Motor Protection Voltage Unbalance and Single-Phasing

COOPER Bussmann

Cooper Bussmann contributes the following information, which is an excerpt from their 190-page handbook *SPD Selecting Protective Devices Based on the 2002 National Electrical Code.* The *SPD* and much more material on motor protection and other application topics are electronically available on www.bussmann.com.

For technical assistance call 636-527-1270.

DUKE ENERGY PROGRESS

Duke Energy Progress provides this type information to assist our customers.

Historically, the causes of motor failure can be attributed to:

Overloads	30%
Contaminants	19%
Single-phasing	14%
Bearing failure	13%
Old age	10%
Rotor failure	5%
Miscellaneous	9%
	100%

From the above data, it can be seen that 44% of motor failure problems are related to HEAT.

Allowing a motor to reach and operate at a temperature 10°C above its maximum temperature rating will reduce the motor's expected life by 50%. Operating at 10°C above this, the motor's life will be reduced again by 50%. This reduction of the expected life of the motor repeats itself for every 10°C. This is sometimes referred to as the "half life" rule.

Although there is no industry standard that defines the life of an electric motor, it is generally considered to be 20 years.

The term, temperature "rise", means that the heat produced in the motor windings (copper losses), friction of the bearings, rotor and stator losses (core losses), will continue to increase until the heat dissipation equals the heat being generated. For example, a continuous duty, 40°C rise motor will stabilize its temperature at 40°C above ambient (surrounding) temperature.

Standard motors are designed so the temperature rise produced within the motor, when delivering its rated horsepower, and added to the industry standard 40°C ambient temperature rating, will not exceed the safe winding insulation temperature limit.

The term, "Service Factor" for an electric motor, is defined as: "a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the Service Factor of the motor."

"Conditions" include such things as operating the motor at rated voltage and rated frequency.

Example: A 10 H.P. motor with a 1.0 S.F. can produce 10 H.P. of work without exceeding its temperature rise requirements. A 10 H.P. motor with a 1.15 S.F. can produce 11.5 H.P. of work without exceeding its temperature rise requirements.

Overloads, with the resulting overcurrents, if allowed to continue, will cause heat build-up within the motor. The outcome will be the eventual early failure of the motor's insulation. As stated previously for all practical purposes, insulation life is cut in half for every 10°C increase over the motor's rated temperature.

Voltage Unbalance

When the voltage between all three phases is equal (balanced), current values will be the same in each phase winding.

The NEMA standard for electric motors and generators recommends that the maximum voltage unbalance be limited to 1%.

When the voltages between the three phases (AB, BC, CA) are not equal (unbalanced), the current increases dramatically in the motor windings, and if allowed to continue, the motor will be damaged.

It is possible, to a limited extent, to operate a motor when the voltage between phases is unbalanced. To do this, the load must be reduced.

Voltage Unbalance in Percent	Derate Motor to These Percentages of the Motor's Rating*
1%	98%
2%	95%
3%	88%
4%	82%
5%	75%

*This is a general "rule of thumb", for specific motors consult the motor manufacturer.

Some Causes of Unbalanced Voltage Conditions

- Unequal single-phase loads. This is why many consulting engineers specify that loading of panelboards be balanced to ± 10% between all three phases.
- Open delta connections.
- Transformer connections open - causing a single-phase condition.
- Tap settings on transformer(s) not proper.
- Transformer impedances (Z) of single-phase transformers connected into a "bank" not the same.
- Power factor correction capacitors not the same. . .or off the line.

Insulation Life

The effect of voltage unbalance on the insulation life of a typical T-frame motor having Class B insulation, running in a 40°C ambient, loaded to 100%, is as follows:

	Insulation Life	
Voltage Unbalance	Service Factor 1.0	Service Factor 1.15
0%	1.00	2.27
1%	0.90	2.10
2%	0.64	1.58
3%	—	0.98
4%	—	0.51

Note that motors with a service factor of 1.0 do not have as much heat withstand capability as does a motor that has a service factor of 1.15.

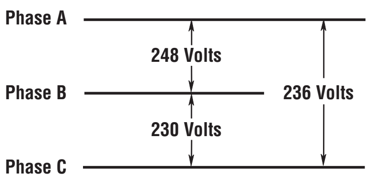
Older, larger U-frame motors, because of their ability to dissipate heat, could withstand overload conditions for longer periods of time than the newer, smaller T-frame motors.

Insulation Classes

The following shows the maximum operating temperatures for different classes of insulation.

Class A Insulation	105°C
Class B Insulation	130°C
Class F Insulation	155°C
Class H Insulation	180°C

How to Calculate Voltage Unbalance and the Expected Rise in Heat



Step 1: Add together the three voltage readings:

248 + 236 + 230 = 714V

Step 2: Find the "average" voltage.

$\frac{714}{3} = 238V$

Step 3: Subtract the "average" voltage from one of the voltages that will indicate the **greatest** voltage difference. In this example:

248 – 238 = 10V

Step 4:

$$100 \times \frac{\text{greatest voltage difference}}{\text{average voltage}}$$

$$= 100 \times \frac{10}{238} = 4.2 \text{ percent voltage unbalance}$$

Step 5: Find the expected temperature rise in the phase winding with the highest current by taking. . .

$2 \times (\text{percent voltage unbalance})^2$

In the above example:

$2 \times (4.2)^2 = 35.28$ percent temperature rise.

Therefore, for a motor rated with a 60°C rise, the unbalanced voltage condition in the above example will result in a temperature rise in the phase winding with the highest current of:

60°C × 135.28% = 81.17°C

The National Electrical Code

The National Electrical Code®, in Table 430.37, requires three overload protective devices, one in each phase, for the protection of all three-phase motors.

Prior to the 1971 National Electrical Code®, three-phase motors were considered to be protected from overload (overcurrent) by two overload protective devices. These devices could be in the form of properly sized time-delay, dual-element fuses, or overload heaters and relays (melting alloy type, bimetallic type, magnetic type, and solid-state type.)

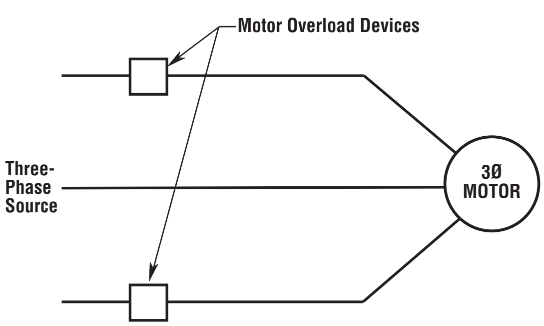


Diagram showing two overload devices protecting a three-phase motor. This was acceptable by the National Electrical Code® prior to 1971.

Two motor overload protective devices provide adequate protection against balanced voltage overload conditions where the voltage between phases is equal. When a balanced voltage overload persists, the protective devices usually open simultaneously. In some cases, one device opens, and shortly thereafter, the second device opens. In either case, three-phase motors are protected against balanced voltage overload conditions.

Three-phase motors protected by two overload protective devices are not assured protection against the effect of single-phasing. For example, when the electrical system is WYE/DELTA or DELTA/WYE connected, all three phases on the secondary side of the transformer bank will continue to carry current when a single-phasing caused by an open phase on the primary side of the transformer bank occurs. As will be seen later, single-phasing can be considered to be the **worst case** of unbalanced voltage possible.

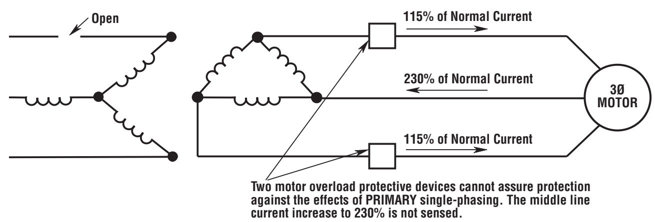
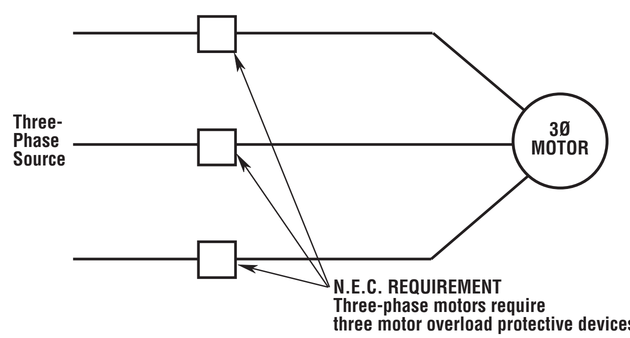


Diagram of a WYE/DELTA transformation with one primary phase open. The motor is protected by two overload devices. Note that one phase to the motor is carrying two times that of the other two phases. Without an overload device in the phase that is carrying two times the current in the other two phases, the motor will burn out.

The National Electrical Code®, Section 430.36 requires that when fuses are used for motor overload protection, a fuse shall be inserted in each phase. Where thermal overload devices, heaters, etc. are used for motor overload protection, Table 430.37 requires one be inserted in each phase. With these requirements, the number of single-phasing motor burnouts are greatly reduced, and are no longer a serious hazard to motor installations. The following figure shows three overload protective devices protecting the three-phase motor.



Since 1971, The National Electrical Code® has required three overload protective devices for the protection of three-phase motors, one in each phase.

Motor Branch Circuit, Short-Circuit and Ground Fault Protection

When sized according to NEC® 430.52, a 3-pole common trip circuit breaker or MCP can not protect against single-phasing damage.

It should be emphasized, the causes of single-phasing cannot be eliminated. However, motors can be protected from the damaging effects of single-phasing through the use of proper overcurrent protection.

Dual-element, time-delay fuses can be sized at or close to the motor's nameplate full-load ampere rating without opening on normal motor start-up. This would require sizing the fuses at 100-125% of the motors full-load current rating. Since all motors are not necessarily fully loaded, it is recommended that the actual current draw of the motor be used instead of the nameplate rating. This is possible for motor's that have a fixed load, but not recommended where the motor load varies.*

Thus, when single-phasing occurs, FUSETRON® FRS-R and FRN-R and LOW-PEAK® LPS-RK_SP and LPN-RK_SP dual-element, time-delay fuses will sense the overcurrent situation and respond accordingly to take the motor off the line.

For motor branch-circuit protection only, the following sizing guidelines† per 430.52 of the National Electrical Code® are allowed.

	Normal	Maximum
• Dual-element, time-delay fuses	175%	225%
• Non-time-delay fuses and all Class CC fuses	300%	400%
• Inverse-time circuit breaker	250%	400% for motors 100 amperes or less. 300% for motors more than 100 amperes.
• Instantaneous only trip** circuit breakers (sometimes referred to as MCPs. These are motor circuit protectors, not motor protectors.)	800%††	1300%†††

† See NEC® 430.52 for specifics and exceptions.

†† 1100% for design E motors

††† 1700% for design E motors & energy efficient design B motors

*When sizing to the actual running current of the motor is not practical, an economic analysis can determine if the addition of one of the electronic "black boxes" is financially justified. These electronic "black boxes" can sense voltage and current unbalance, phase reversal, single-phasing, etc.

**Instantaneous only trip breakers are permitted to have time-delay. This could result in more damaging let-through current during short-circuits.

Note: When sized according to table 430.52, none of these overcurrent devices can provide single-phasing protection.

Single-Phasing

The term **single-phasing**, means one of the phases is open. A secondary single-phasing condition subjects an electric motor to the **worst possible case** of voltage unbalance.

If a three-phase motor is running when the "single-phase" condition occurs, it will attempt to deliver its full horsepower …enough to drive the load. The motor will continue to try to drive the load…until the motor burns out…or until the properly sized overload elements and/or properly sized dual-element, time-delay fuses take the motor off the line.

For lightly loaded three-phase motors, say 70% of normal full-load amperes, the phase current will increase by the square root of three ($\sqrt{3}$) under secondary single-phase conditions. This will result in a current draw of approximately 20% more than the nameplate full load current. If the overloads are sized at 125% of the motor nameplate, circulating currents can still damage the motor. That is why it is recommended that motor overload protection be based upon the actual running current of the motor under its given loading, rather than the nameplate current rating.

Single-Phasing Causes Are Numerous

One fact is sure: Nothing can prevent or eliminate all types of single-phasing.

There are numerous causes of both primary and secondary single-phasing. A device must sense and respond to the resulting increase in current when the single-phasing condition occurs…and do this in the proper length of time to save the motor from damage.

The term "single-phasing" is the term used when one phase of a three-phase system opens. This can occur on either the primary side or secondary side of a distribution transformer. Three-phase motors, when not individually protected by three time-delay, dual-element fuses, or three overload devices, are subject to damaging overcurrents caused by **primary** single-phasing or **secondary** single-phasing.

Single-Phasing on Transformer Secondary – Typical Causes

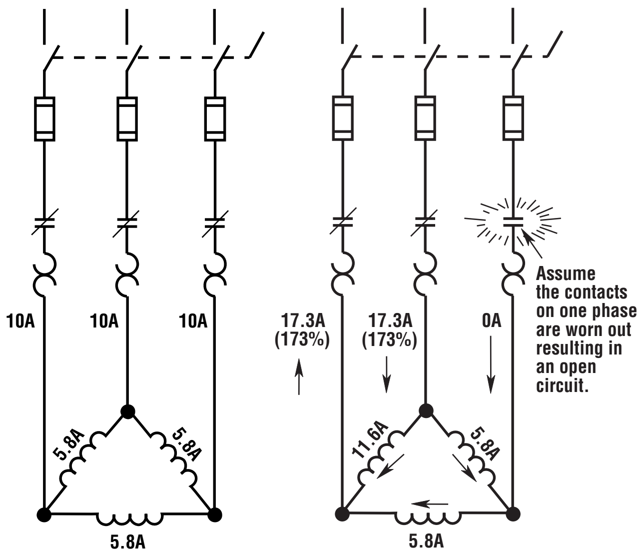
1. Damaged motor starter contact–one pole open. The number of contact kits sold each year confirms the fact that worn motor starter contacts are the most common cause of single-phasing. Wear and tear of the starter contacts can cause contacts to burn open, or develop very high contact resistance, resulting in single-phasing. This is most likely to occur on automatically started equipment such as air conditioners, compressors, fans, etc.
2. Burned open overload relay (heater) from a line-to-ground fault on a 3 or 4 wire grounded system. This is more likely to occur on smaller size motor starters that are protected by non-current-limiting overcurrent protective devices.
3. Damaged switch or circuit breaker on the main, feeder, or motor branch circuit.
4. Open fuse or open pole in circuit breaker on main, feeder, or motor branch circuit.
5. Open cable or bus on secondary of transformer terminals.
6. Open cable caused by overheated lug on secondary side connection to service.
7. Open connection in wiring such as in motor junction box (caused by vibration) or any pull box. Poor connections, particularly when aluminum conductors are not properly spliced to copper conductors, or when aluminum conductors are inserted into terminals and lugs suitable for use with copper conductors or copper-clad conductors only.
8. Open winding in motor.
9. Open winding in one phase of transformer.
10. **ANY** open circuit in **ANY** phase **ANYWHERE** between the secondary of the transformer and the motor.

Hazards of Secondary Single-Phasing for a Three-Phase Motor

When one phase of a secondary opens, the current to a motor in the two remaining phases theoretically increases to 1.73 (173%) times the normal current draw of the motor. The increase can be as much as 2 times (200%) because of power factor changes. Where the motor has a high inertia load, the current can approach locked rotor values under single-phased conditions. Three properly sized time-delay, dual-element fuses, and/or three properly sized overload devices will sense and respond to this overcurrent.

SINGLE-PHASING ON SECONDARY

NORMAL CONDITION **SINGLE-PHASING CONDITION**

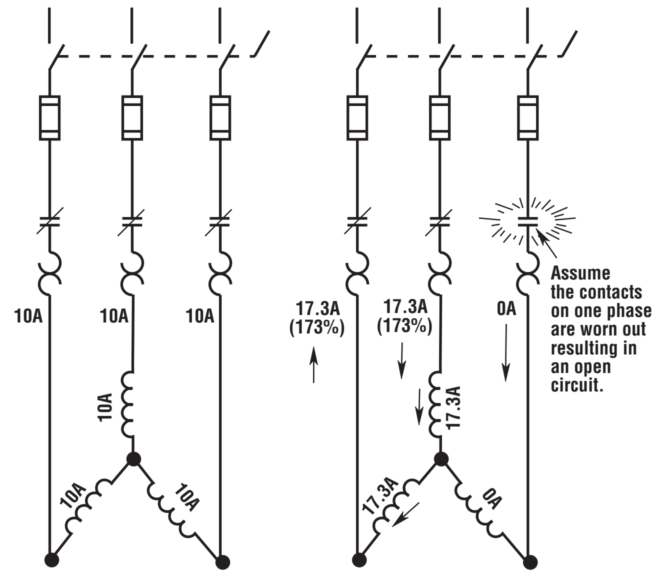


Delta-Connected Motor
FLA = 10 Amperes

(Delta-Connected Motor) Diagram showing the increase in current in the two remaining phases after a single-phasing occurs on the secondary of a transformer.

NORMAL CONDITION **SINGLE-PHASING CONDITION**

WYE-Connected Motor



FLA = 10 Amperes

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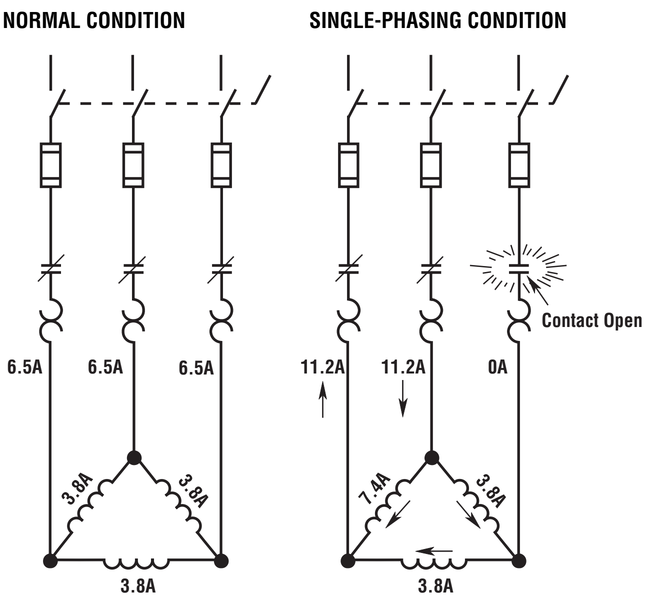
SINGLE-PHASING ON SECONDARY



Delta-connected three-phase motor loaded to only 65% of its rated horsepower. Normal FLA = 10 amperes. Overload (overcurrent) protection should be based upon the motor's actual current draw for the underloaded situation for optimum protection. If load varies, overload protection is difficult to achieve. Temperature sensors, phase failure relays and current differential relays should be installed.

When a motor is single-phased, the current in the remaining two phases increases to 173% of normal current. Normally the overload relays will safely clear the motor from the power supply. However, should the overload relays or controller fail to do so, LOW-PEAK® or FUSETRON® time-delay, dual-element fuses, properly sized to provide back-up overload protection, will clear the motor from its power supply.

If the overload relays were sized at 12 amperes, based upon the motor nameplate F.L.A. of 10 amperes, they would not "see" the single-phasing. However, if they were sized at 8 amperes (6.5A x 1.25 = 8.13 amperes), they would "see" the single-phasing condition.

Single-Phasing on Transformer Primary – Typical Causes

1. Primary wire broken by:
   - a. Storm – wind
   - b. Ice – sleet – hail
   - c. Lightning
   - d. Vehicle or airplane striking pole or high-line
   - e. Falling trees or tree limbs
   - f. Construction mishaps
2. Primary wire burned off from short-circuit created by birds or animals.
3. Defective contacts on primary breaker or switch – failure to make up on all poles.
4. Failure of 3-shot automatic recloser to make up on all 3 poles.
5. Open pole on 3-phase automatic voltage tap changer.
6. Open winding in one phase of transformer.
7. Primary fuse open.

Hazards of Primary Single-Phasing for a Three-Phase Motor

Probably the most damaging single-phase condition is when one phase of the primary side of WYE/DELTA or DELTA/WYE transformer is open. Usually these causes are not within the control of the user who purchases electrical power. When primary single-phasing occurs, unbalanced voltages appear on the motor circuit, causing excessive unbalanced currents. This was covered earlier in this bulletin.

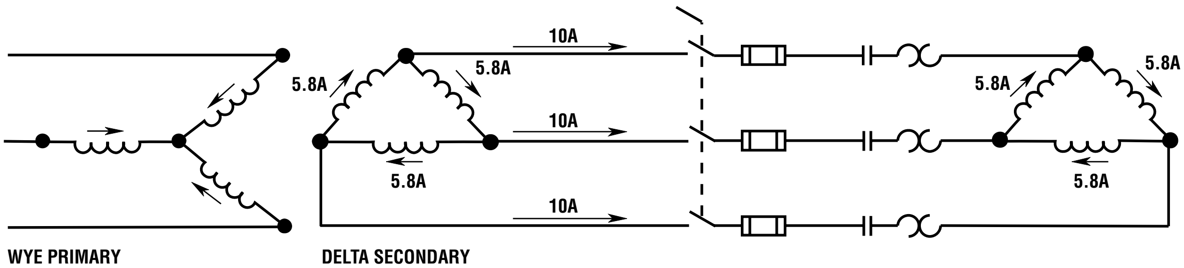
When primary single-phasing occurs, the motor current in one secondary phase increases to 230% of normal current. Normally, the overload relays will protect the motor. However, if for some reason the overload relays or controller fail to function, the LOW-PEAK® or FUSETRON® dual-element fuses properly sized to provide backup overload protection will clear the motor from the power supply.

Effect of Single-Phasing on Three-Phase Motors

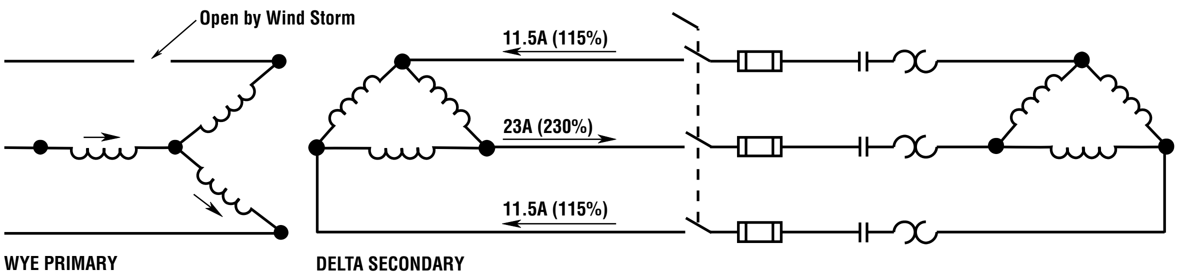
The effects of single-phasing on three-phase motors varies with service conditions and motor thermal capacities. When single-phased, the motor temperature rise may not vary directly with the motor current. When single-phased, the motor temperature rise may increase at a rate greater than the increase in current. In some cases, protective devices which sense only current may not provide complete single-phasing protection. However, PRACTICAL experience has demonstrated that motor running overload devices properly sized and maintained can greatly reduce the problems of single-phasing for the majority of motor installations. In some instances, additional protective means may be necessary when a higher degree of single-phasing protection is required. Generally, smaller horsepower rated motors have more thermal capacity than larger horsepower rated motors and are more likely to be protected by conventional motor running overload devices.

SINGLE-PHASING ON PRIMARY
Delta-Connected Motor; FLA = 10 Amperes

NORMAL CONDITION



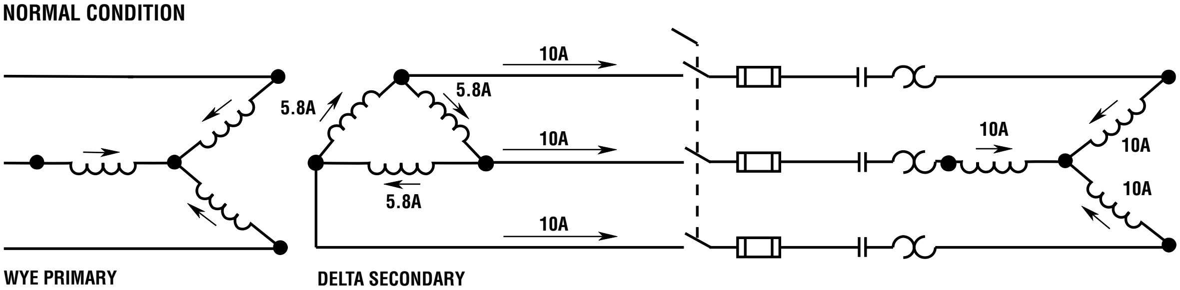
SINGLE-PHASING CONDITION



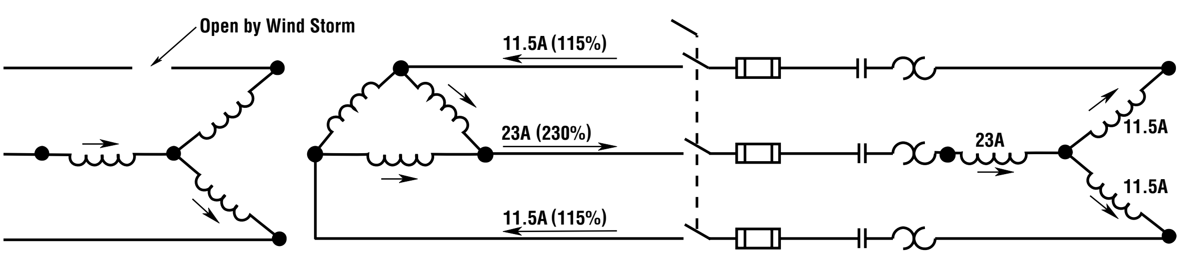
(Delta-Connected Motor) Diagram showing how the phase currents to a three-phase motor increase when a single-phasing occurs on the primary. For older installations where the motor is protected by two overload devices, the phase winding having the 230% current will burn up. However, properly sized overload relays or LOW-PEAK® or FUSETRON® dual-element, time-delay fuses will clear the motor from the power supply.

SINGLE-PHASING ON PRIMARY
Wye-Connected Motor; FLA = 10 Amperes

NORMAL CONDITION



SINGLE-PHASING CONDITION



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