
# Underexplored Three-Phase Power Failure Conditions

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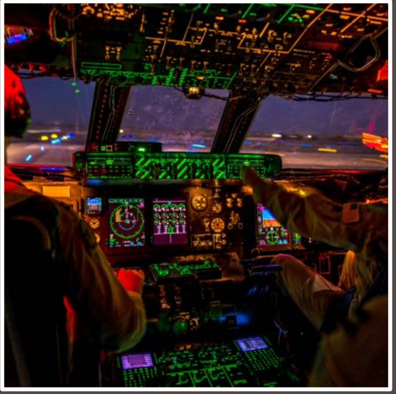
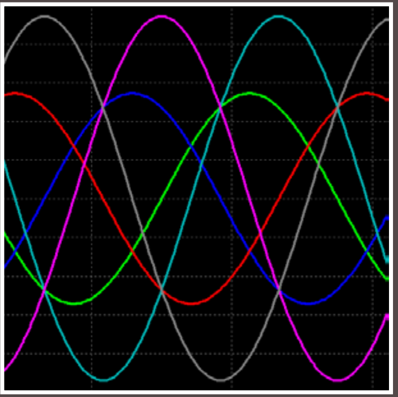
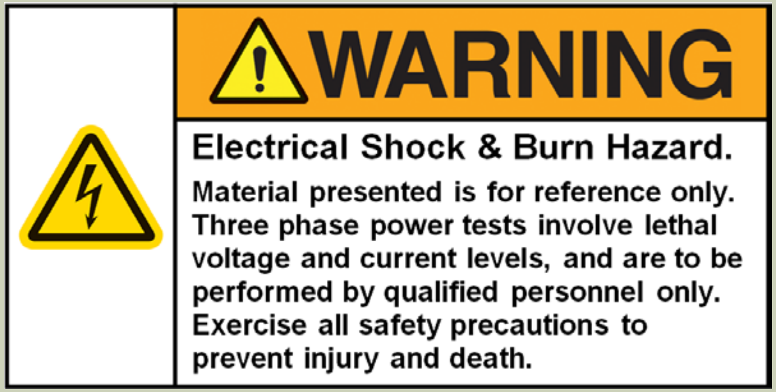


Back to fundamentals with "Enhanced TAC602" explained

# Outline

- Three Phase Power Failure Conditions
  - Including some underexplored but common occurrences
  - Focus is on one and two phase failures, not on power interruptions where all three phases fail
- Power Standards (MIL-STD-704 and DO-160)
- Hardware Example #1, Three Phase Power Converter with Full Wave Bridge Front End
- Hardware Example #2, Three Phase Power Converter with Delta-Configured PFC Front End
- Hardware Example #3, Three Phase Induction Motor
- Suggested Enhancements for MIL-HDBK-704 and DO-160
- Failures of the Neutral Connection
- Design Mitigation
- Summary
- References
- Q and A

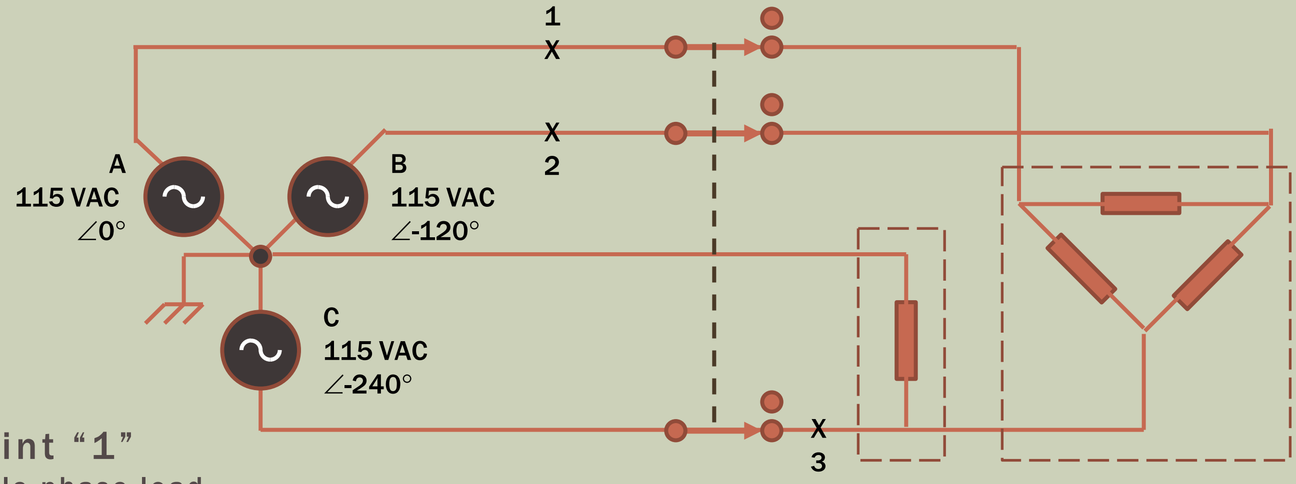


# Three Phase Power Failure Conditions

including some underexplored but common occurrences

# Simple 3-Phase Power Failure Examples

- 3Ø Wye Source (115/200 VAC)
- Single-Phase Load C-N (moderate size with high inrush)
- 3Ø Delta Load (moderate size)




- Phase A opens at point "1"
  - No direct impact on single phase load
  - Phase A input of delta load "sees" a high Z
- Phase B opens at point "2"
  - Similar situation as above
- Phase C opens at point "3"
  - Phase C input of delta load "sees" a low Z to neutral
- These open points can occur during operation or be a pre-existing condition when power is applied

# Power Standards

MIL-STD-704
and
DO-160

# Power Standards

- In avionics, two widely used standards for power quality include
  - MIL-STD-704
    - Exclusively covers power quality (phase loss, steady-state voltage, etc.)
    - Focus on the phase failure portion
  - RTCA DO-160
    - Covers power quality in addition to other environmental conditions
    - Focus on the phase failure portion
- Both these standards are thorough and comprehensive
- Enhancements should be considered
  - To clarify the definition of a phase loss
  - To capture additional 3Ø power failure modes that can occur in the field and during factory tests
- Other standards exist but are not covered in this discussion as the above standards are commonly used

# MIL-STD-704/MIL-HDBK-704
# Phase Failure

- MIL-STD-704, originally introduced in 1959, now stands at revision F which was released in 2004.
- MIL-STD-704F section 4.2.3 states that "…the loss of one or more phases of AC power to any utilization equipment terminal shall not result in an unsafe condition or damage to utilization equipment."
- However, it is not clear how to define the loss of a phase, nor if the loss occurs during operation and/or is a pre-existing condition when power is applied.
- Accompanying handbook (MIL-HDBK-704) is an excellent document that clarifies and defines the test conditions necessary to demonstrate MIL-STD-704 compliance, including the area of one and two phase power failure.
  - Method TAC602 in the handbook defines a phase loss as a Zero-Volt potential (essentially a short from the lost phase to the neutral with the source phase disconnected).
  - "The voltage must decrease from the steady state voltage to 0 Volts within ½ cycle (1.25 milliseconds), remain at 0 Volts for the duration listed for the test condition, and return from 0 Volts to the steady state voltage within ½ cycle (1.25 milliseconds)".

# MIL-STD-704/MIL-HDBK-704
# Phase Failure (continued)

- Ten conditions (A through J) are defined for phase loss;

| Test Condition | Phases | Duration of Power Failure |
|---|---|---|
| One Phase Power Failure | | |
| A | Phase A | 7 seconds |
| B | Phase B | 7 seconds |
| C | Phase C | 7 seconds |
| D | Phase A | Indefinitely |
| E | Phase B | Indefinitely |
| F | Phase C | Indefinitely |
| Two Phase Power Failures | | |
| G | Phase A & B | 7 seconds |
| H | Phase B & C | 7 seconds |
| I | Phase A & B | Indefinitely |
| J | Phase B & C | Indefinitely |

- For each condition:
  - The UUT (Unit Under Test) is first powered normally
  - Correct UUT operation is verified
  - The UUT is subject to the failure condition
  - After the power returns to normal, confirm that UUT is not damaged and returns to normal performance
- Conditions A, B, C, G, and H are each performed 5 times, while conditions D, E, F, I, and J are each performed once
- For the indefinite time duration, typically 30 minute exposure is used

# MIL-STD-704/MIL-HDBK-704 Limitations

- For all conditions, the system under test is operating from normal power when the failure is introduced
  - The system is not tested under the condition where power is applied with a pre-existing fault condition
- Only the low impedance (Zero-Volt) condition is tested
  - Arguably, it is at least as likely that a phase loss can occur in an open-circuit condition (as discussed previously)
- Two phase loss of A&C is not tested
  - May not be an issue for balanced delta loads
- Loss of the neutral is not tested
  - Not an issue for delta loads

# RTCA DO-160

- RTCA DO-160 (of latest revision G) has a similar situation
- Section 16.5.2.4a states that “All three phase ac loads are to be designed such that no damage or unsafe condition will occur during and following removal of one or more input phase connections.”
- Here too it is not clear if the phase loss would be a Zero-Volt condition or an open-circuit condition
  - The latter is implied by the wording “… remove phase X …” in section 16.5.2.4bb
  - For this presentation the open condition is assumed
- Nevertheless, the document does cover the conditions of introducing the phase loss during operation and applying power with a pre-existing fault condition

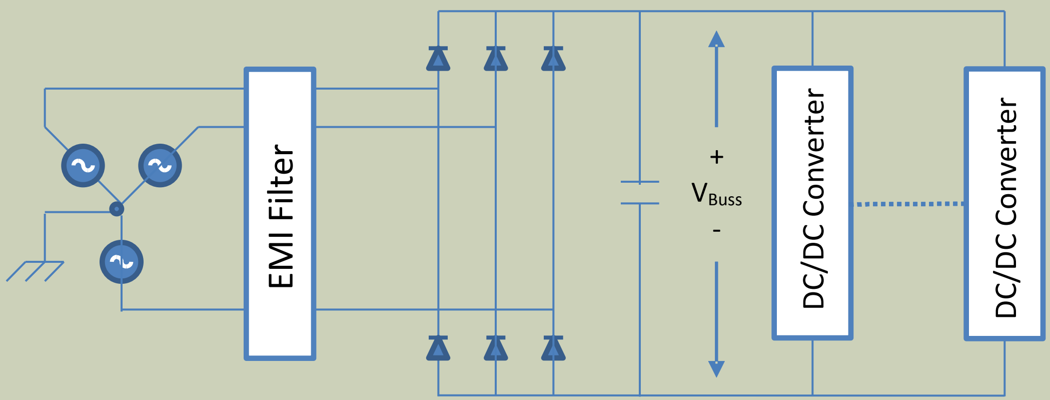
# RTCA DO-160 Limitations

- Not all phases are required to be tested in the single-phase fault case and not all pairs are required to be tested in the dual-phase fault case
  - Single phase loss is applied to “the phase that is most susceptible to damage from a loss of single phase”
  - Dual-phase loss is applied to “the phases that are most susceptible to damage from the loss of two phases”
  - Phases selected shall be justified and documented in the test report
  - Phase selection may be subject to challenges depending on design, customer and application – a test of all conditions might be more efficient/simpler than testing a subset and convincing colleagues and customer that the subset is sufficient
- Only the open condition is tested
- Loss of the neutral is not tested

# Hardware Example #1

## Three Phase Power Converter with Full Wave Bridge Front End

# Hardware Example #1
# Full Wave Bridge Power Converter

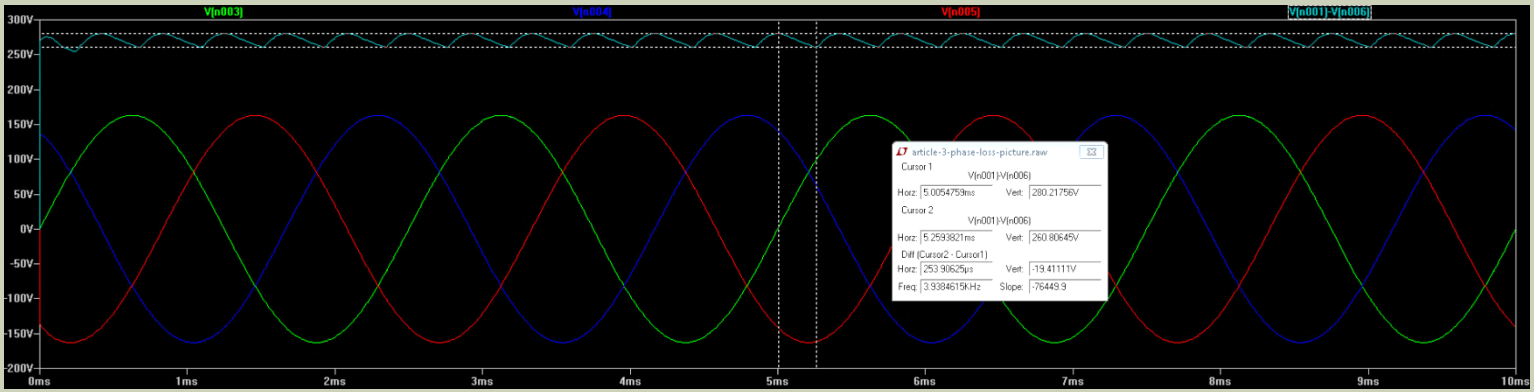



- Simplified schematic of a typical power converter with a full-wave bridge front end
- Three-phase input (115/200 VAC, 400 Hz) is passed through an EMI Filter, then rectified by a full-wave bridge and filtered with a bulk capacitor creating a high voltage DC buss ($V_{Buss}$)
- Buss voltage is then passed onto a set of DC/DC Converters that generate the voltages required by the application
- For simplicity, the details of the EMI Filter are not shown, and no Power Factor Correction (PFC) elements are used

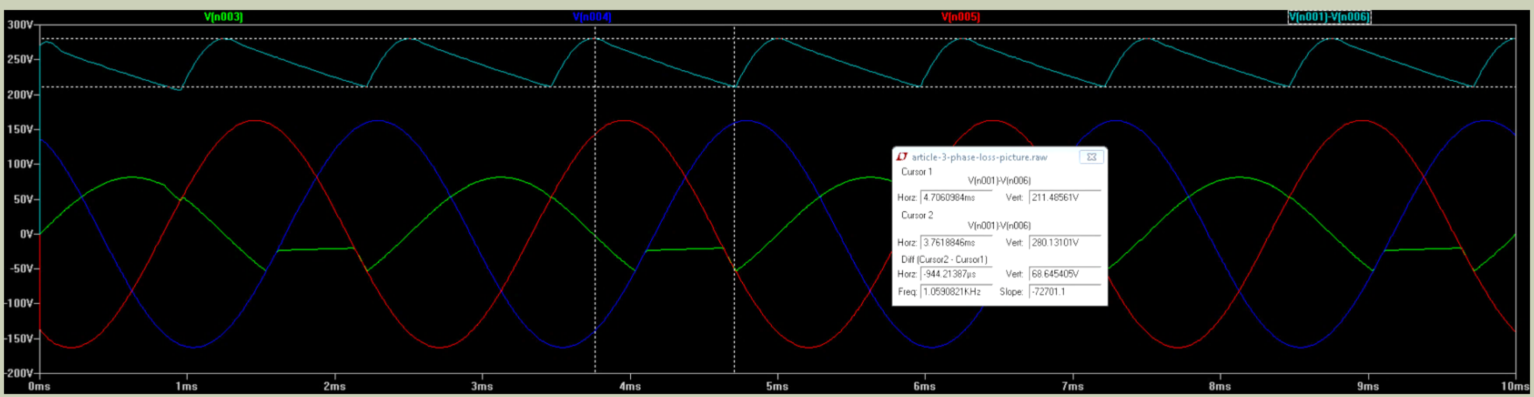
# Hardware Example #1 Simulation Notes

- Using LTSpice, the resulting DC Buss voltage is simulated under normal and various phase loss conditions
- In the following plots
  - Green, red and blue traces correspond to phase A, B and C respectively
  - Aqua trace is the DC bus voltage
  - Horizontal axis 0-10 ms
  - Vertical axis -200 to 300 V
- Summary table provided

# Hardware Example #1 Simulation Results

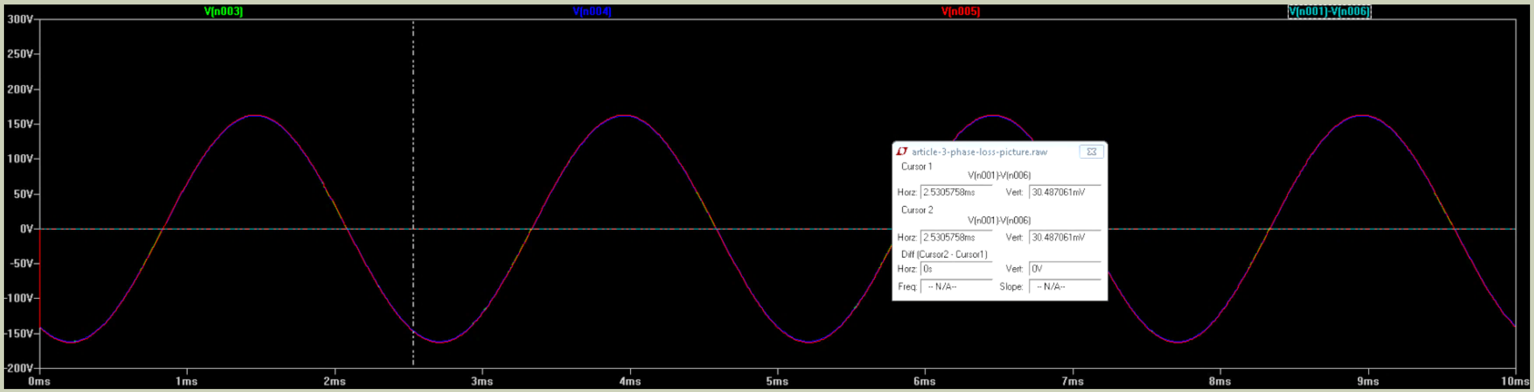



Normal Three-Phase Power Conditions

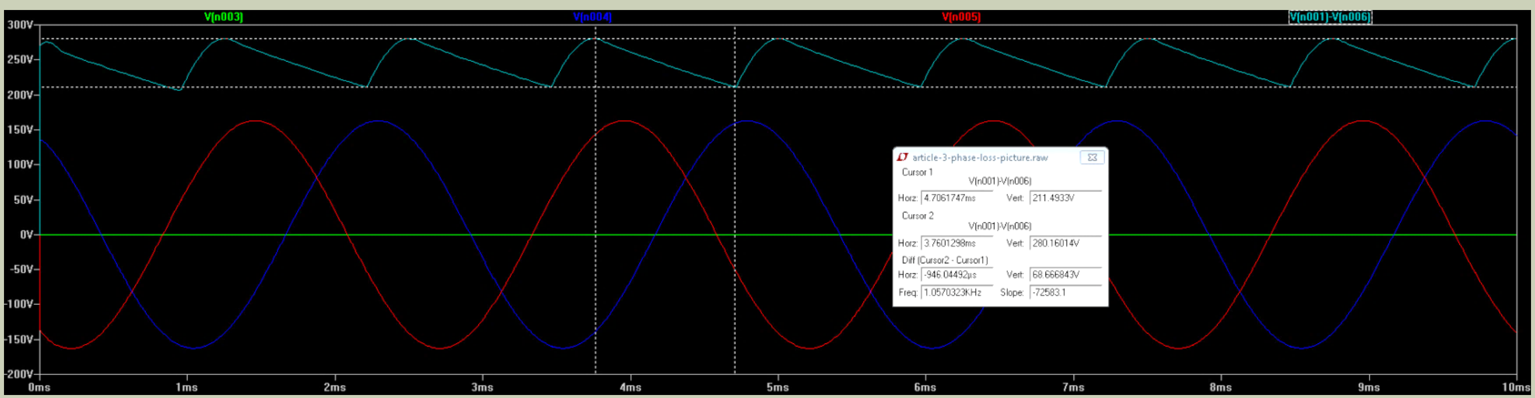



One Phase Loss, High-Z Condition

# Hardware Example #1
# Simulation Results (continued)

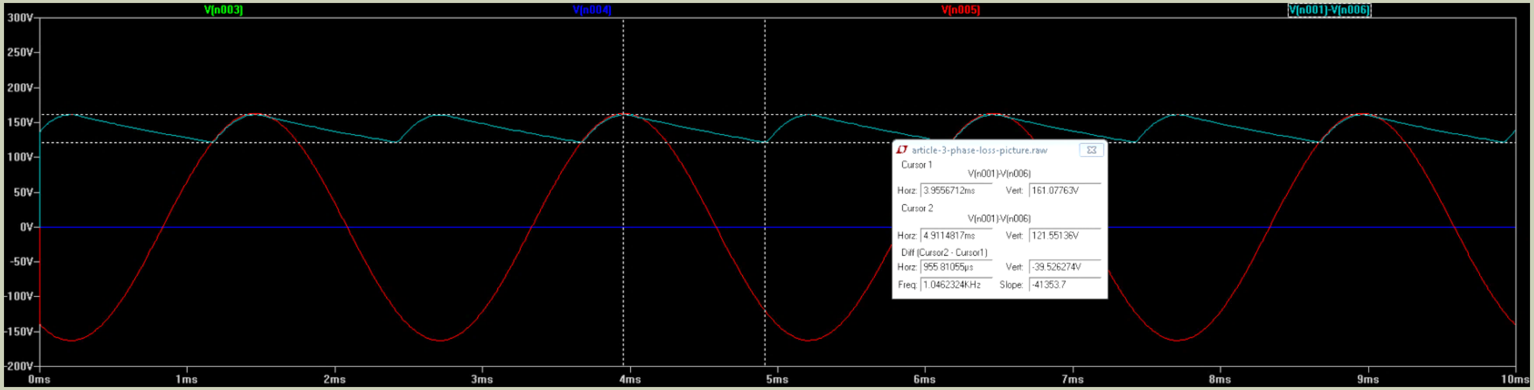



Two Phase Loss, High-Z Condition (Trivial)




One Phase Loss, Zero-Volt Condition

# Hardware Example #1
# Simulation Results (continued)




Two Phase Loss, Zero-Volt Condition

# Hardware Example #1 Simulation Summary

| Condition | Average (V) | Ripple (Vpp) | Ripple (Hz) |
|---|---|---|---|
| Normal | 271 | 19 | 2400 |
| One Phase Loss, High-Z | 246 | 69 | 800 |
| Two Phases Loss, High-Z | 0 | 0 | N/A |
| One Phase Loss, Zero-Volt | 246 | 69 | 800 |
| Two Phase Loss, Zero-Volt | 142 | 40 | 800 |

- Under normal conditions, the DC Buss potential with its peak-to-peak ripple is well within commonly available DC/DC Converter “bricks” leaving overhead for the normal steady-state conditions
- Loss of one phase in either the High-Z or Zero-Volt condition results in a reduced buss voltage with increased ripple
- Two phase losses in High-Z condition results in the trivial case of zero buss potential
- Two phase loss in the Zero-Volt case is very different
  - Resulting buss potential is 142 V with moderate ripple
  - Depending on the input voltage turn-on and turn-off thresholds of the converter modules, this condition can result in repeated on/off cycling of the modules which can lead to reliability issues (reference upper right figure)

# Hardware Example #1
# Simulation Summary (continued)

- Vicor Application Note Example


To prevent damage, allow a minimum of 1s between power on / off / on cycles to allow for the reinitialization of converter soft start.

- For the context of this example, it is anticipated that energizing this three-phase Power Converter from a pre-existing phase fault condition is not worse than introducing the fault condition during operation

# Hardware Example #1
# Score Card

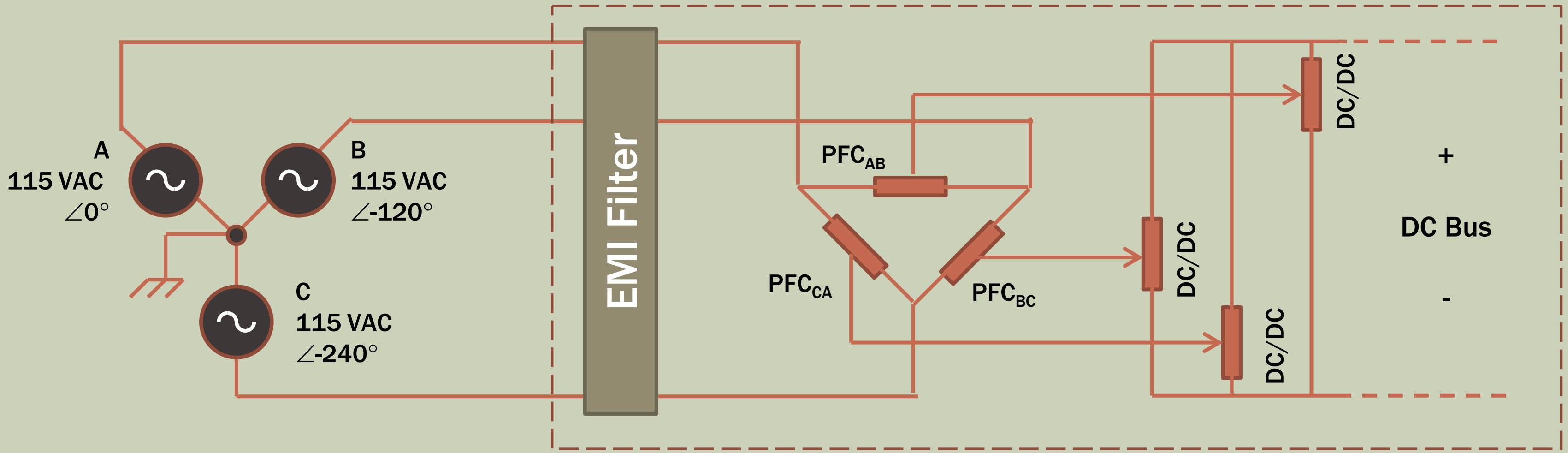
| Condition | Result and Notes | 704 | DO-160 |
|---|---|---|---|
| Single Phase,<br>0-Volt Failure, During Operation | Buss voltage remains within input range of Converters and would operate correctly. | Tested | Not Tested |
| Single Phase,<br>0-Volt Failure, Pre-Existing | Buss voltage remains within input range of Converters and would operate correctly. | Not Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, During Operation | Converters may attempt to initialize at an 800 Hz rate, possibly resulting in damage. | Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, Pre-Existing | Converters may attempt to initialize at an 800 Hz rate, possibly resulting in damage. | Not Tested | Not Tested |
| Single Phase,<br>High-Z Failure, During Operation | Buss voltage remains within input range of Converters and would operate correctly. | Not Tested | Tested |
| Single Phase,<br>High-Z Failure, Pre-Existing | Buss voltage remains within input range of Converters and would operate correctly. | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, During Operation | Power Converter does not operate, no damage (trivial case) | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, Pre-Existing | Power Converter does not operate, no damage (trivial case) | Not Tested | Tested |

Notes:
1. Assume the DC/DC Converters cover an input range of 180 to 400 VDC with an under-voltage turn-off threshold of 150 VDC.
2. Assume that the bridge is sized to handle the additional current resulting from the single phase faults.

# Hardware Example #2

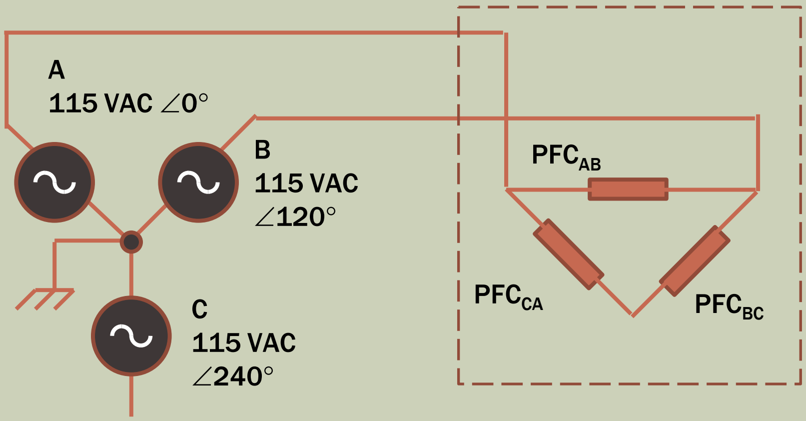
Three Phase Power Converter with Delta-Configured PFC Front End

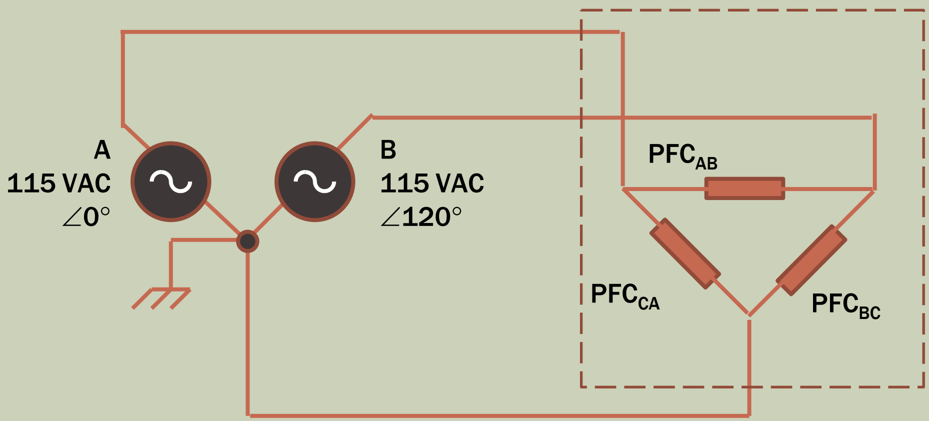
# Hardware Example #2
# PFC Power Converter




- Simplified schematic of a power converter
  - Three PFC modules connected line-to-line in delta configuration
  - Each PFC powers an individual respective DC/DC Converter
  - DC/DC Converters are paralleled with current share or may be used to power individual (preferably similar) loads directly

# Hardware Example #2 Discussion




- When Phase C fails open
  - PFC$_{AB}$ continues to have correct input voltage
  - PFC$_{CA}$ and PFC$_{BC}$ are connected in series
  - Two negative impedances in series can result in unstable operation that can be destructive
- When Phase C fails Zero-Volt
  - PFC$_{AB}$ continues to have correct input voltage
  - PFC$_{CA}$ and PFC$_{BC}$ are connected to a stable source equal to the line-to-neutral magnitude
  - Stable condition

# Hardware Example #2 Discussion (continued)

- For the context of this example, it is anticipated that energizing this three-phase Power Converter from a pre-existing phase fault condition is not worse than introducing the fault condition during operation
- As of this writing, little published work was found regarding the series connection of two or more DC/DC Converters or negative impedances in general
- Email and phone discussions with a few DC/DC Converter and PFC module suppliers confirmed the likely or certain destruction of their modules in the input-series configuration
- "Input-Voltage Balancing of Series-Connected Converters" by Jang, Jovanović, and Dillman
  - Discusses a method to accomplish the series connection
  - Adds considerable complication
  - Requires circuit access that may not be available in common DC/DC Converter or PFC modules

# Hardware Example #2
# Score Card

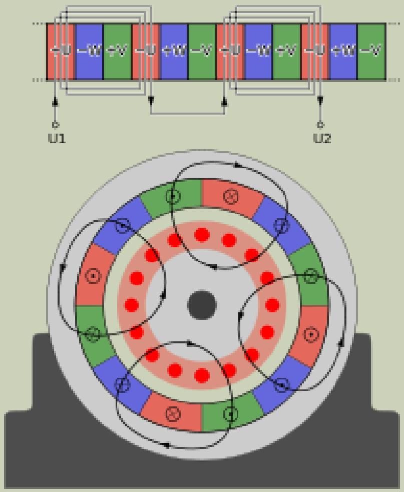
| Condition | Result and Notes | | 704 | DO-160 |
|---|---|---|---|---|
| Single Phase,<br>0-Volt Failure, During Operation | Stable PFC Voltages | | Tested | Not Tested |
| Single Phase,<br>0-Volt Failure, Pre-Existing | Stable PFC Voltages | | Not Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, During Operation | Stable PFC Voltages | | Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, Pre-Existing | Stable PFC Voltages | | Not Tested | Not Tested |
| Single Phase,<br>High-Z Failure, During Operation | Unstable PFC operation | | Not Tested | Tested |
| Single Phase,<br>High-Z Failure, Pre-Existing | Unstable PFC operation | | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, During Operation | Power Converter does not operate, no damage (trivial case) | | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, Pre-Existing | Power Converter does not operate, no damage (trivial case) | | Not Tested | Tested |

# Hardware Example #3

Three Phase Induction Motor

# Hardware Example #3
# 3 Phase Induction Motor

- Commonly used for blowers in airborne and ground applications
- Operate from the 3Ø mains power
- In an induction motor (asynchronous motor) the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field generated by the stator winding
- The stator consists of poles carrying supply current to induce a rotating magnetic field that penetrates the rotor and causes it to rotate




Typical winding pattern for a three-phase, four-pole motor.

Typical 3 Phase Blower
*Courtesy Rotron*

# Hardware Example #3 Discussion

- 3Ø Induction Motor can react very differently under the four sets of phase failure conditions
  - Zero-Volt phase failure occurring during operation
  - High-Impedance phase failure occurring during operation
  - Pre-existing Zero-Volt phase failure when power is applied
  - Pre-existing High-Impedance phase failure when power is applied
- Tests were performed on a blower to highlight the impact of phase loss
  - 115/200 VAC, 400 Hz
  - Room temperate (about 25 °C)
  - Low pressure drop
  - Typical Power Consumption under Normal Conditions: 80 W, 148 VA, 0.54 PF
  - Fan tested alone – if paralleled with other items results may have been effected

# Hardware Example #3
# Test Results for High-Z Conditions

| Condition | Results |
|---|---|
| Single Phase, High-Z Failure, During Operation | Fan continued to rotate but at low speed; after 17 minutes, temperature stabilized at 45 °C.<br><br>Power Consumption: 55 W, 112 VA, 0.49 PF |
| Single Phase, High-Z Failure, Pre-Existing | Fan did not rotate. After 3 minutes the temperature was 50 °C and rising – test was terminated due to damage concern.<br><br>Power Consumption: 87 W, 130 VA, 0.67 PF |
| Two Phase, High-Z Failure, During Operation | Fan does not rotate or draw power (trivial case) |
| Two Phase, High-Z Failure, Pre-Existing | Fan does not rotate or draw power (trivial case) |

# Hardware Example #3
# Test Results for Zero-Volt Conditions

| Condition | Results |
|---|---|
| Single Phase, Zero-Volt Failure,<br>During Operation | Fan continued to rotate but at moderate speed; after 10 minutes, temperature stabilized at 35 °C.<br><br>Power Consumption: 55 W, 111 VA, 0.50 PF |
| Single Phase, Zero-Volt Failure,<br>Pre-Existing | In about 80% of trials, the fan rotated. When rotating, the results were the same as above. When stalled, after 4 minutes the temperature was 50 °C and rising – test was terminated due to damage concern.<br><br>Power Consumption when Rotating: Same as above<br>Power Consumption when Stalled: 51 W, 103 VA, 0.50 PF |
| Two Phase, Zero-Volt Failure,<br>During Operation | Fan continued to rotate at very low speed. After 14 minutes the temp was 50 °C and rising – test was terminated due to damage concern.<br><br>Power Consumption: 17 W, 50 VA, 0.34 PF |
| Two Phase, Zero-Volt Failure,<br>Pre-Existing | Fan did not rotate. After 14 minutes the temp was 50 °C and rising – test was terminated due to damage concern.<br><br>Power Consumption: 8 W, 26 VA, 0.31 PF |

# Hardware Example #3
# Score Card

| Condition | Result and Notes | 704 | DO-160 |
|---|---|---|---|
| Single Phase,<br>0-Volt Failure, During Operation | Fan continued to rotate at moderate speed, no damage to fan ⇧ | Tested | Not Tested |
| Single Phase,<br>0-Volt Failure, Pre-Existing | Fan usually rotates at moderate speed, when stalled possible fan damage ⇔ | Not Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, During Operation | Fan rotates at very low speed, possible fan damage ⇩ | Tested | Not Tested |
| Two Phase,<br>0-Volt Failure, Pre-Existing | Fan does not rotate, possible fan damage ⇩ | Not Tested | Not Tested |
| Single Phase,<br>High-Z Failure, During Operation | Fan continued to rotate at low speed, no damage to fan ⇧ | Not Tested | Tested |
| Single Phase,<br>High-Z Failure, Pre-Existing | Fan does not rotate, possible fan damage ⇩ | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, During Operation | Fan does not rotate or draw power, no fan damage ⇧ | Not Tested | Tested |
| Two Phase,<br>High-Z Failure, Pre-Existing | Fan does not rotate or draw power, no fan damage ⇧ | Not Tested | Tested |

# Suggested Enhancements

for

MIL-HDBK-704

and

DO-160

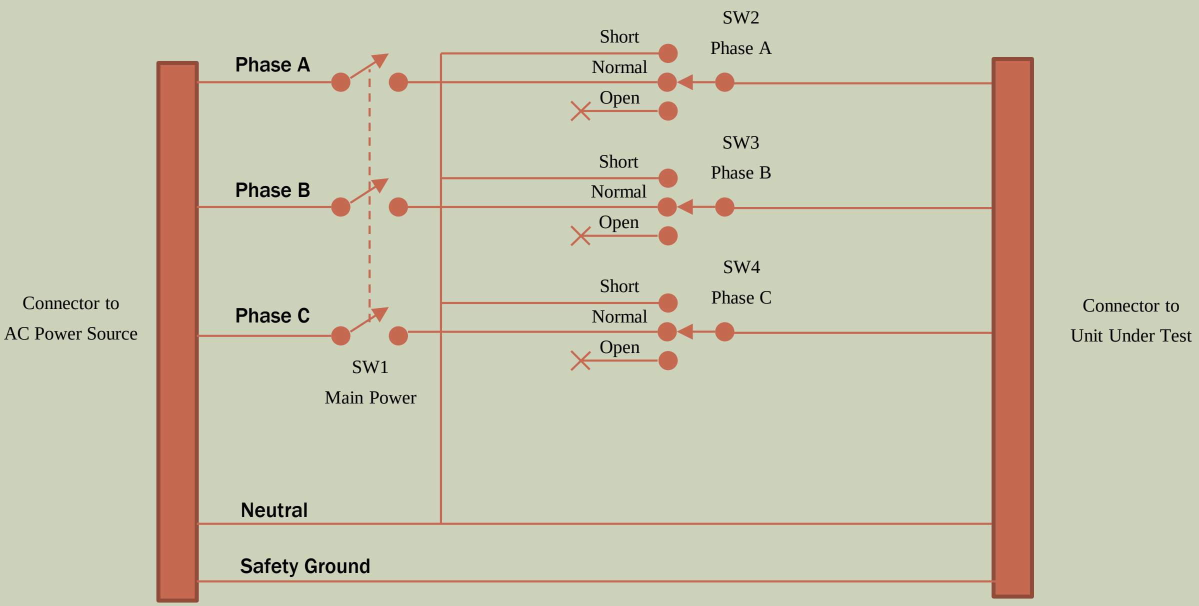
# Suggestions for MIL-HDBK-704 & DO-160

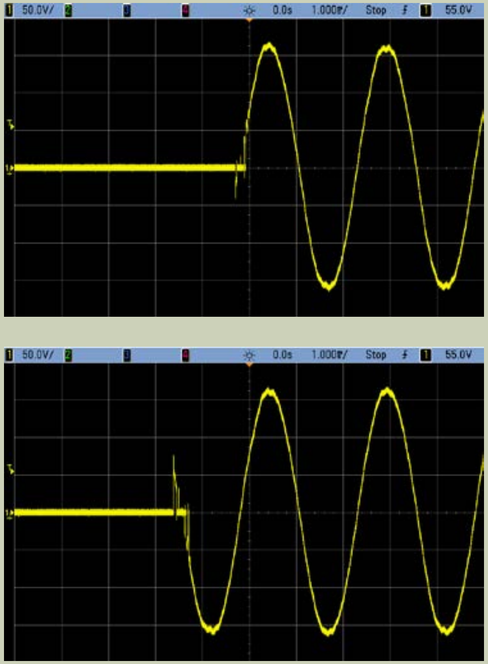
- MIL-HDBK-704 and DO-160 are thorough and comprehensive
- Nevertheless it is proposed that these documents be enhanced to include at least four sets of 3Ø failure conditions
- In MIL-HDBK-704, TAC602 (the 400 Hz phase failure method):
  - Perform the phase failure conditions as TAC602 now stands, but add failure condition of A&C
  - Repeat all the TAC602 conditions, but with the phase loss defined as a High-Z condition (can skip G-J if UUT is delta configuration)
  - Perform TAC602 conditions D, E, F, I and J (the 30 minute durations) where the phase loss(es) is as defined in the handbook (Zero-Volt) as a pre-existing condition when power is applied
  - Perform TAC602 conditions D, E, F, I and J where the phase loss(es) is defined as an High-Impedance (open-circuit) as a pre-existing condition when power is applied (can skip I and J if UUT is delta configuration)
  - More on the neutral failures later
  - Parallel update on the TVF602 method (variable frequency power)
- A similar enhancement can pertain to RTCA DO-160

# Reason for Additional Tests

- As seen in prior examples, hardware can react very differently under the four sets of three phase power failure conditions
  - Introducing a Zero-Volt fault during normal UUT operation
  - Introducing a High-Z fault during normal UUT operation
  - Applying power with a pre-existing Zero-Volt fault to the UUT
  - Applying power with a pre-existing High-Z fault to the UUT
- By designing/qualifying a system to cover all four scenario sets will help ensure reliable operation in the field

# Conceptual Schematic of Delta “Enhanced TAC 602” Test Fixture



Switch Bounce Examples

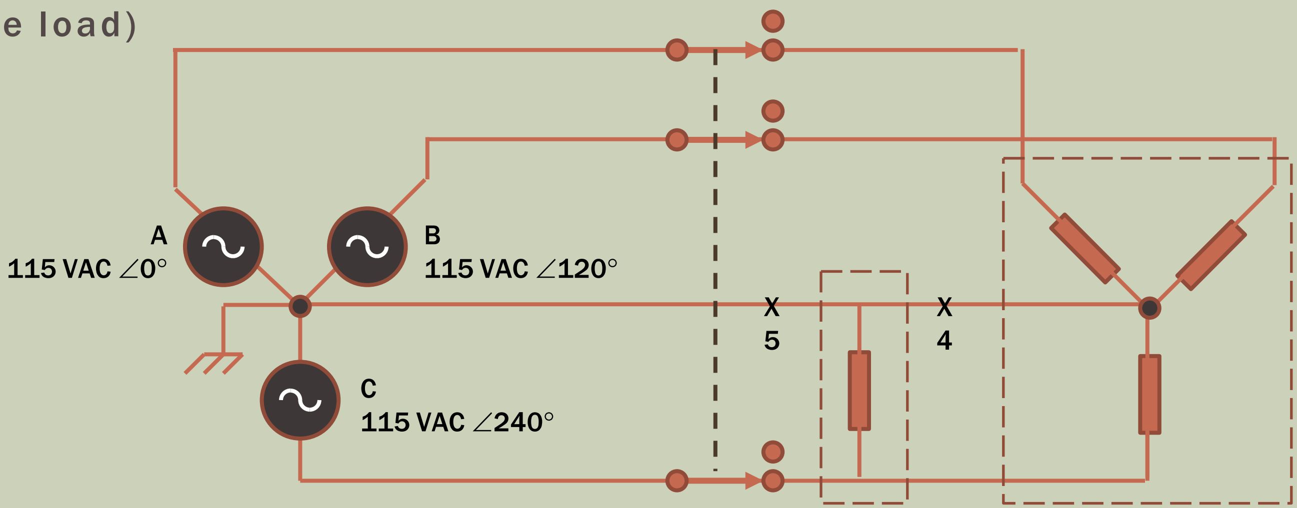
Note:

If mechanical switches/relays were used, it may satisfy the intent of the enhancement but may not technically comply with MIL-HDBK-704 that requires “The voltage must decrease from the steady state voltage to 0 Volts within ½ cycle (1.25 milliseconds), remain at 0 Volts for the duration listed for the test condition, and return from 0 Volts to the steady state voltage within ½ cycle (1.25 milliseconds)”.

# Failures of the Neutral Connection

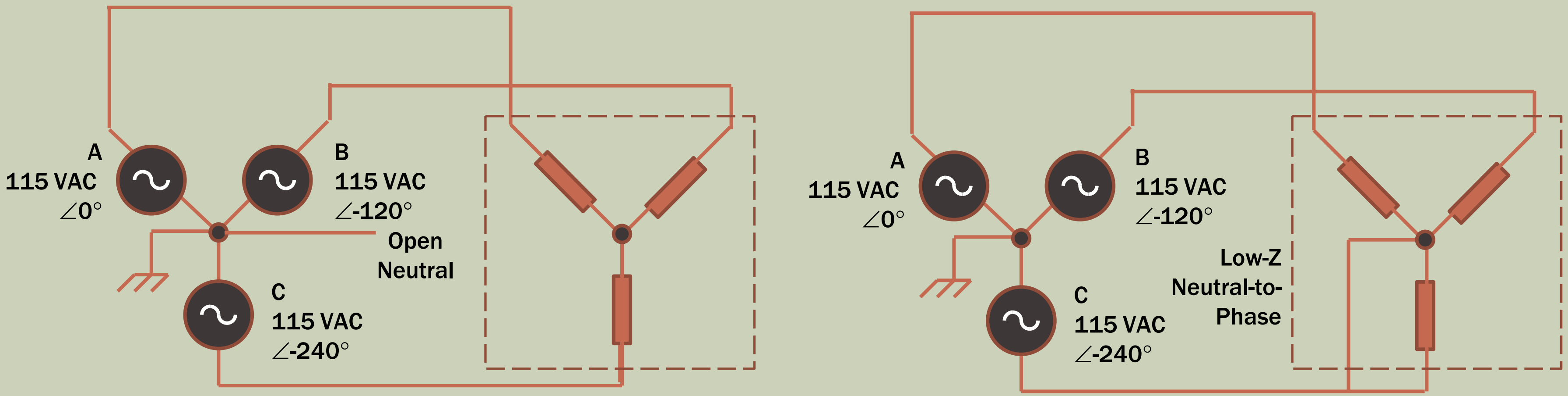
# Simple Neutral Connection Failure Examples

- 3Ø Wye source (115/200 VAC)
- Single-Phase Load C-N (moderate size with high inrush)
- 3Ø Wye Load (moderate load)



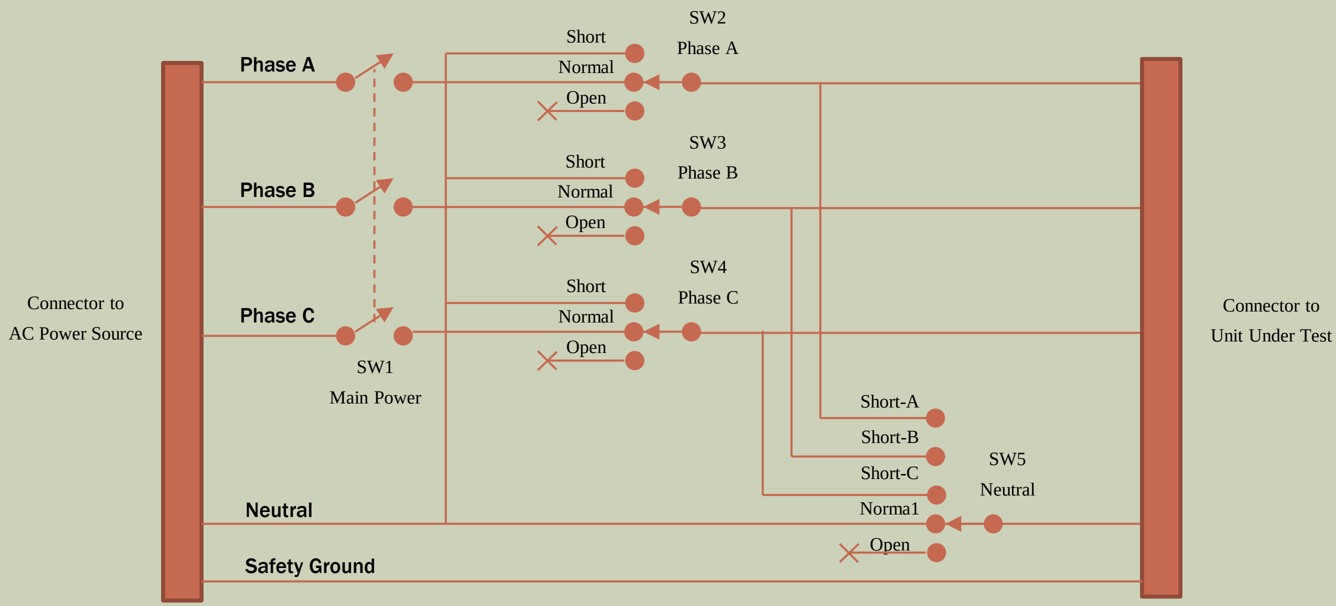

- Refer to earlier slide for discussion of opens at points 1, 2 and 3
- Neutral opens at point "4"
  - No direct impact on single phase load
  - Neutral of wye load "sees" a high Z
- Neutral opens at point "5"
  - Impacts single phase load
  - Neutral of wye load "sees" a low Z from neutral to phase C
- As before, these open points can occur during operation or be a pre-existing condition when power is applied

# Wye Loads with Neutral Failure




- Wye loads can be susceptible to failures of the neutral connection
- For instance, if three PFCs were configures in a wye configuration
  - Instability can result in a manner similar to example #2 if the open occurs at point 4
  - Over-stress can occur if the open occurs at point 5 as a low impedance results between the neutral and phase C, which causes the A and B legs to be exposed to the line-to-line potential rather than the line-to-neutral potential
- For wye loads, MIL-STD-704 and DO-160 should be further enhanced to take failures of the neutral connection into consideration

# Conceptual Schematic of Wye "Enhanced TAC 602" Test Fixture




- Including neutral tests complicates Test Fixture and test methods
- If 3 phase wye load does not share power with any single phase loads, the neutral-to-phase conditions on SW5 may not apply

# Design Mitigation

to tolerate all modes of power failure

# Hardware Design Mitigation

- Design 3Ø hardware/system as a delta configuration (in lieu of wye) whenever practical
  - Inherently immune to neutral connection failures
  - Typically better load balance among the three phases
  - Potentially less recurring cost by virtue of fewer connections
  - Reduced qualification testing costs
- Account for operation under all “Enhanced TAC602” conditions
  - During design (and qualification)
  - In hardware example #1, add comparator circuit to monitor buss voltage to enable/disable upstream converters (using the appropriate threshold, hysteresis and delay) to prevent buss ripple from cycling modules on/off at a high frequency rate
  - In hardware example #2, add AC Power Monitor or imbalance detector to facilitate shut-down (timing may be critical)
  - In hardware example #3 add AC Power Monitor or over-temperature sensor to facilitate shut-down (if only thermally-induced failures are of concern, timing may be less critical because of relatively long thermal time constants)

# Hardware Design Mitigation (continued)

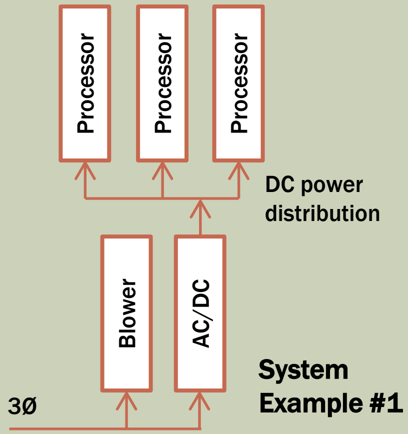
- AC Power Monitors can be designed or purchased
- Commercial, industrial and avionics grade units available (in addition to phase loss, they typically monitor other parameters such as phase rotation)

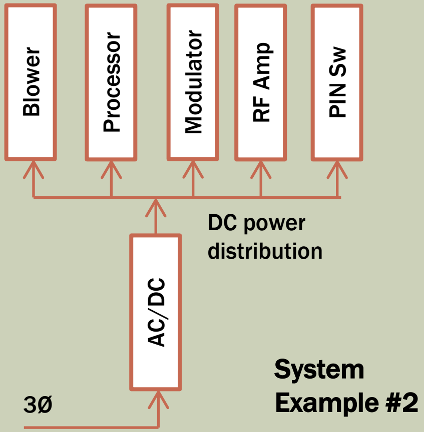
Avionics Grade Monitor
*Courtesy BC Systems*

Industrial Grade Monitor
*Courtesy Macromatic*

# System Design Mitigation

- Even if 3Ø loads of a system can tolerate all phase loss scenarios, the impact at the system level must be considered
- System Example #1:
  - Blower contains an over-temp cut-off switch allowing it to survive any phase loss condition
  - AC/DC Power Converter can survive any phase loss condition while providing up to 70% capacity under a single phase loss
  - Although individual components can survive, the system may not be able to survive if the reduced air flow was not accounted for – mitigation options:
    - Extra thermal margin (may not practical especially in critical SWaP applications)
    - Reduce clock rate
    - System-level temp sensor to facilitate partial or complete system shutdown
- System Example #2:
  - AC/DC Power Converter can survive any phase loss condition, but can lose regulation on reverse bias voltage for PIN switch – resulting in a vulnerable state if RF Amplifier is operated.
  - Although the 3Ø component can survive, the system may not be able to survive if the resulting PIN vulnerability is not accounted for – mitigation options:
    - Disable RF Amplifier when all relevant voltages are not within regulation
    - Disable Modulator when all relevant voltages are not within regulation

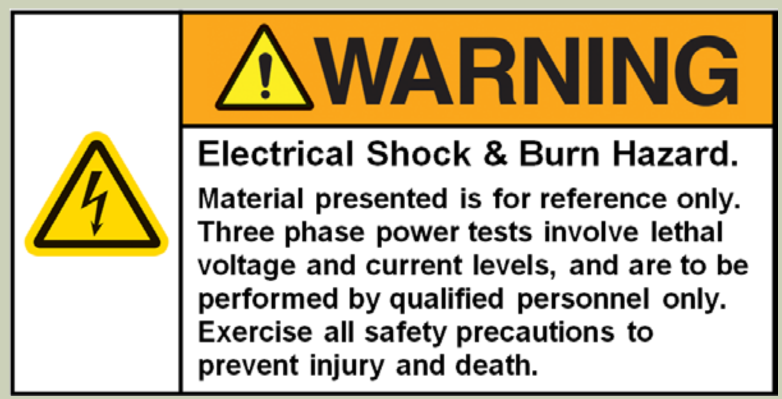


# Summary

# Summary

- It is possible to pass a MIL-HDBK-704 phase failure condition, but fail when subject to the companion DO-160 condition or real-world conditions
- Vice versa; It is possible to pass a DO-160 phase failure condition, but fail when subject to the companion MIL-HDBK-704 condition or real-world conditions
- When designing and qualifying any three-phase hardware/system, all phase failure conditions must be considered to ensure reliable operation
  - Introducing a fault as Zero-Volt potential during UUT operation
  - Introducing a fault as a High-Impedance during UUT operation
  - Energizing the UUT with a pre-existing Zero-Volt fault
  - Energizing the UUT with a pre-existing High-Impedance fault
  - If wye load, additional neutral failure modes should be included



# References

# References

- MIL-STD-704F
- MIL-HDBK-704 (with notations)
  - Notations are NOT official and are made for reference only
  - Please email colotti@ieee.org for notation suggestions
- RTCA DO-160 (requires purchase)
- LTSpice
- Protection of three-phase motors from unbalance (loss of phase and phase rotation)
- Vicor Maxi, Mini, Micro Family, Design Guide & Applications Manual
- Induction Motor, Wikipedia
- Input-Voltage Balancing of Series-Connected Converters
- Retlif Testing Laboratories (capable of performing enhanced TAC602)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