current. Knowing this, we try to oversize the auto transformer to reduce the inrush problem. This also matches the requirement to oversize the protective circuit breaker so that it will hold in during inrush. For integral horsepower motors, size the auto transformer for at least 2x the motor full load current.

The second problem is the soft phase produced by the open delta connection for three phase voltages. It is a problem, but a small problem. If the system is sized 2x, as suggested previously, the soft phase will not adversely affect motor starting or operation. If you run into trouble, check the supply. You probably have marginally imbalanced voltage coming in and by chance, aggravated the problem with the soft phase. Change the common-leg of the open delta and the problem should go away.

The third problem is that auto transformers are a very small devices on a large electric distribution system. They are overlooked. If the old cooler is replaced with a new cooler, no one looks at the auto transformers. Probably no one still working for the firm even knows they are in the circuit. It is common beyond belief to find the old 240V cooler was replaced with a new 208V unit, but is getting 240V from the auto transformer. As indicated earlier, motors are usually happy running on slightly high voltage. But, it is still not a good idea.

**Use and protection of auto transformers per the National Electric Code -**
The 2005 National Electric Code, section 450.4 discusses use of the auto transformer connection. Three points are critical. First, protection must be set at 1.25x the full load rating of the transformer, or the next higher standard size. Second, only the primary need be protected in the buck-boost application we are using. Third, there are additional connection forms, Tee and Zig-Zag, which have additional requirements that do not apply to us.

**Motor inrush current and sizing the transformer and protective circuit breaker** - A motor functions by magnetic fields. Magnetic fields need extra current to form them before the motor can spin. Typically, 6x normal current flows during the inductive inrush current portion of motor starting. In addition, motors must get some mass rotating before they can do any useful work, like pushing air or cutting sawdust. The starting inertial load adds to inrush current and takes longer to subside. Typically, an oscilloscope trace of a motor starting will show the 6x inductive inrush for about one cycle (.016sec) and inertial inrush for up to 10 seconds.

Don't gloss over this discussion of inrush. There is magnetic inrush and mechanical load inrush. Magnetic inrush almost momentary. Mechanical inrush lasts up to 10 seconds. Magnetic inrush is 6x full load current. Mechanical inrush is about 2.5x full load current.

Clearly, the auto transformer must have overload capabilities or must be oversized to handle inrush. Auto transformers do not have much overload capability. They must be oversized to handle inrush. A larger auto transformer means larger conductors feeding it and a larger protective circuit breaker.

A standard circuit breaker is thermal-magnetic. For a 20A CB, the thermal portion trips it off when 30 amps flows for 10 minutes or when 100 amps flows for 10 seconds. The magnetic portion trips it off when 1,000 amps tries to flow. For most circuit breakers, the 1,000 amps flows for about 3 cycles, or .048 seconds. Circuit protection is addressed in the PDHonline course, "Minimal Selective Coordination.

The conclusion is to size the auto transformer for 2x to 3x the full load current of the motor. Size the supply conductors for the transformer rating. Size the circuit breaker for the conductors.

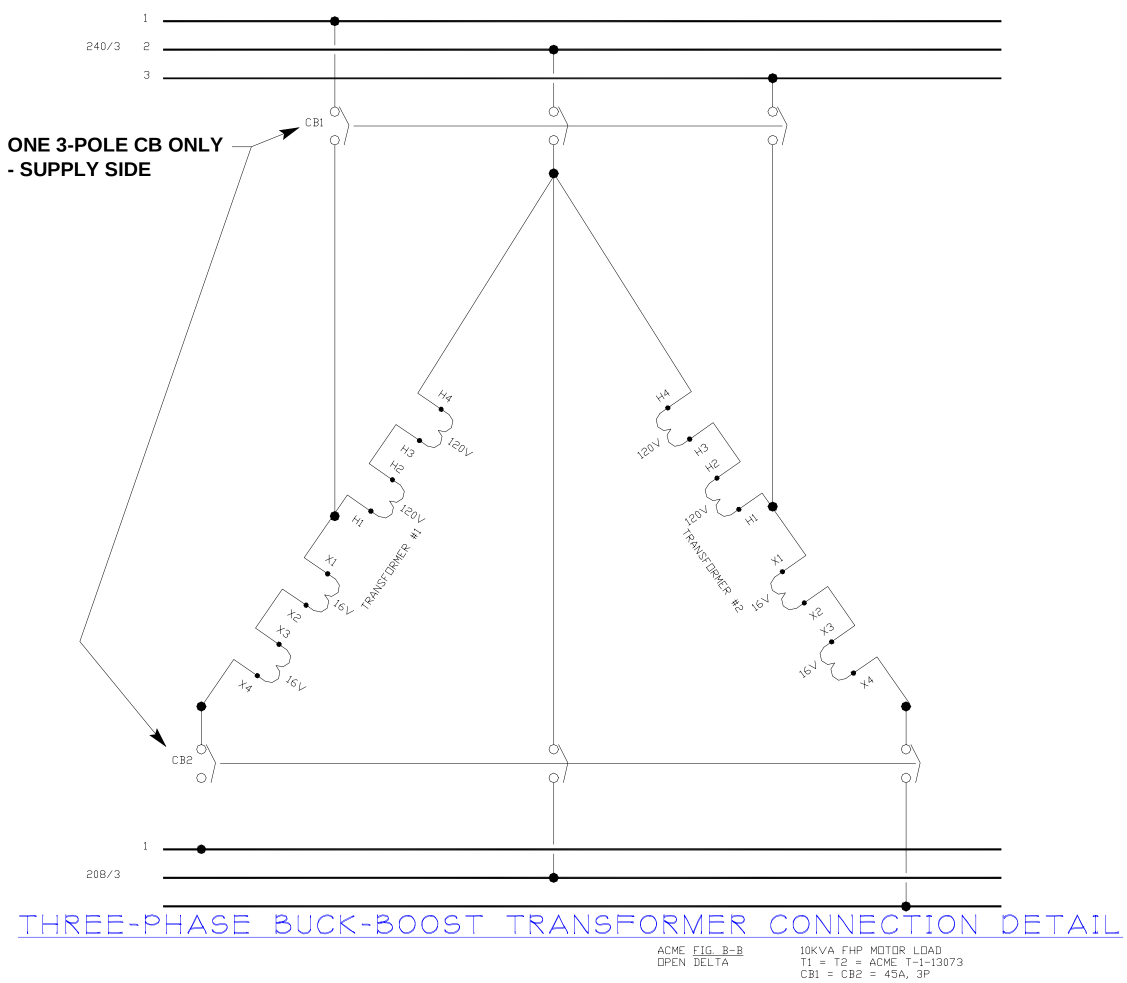
**Quick Summary of sizing an auto transformer and circuit breaker for a small single-phase electric motor -**

1) Record the nameplate volts, amps and phases of the motor.
2) Identify the supply voltage for the motor, 120V, 240V - not 115 or 230.
3) Use the manufacturer's table to select the available voltage, the desired supply voltage and the amps required. Go to at least 2x the nameplate amps.
4) Size the supply conductors and circuit breaker for the auto transformer amps.
5) If the motor is 3-phase, you need two transformers.
6) Check the voltage before trying to start the motor. (It is very easy to connect to the wrong terminals.)

**Quick Summary of sizing an auto transformer and circuit breaker for a small three-phase electric motor -**

1) Record the nameplate volts, amps and phases of the motor.
2) Identify the supply voltage for the motor, 120V, 240V - not 115 or 230.
3) Use the manufacturer's table to select the available voltage, the desired supply voltage and the amps required. Go to at least 2x the nameplate amps.
4) Size the supply conductors and circuit breaker for the auto transformer amps.
5) If the motor is 3-phase, you need two transformers.
6) Check the voltage before trying to start the motor. (It is very easy to connect to the wrong terminals.)

**Open-delta graphic** - The following is a standard design detail for use of two auto transformers in buck-boost configuration.



**Sample Calculation of Motor Inrush Current** -

Given: 5HP HVAC exhaust fan rated 230/3/60, started across-the-line, no transformer

Find: Approximate inrush current.

Solution:

A) You have to know something about mechanical loads. Fans are exponential loads. Break-away friction load momentarily, initial useful load near zero, rises slowly, then rapidly to full-load, no overshoot. Additionally, some process fan loads start with cold air but run normally with hot or superheated air. Cold air has much higher density and can trip out a fan sized for hot air.

HVAC fan applications are benign. The air is always close to 70F.

B) 2005 NEC Table 430.250 (below) shows the full load current for a NEMA B 5HP motor at 230/3/60 to be 9.6A.

**Table 430.250 Full-Load Current, Three-Phase Alternating-Current Motors**

The following values of full-load currents are typical for motors running at speeds usual for belted motors and motors with normal torque characteristics.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

| | Induction-Type Squirrel Cage and Wound Rotor (Amperes) | | | | | | | Synchronous-Type Unity Power Factor* (Amperes) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Horsepower** | **115 Volts** | **200 Volts** | **208 Volts** | **230 Volts** | **460 Volts** | **575 Volts** | **2300 Volts** | **230 Volts** | **460 Volts** | **575 Volts** | **2300 Volts** |
| ½ | 4.4 | 2.5 | 2.4 | 2.2 | 1.1 | 0.9 | — | — | — | — | — |
| ¾ | 6.4 | 3.7 | 3.5 | 3.2 | 1.6 | 1.3 | — | — | — | — | — |
| 1 | 8.4 | 4.8 | 4.6 | 4.2 | 2.1 | 1.7 | — | — | — | — | — |
| 1½ | 12.0 | 6.9 | 6.6 | 6.0 | 3.0 | 2.4 | — | — | — | — | — |
| 2 | 13.6 | 7.8 | 7.5 | 6.8 | 3.4 | 2.7 | — | — | — | — | — |
| 3 | — | 11.0 | 10.6 | 9.6 | 4.8 | 3.9 | — | — | — | — | — |
| 5 | — | 17.5 | 16.7 | 15.2 | 7.6 | 6.1 | — | — | — | — | — |
| 7½ | — | 25.3 | 24.2 | 22 | 11 | 9 | — | — | — | — | — |

C) Inductive inrush current is about 6x full-load current,

6 x 9.6A = 57.6A for about .1 second

D) Mechanical inrush current is about 2.5x full-load current,

2.5 x 9.6A = 24.0 A for 3 – 10 seconds

Answer: A peak-holding ammeter will report about 24.0A inrush current.

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Given: 5HP HVAC exhaust fan rated 230/3/60, auto transformer connected

Find: Approximate inrush current.

Solution:

A) Same fan discussed above.

B) 2005 NEC Table 430.250 (below) shows the full load current for a NEMA B 5HP motor at 230/3/60 to be 9.6A.

C) A transformer has about 5% voltage drop, but that is 5% at rated voltage.
5% at 32V --> 5 x 32/240 --> .7% in auto transformer connection.

We oversized the transformer 3x to accommodate inrush, so net voltage drop is

.7% / 3 = .2%

D) Inductive inrush current is about 6x full-load current, but I = V^2 / X, so

Inductive inrush = 6 x 9.6A x .998 x .998 = 57.4A for about .1 second

E) Mechanical inrush current is about 2.5x full-load current, but I = v^2 / Z, so

Mechanical inrush = 2.5 x 9.6A x ..998 x ..998 = 23.9 A for slightly more than 3 – 10 seconds.

[Reduced voltage means reduced torque means longer start. There are computer programs to predict the exact time extension. This is one of the reasons that motor HP is always larger than load HP - to avoid overload trips on low voltage at start.]

Answer: A peak-holding ammeter will report about 23.9A inrush current.

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Given: 5HP HVAC exhaust fan rated 230/3/60, started across-the-line, no transformer

Find: Approximate voltage dip at start current.

Solution:

A) Same fan discussed above.

B) 2005 NEC Table 430.250 (below) shows the full load current for a NEMA B 5HP motor at 230/3/60 to be 9.6A.

C) The NEC requires electrical distribution be designed for no more than 5% voltage drop at full-load current. 9.6A would be sourced by a 20A circuit, so motor full-load is 9.6 / 20 = 48% circuit loading. Running voltage drop would be 9.6 / 20 x 5% = 2.4%.

D) From no-transformer mechanical inrush current calculated above, 24.0A,

Inrush voltage dip = 24 / 20 x 5% = 6%

[1% voltage dip is visible on incandescent lights.]

---

Given: 5HP HVAC exhaust fan rated 230/3/60, auto transformer connected

Find: Approximate voltage dip at start current.

Solution:

A) Same fan discussed above.
B) Nominal distribution system voltage drop from above calculations, 2.4%. Transformer voltage drop from above calculations, .7%. Total drop, 3.1%.

E) From no-transformer mechanical inrush current calculated above, 24.0A,

Inrush voltage dip = 23.9 / 20 x 5.7% = 6.8%

[1% voltage dip is visible on incandescent lights.]