

# PV Inverter Designs and Operation

# Agenda

- Grid Tied Inverters for RE Distributed Generation
  - H-Bridge and Need for Isolation
    - Isolated Inverters
    - Transformerless Inverter
  - The UL1741 Inverter – General
  - Review of Isolation, Isolated Inverters
  - Transformerless Inverters vs. Isolated
  - Ground Fault Detection
  - DC Injection
  - Anti-Islanding

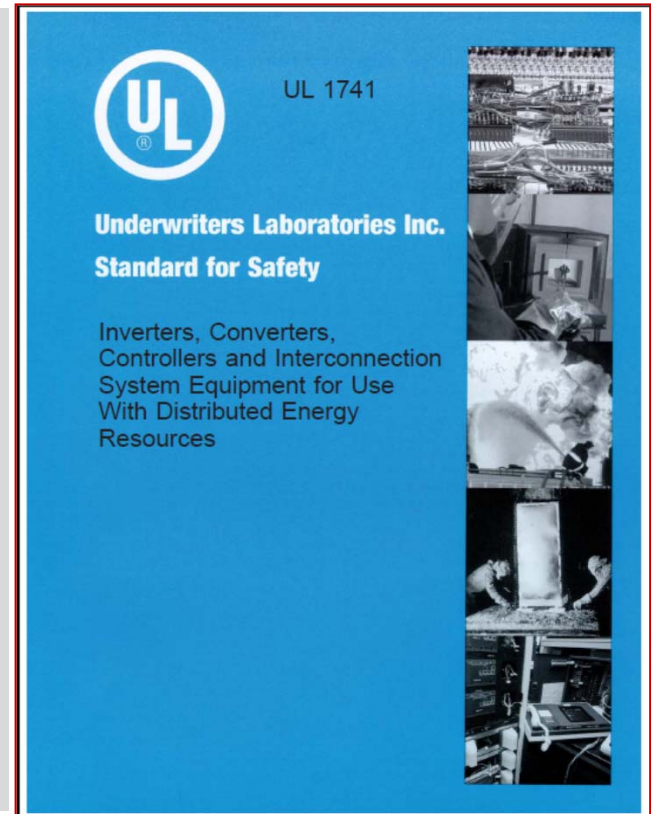
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# PV Inverter Regulations in US

## **UL Standard 1741:**

*Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources*

- UL1741 is the primary design standard for PV inverters and combiner boxes in North America
- **Coverage includes Grid Tied Isolated and Transformerless Inverters**
- **No prohibition on use of 1000V PV strings**



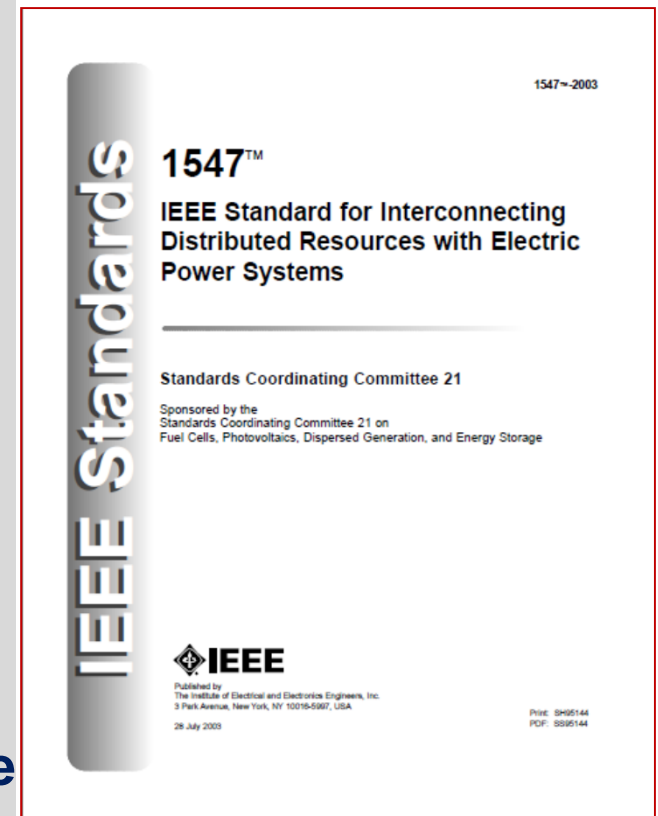
*UL, CSA and other NTRLs are actively Listing/Certifying 600V and 1000V Inverters and Combiners to UL1741*

# PV Inverter Regulations in America

## **IEEE 1547 and IEEE1547.1:**

*IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*

- Referenced by UL1741 as the primary design document for interconnecting inverters to the grid in North America
- **Provides details of necessary conditions on a grid to allow interconnection of Distributed Generation**
- **Provide details of abnormal conditions where Distributed Generation must be removed from Grid**

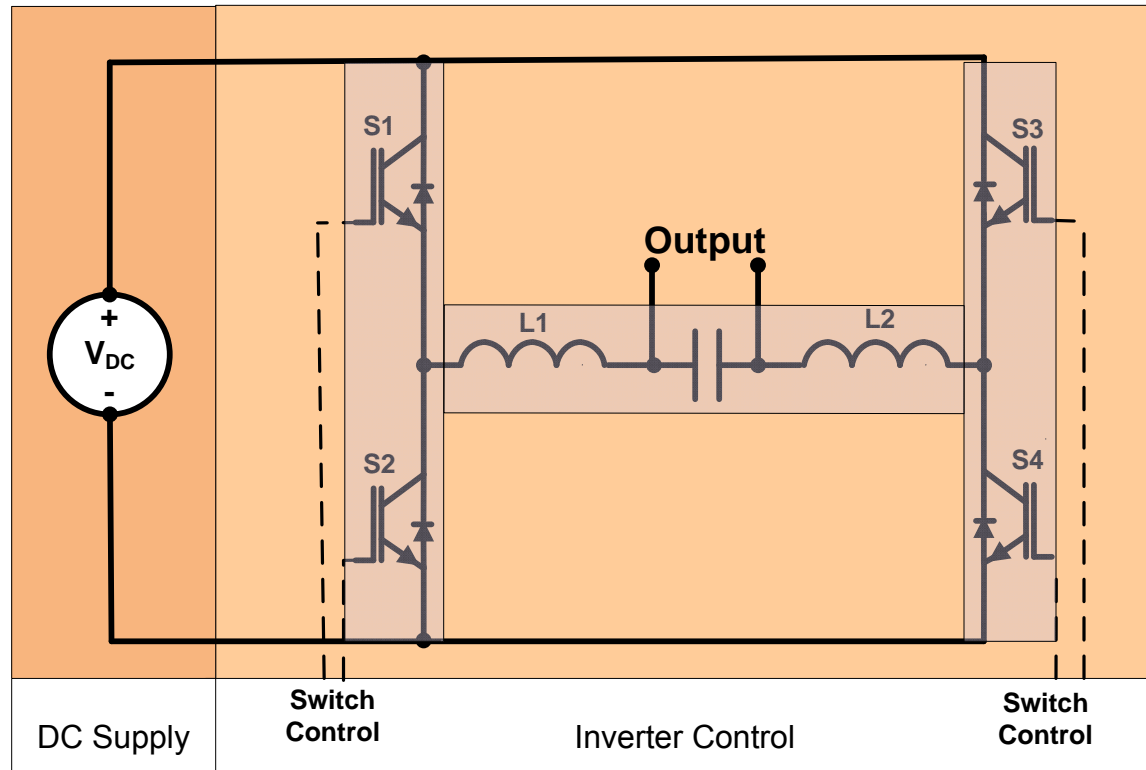


# The UL1741 Inverter Operation

**The UL1741 listed inverter acts as a current source that injects available energy from a PV array into the connected Grid and uses line voltage and frequency measurements to synchronize to it's grid connection**

- The inverter operates as a two-wire (1 $\emptyset$ ) or 3-wire (3 $\emptyset$ ) current source
- The inverter must control the injected current such that it is balanced on all available phases at all times: by design, it cannot support neutral current
- The inverter utilizes measured values of grid voltage and frequency but cannot control the line voltage or frequency at the point of interconnection to the grid

# Basic Inverter Operation – H-Bridge



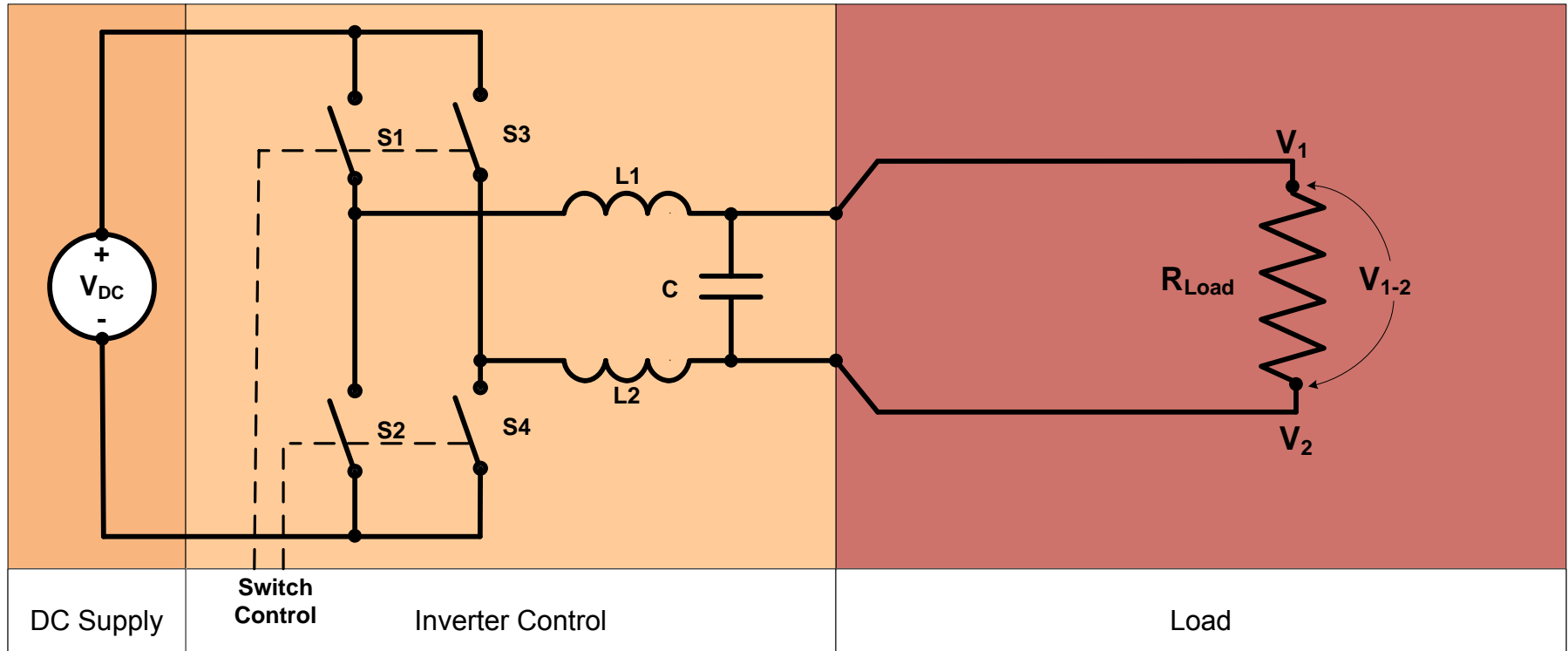
Basic H-Bridge Layout

## AC from DC

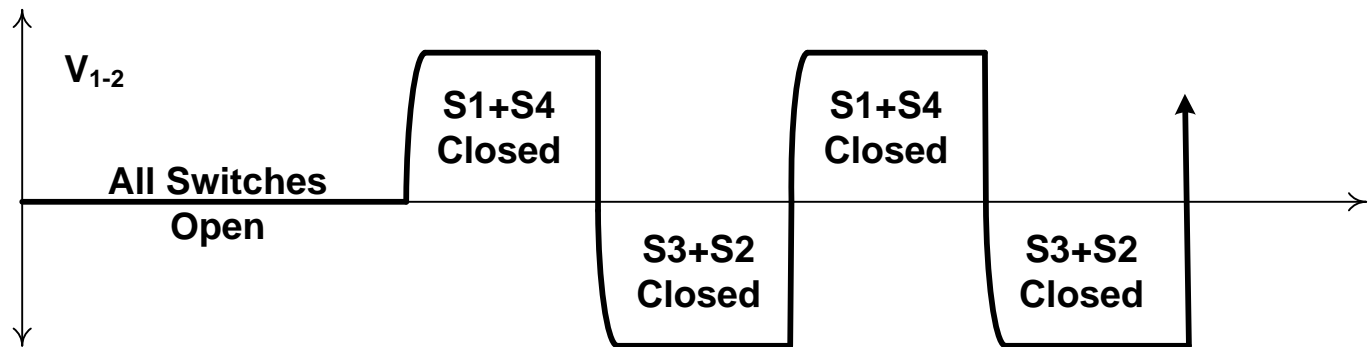
H-bridge designs were early workhorse of inverter technology

Simple Bridge design consists of four semiconductor switches and an output filter

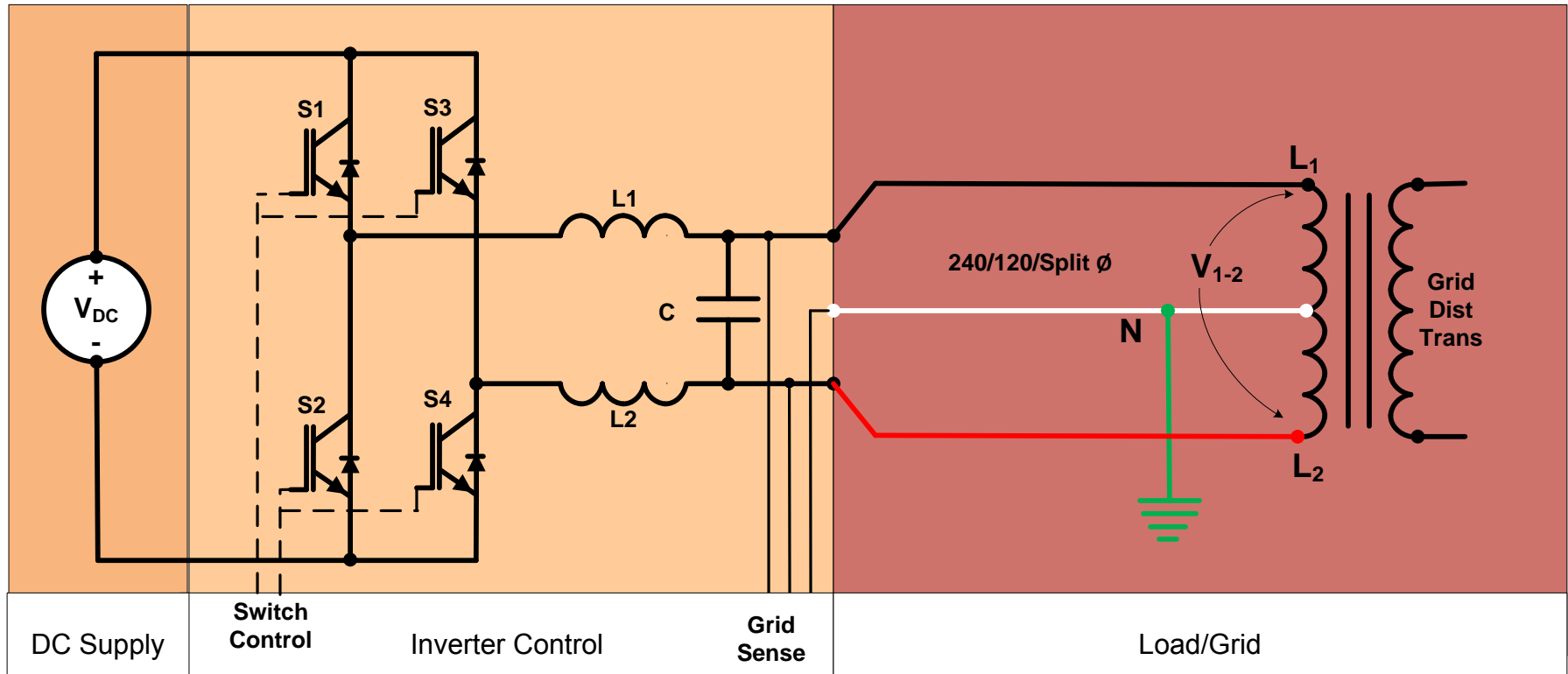
# Basic Inverter Operation – H-Bridge



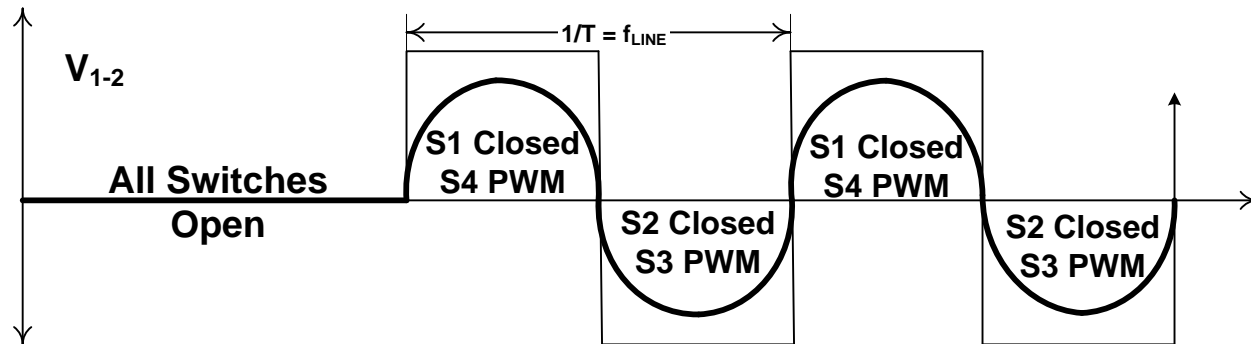
Simplified Open Loop H-Bridge Design with Resistive Load



# The UL1741 Inverter Operation – “Grid Tied”

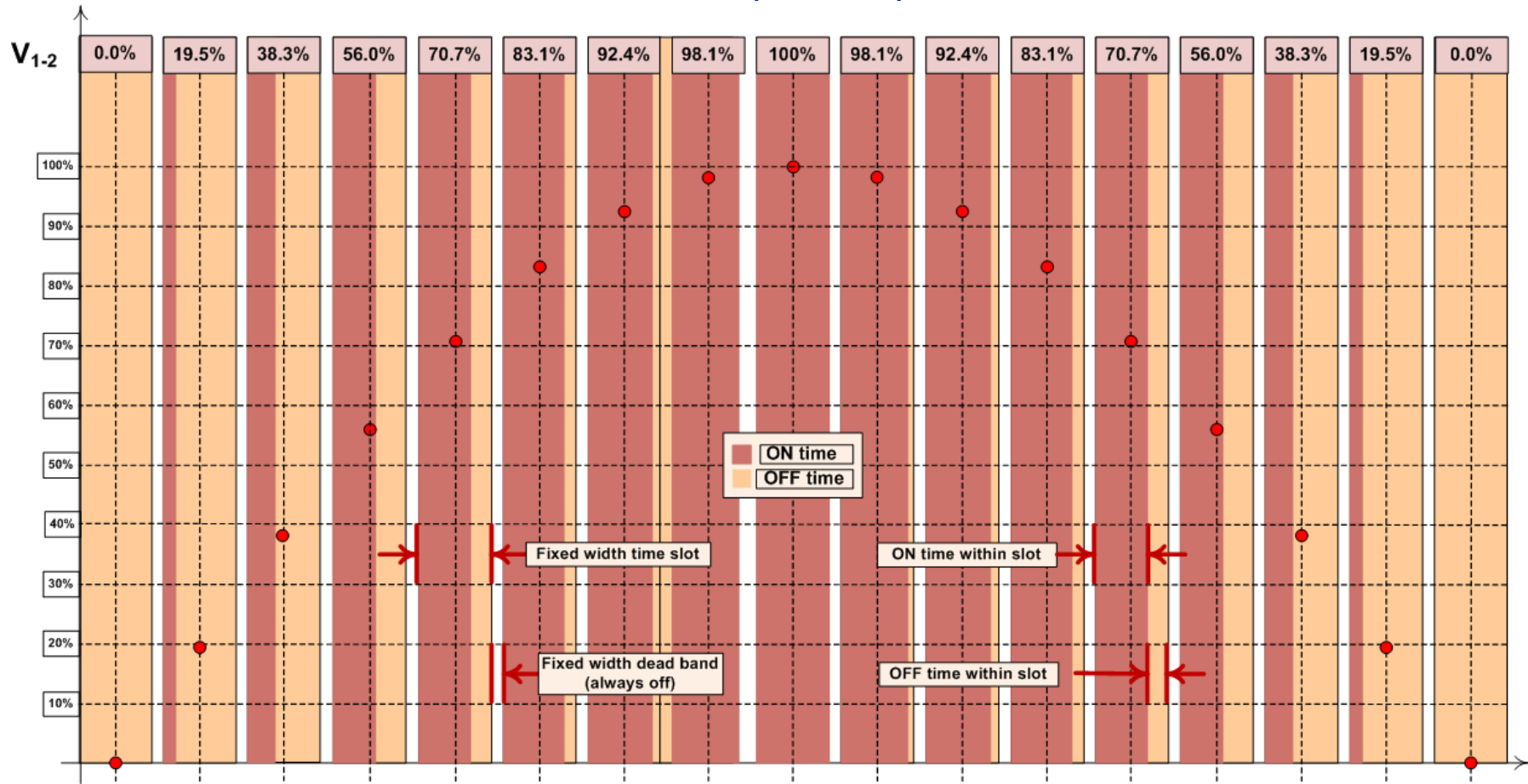


**Closed Loop PWM H-Bridge Grid Tied Design (Simplified)**



# The UL1741 Inverter Operation

## Basic Pulse Width Modulation (PWM)



**H-bridge PWM output**

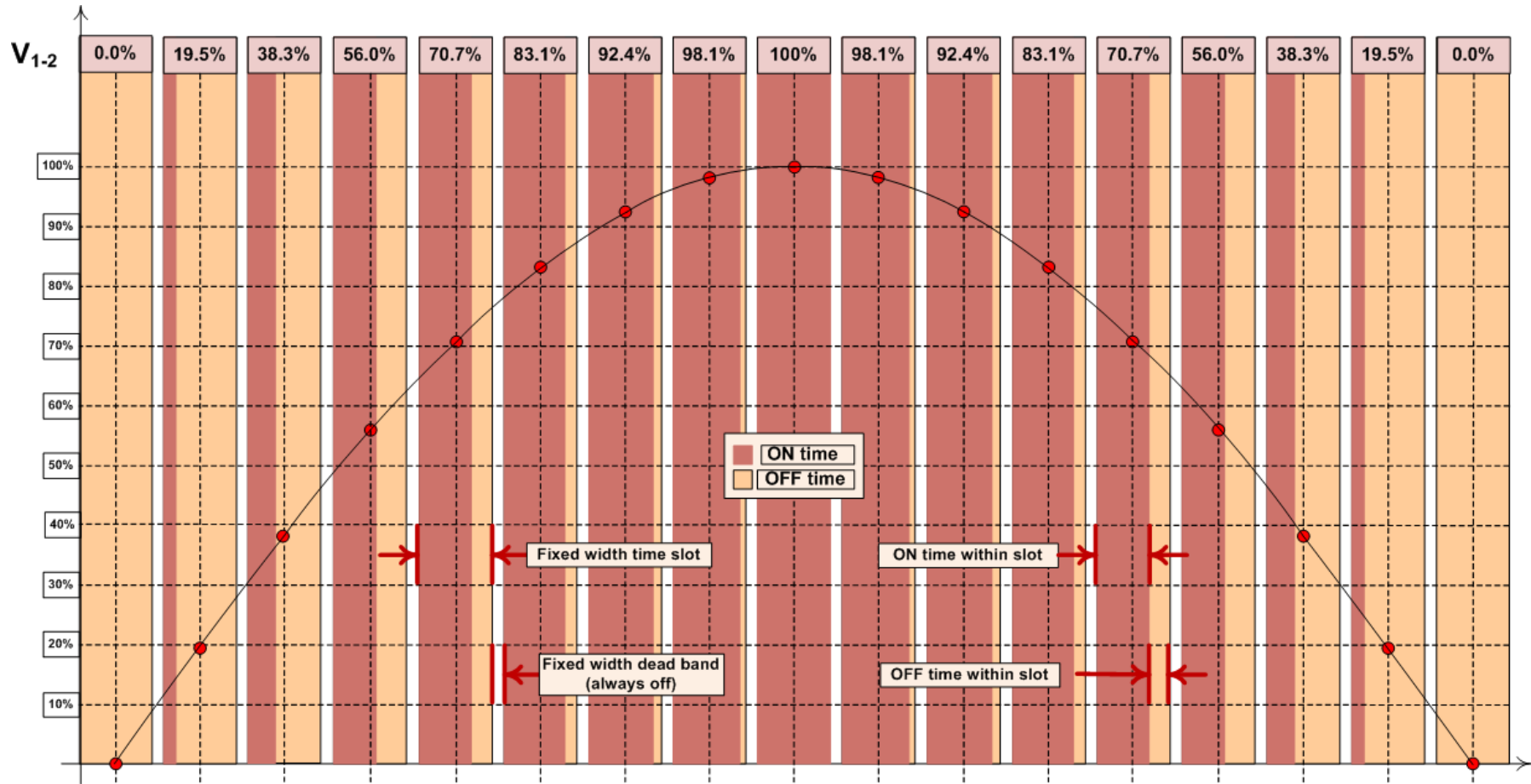
**Half cycle shown (S1 Closed + S4 PWM)**

Waveform is divided into a number of small equal time segments determined by PWM switching frequency

Each segment is turned on for a given duty cycle depending on  $V$ ,  $f$  of grid

# The UL1741 Inverter Operation

## Basic Pulse Width Modulation (PWM)



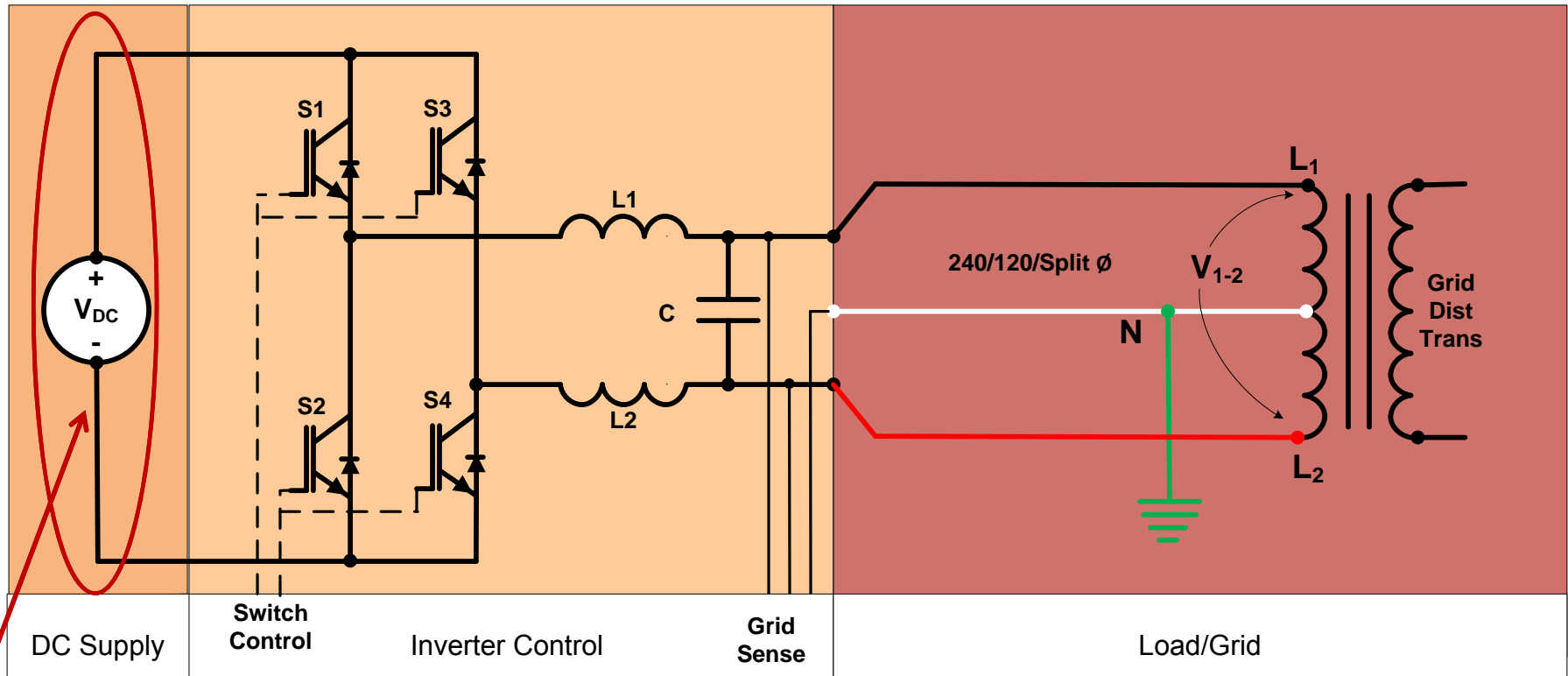
**H-bridge PWM output**

**Half cycle shown (S1 Closed + S4 PWM)**

Waveform is divided into a number of small equal time segments determined by PWM switching frequency

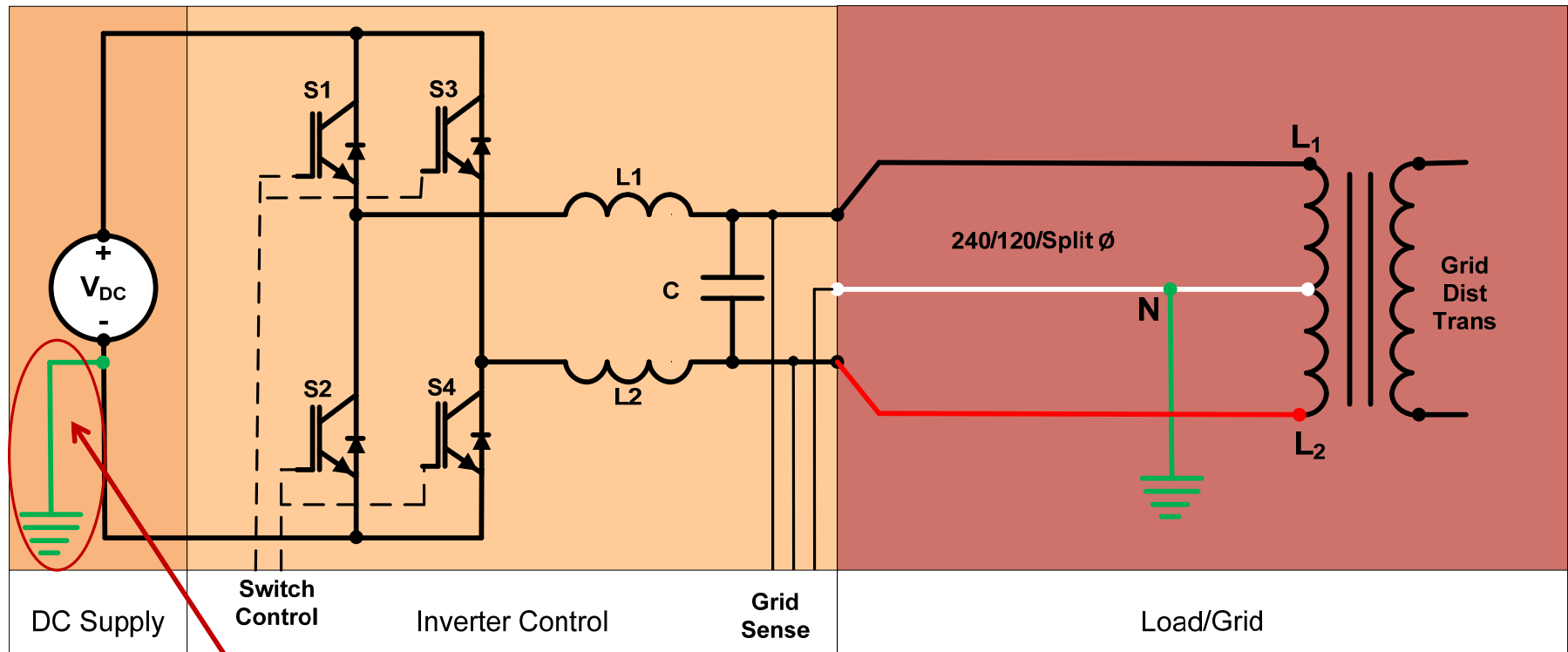
Each segment is turned on for a given duty cycle depending on  $V$ ,  $f$  of grid

# The UL1741 Inverter Operation



- Note the schematic shown above has a floating DC source – i.e., neither the POS nor NEG side is referenced to GND/PE
- What happens if one side of the array is referenced to GND/PE?
- When and why would this be necessary?

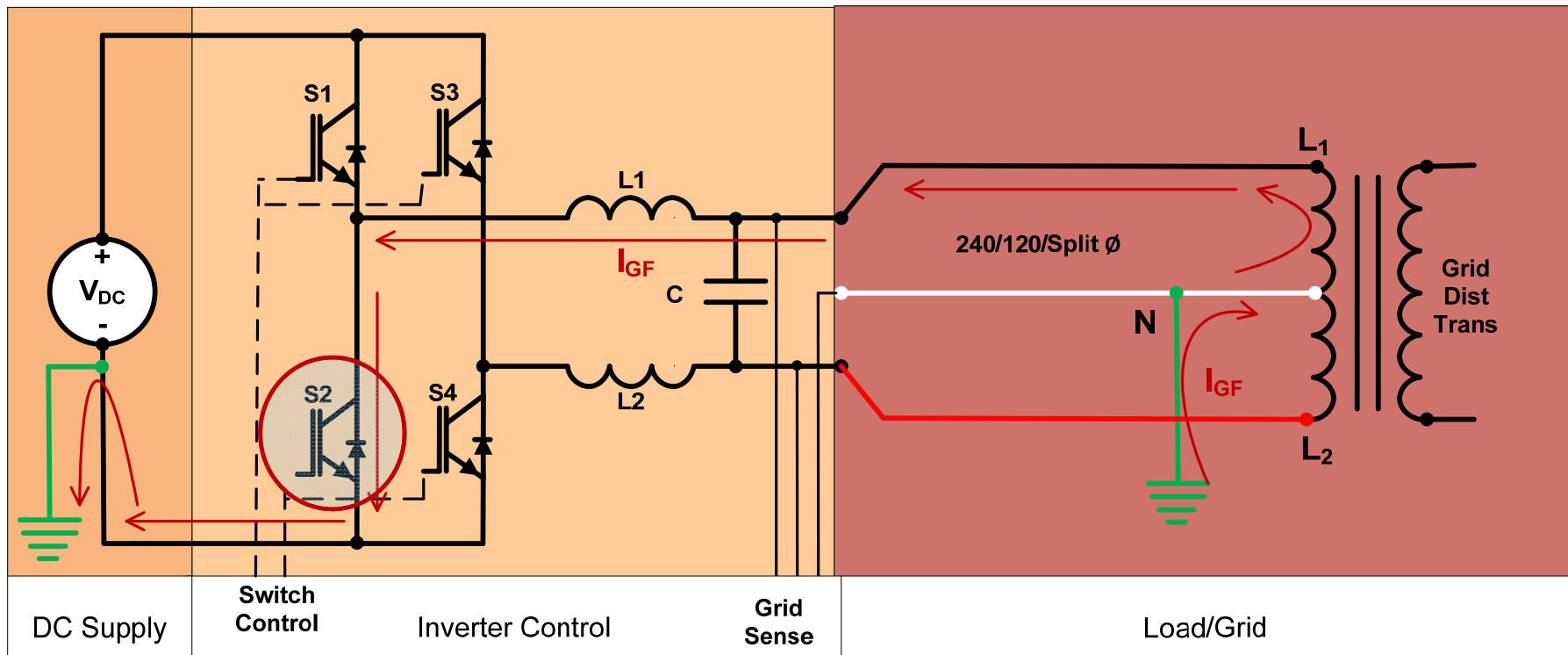
# Inverter Operation – Need for Isolation



Historically, NA electric codes required energy sources above a certain size (VA rating) to have one side of the source (array) to be referenced (bonded) to GND/PE

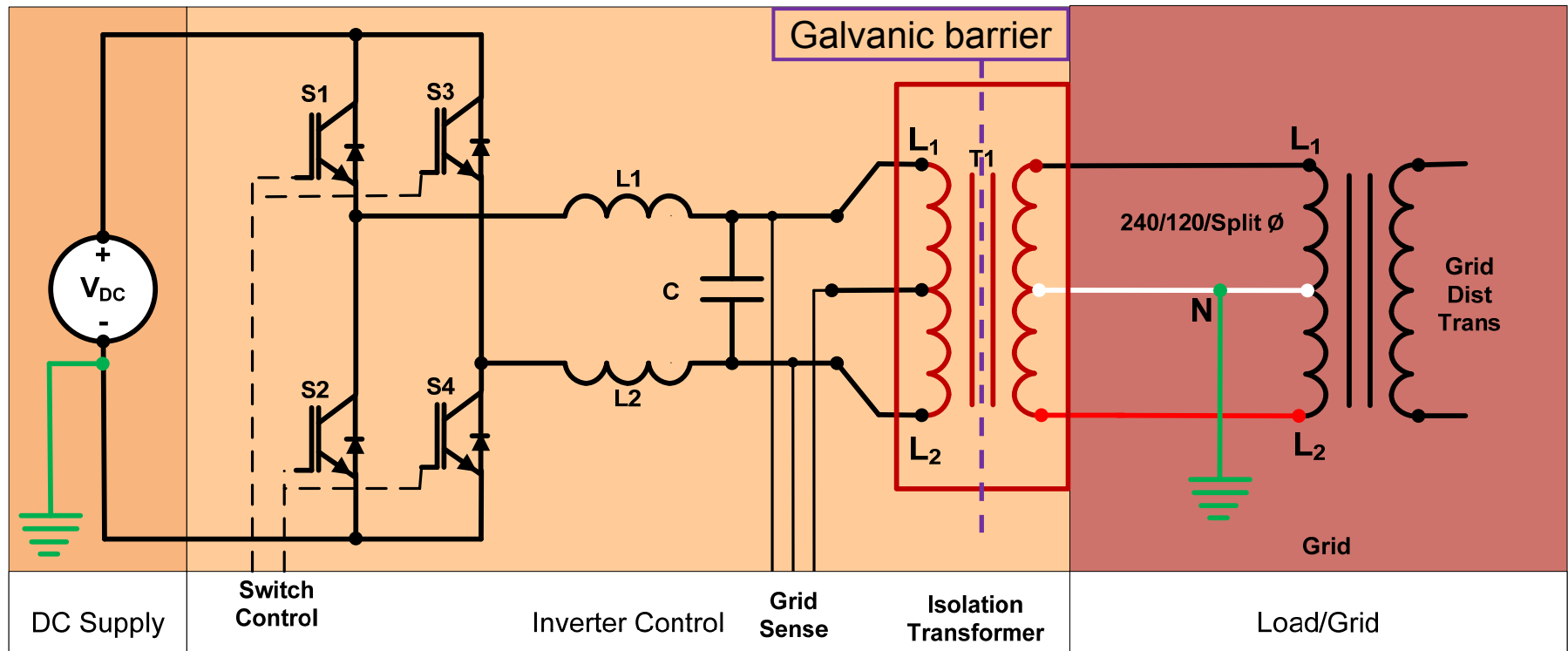
For the **H-Bridge** construction, if the NEG (or POS) side of the DC source is referenced to ground...a problem arises!

# Inverter Operation – Need for Isolation



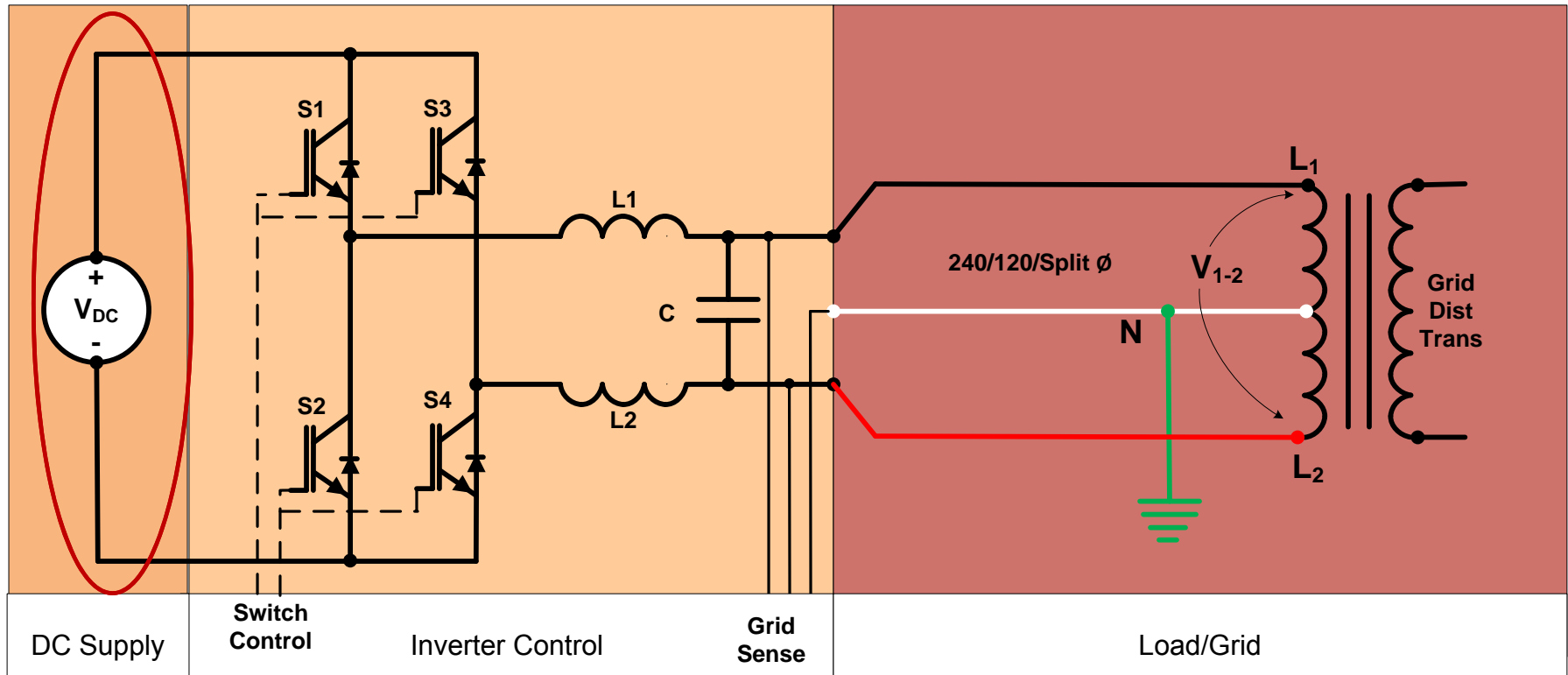
- The H-Bridge is **not** an isolated circuit: input and output sides are common through the switches
- With both the array and grid side of the H-Bridge tied to GND as shown, if switches [S3 & S2] or [S1 & S4] are closed, fault current **IGF** flows and will destroy switch S2/S4

# Inverter Operation – Transformer Isolated Inverter



- Thus, the emergence of the **Transformer Isolated inverter**
- Isolation transformer, T1, provides a galvanic barrier between the two ground references and allows normal operation of the H-bridge circuit

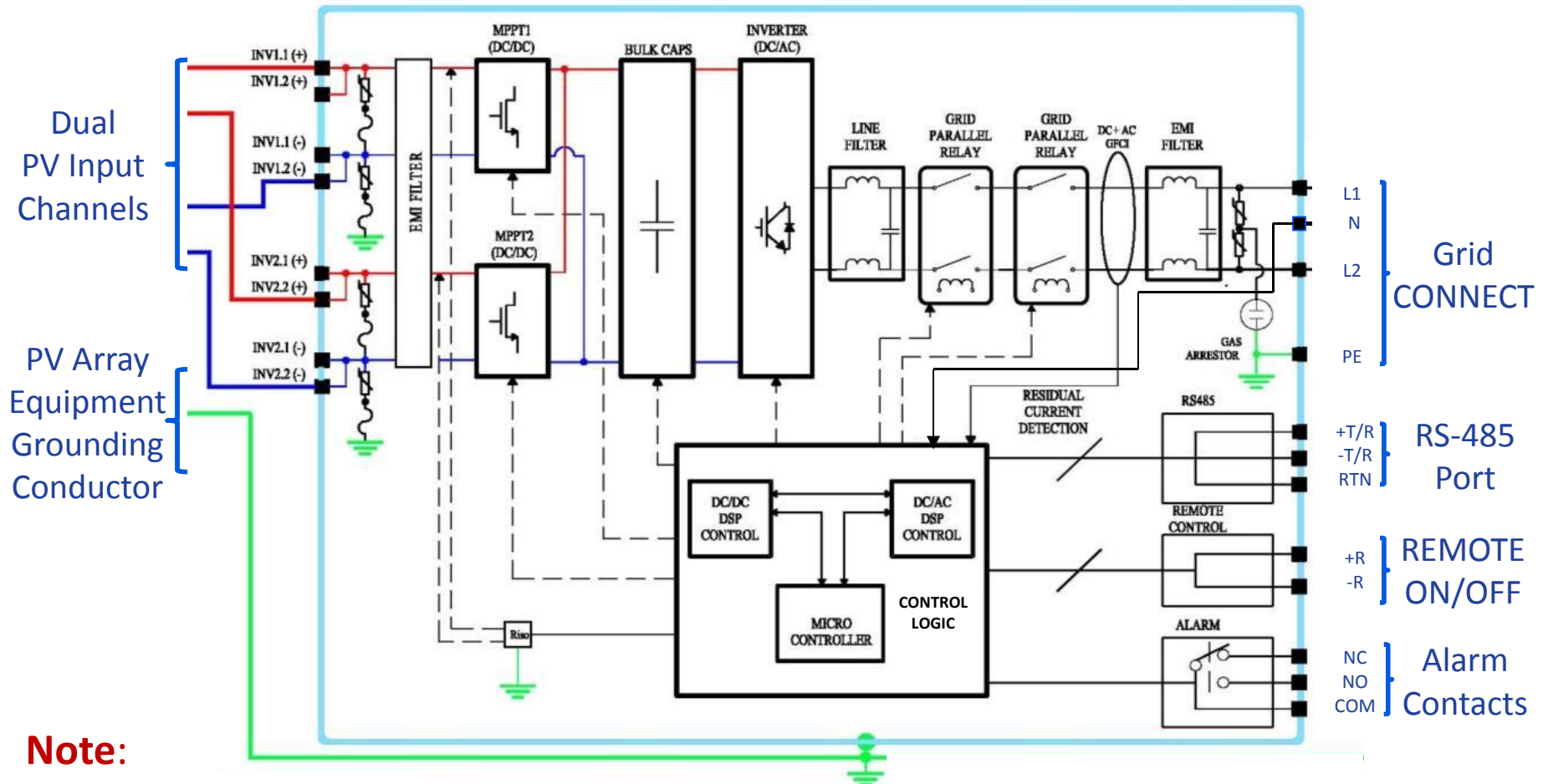
# Inverter Operation – Transformerless Inverter



- What about the newer transformerless inverters?
- TL designs **require** floating strings – neither POS nor NEG side of array is referenced to GND
- Floating strings are permissible per NEC 690.35
- Requires double insulated array wiring and locking MC4 conn

# ABB PV String Inverters

What's Inside the Aurora **Transformerless** Design?

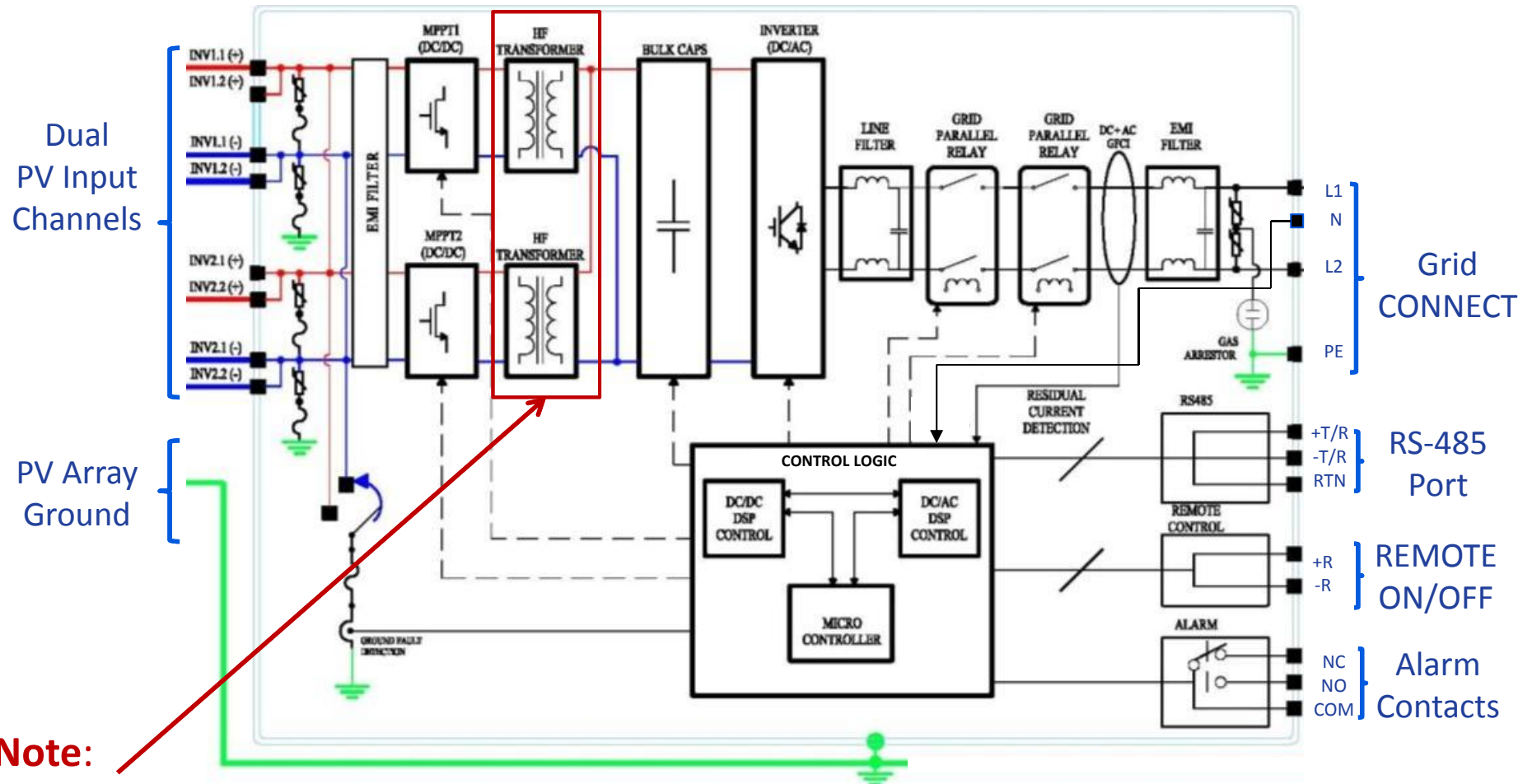


**Note:**

The -TL design has no galvanic isolation between input and output – the array(s) are referenced to the grid (i.e., a “floating” array)

# Aurora PV String Inverters

What's Inside the Aurora **HF Transformer Isolated** Design?



**Note:**

P1 Isolated versions provide array to grid galvanic isolation via a **HF isolation Transformer** after each boost stage

# Aurora Solar String Inverters

## *Transformerless vs. Isolated: What are the Differences? (1 of 2)*

- **Efficiency**
  - -TL Inverters generally have higher efficiency ratings than Isolated Inverters
    - do not have losses associated with an isolation transformer
- **Isolation**
  - Isolated Inverters have an internal isolation transformers that provide required galvanic isolation
  - -TL Inverters do not have (or need) galvanic isolation between input and output because arrays are floating with respect to ground (referenced to grid)
- **String Wiring**
  - -TL Inverters **require the PV circuit to be floating**, i.e., **cannot** be referenced to ground (re: NEC 690.35, floating arrays)
  - Isolated Inverters **require PV circuits to be ground referenced** in order to insure the fuse-controlled GFD operational (NEC 690.5)

# Aurora Solar String Inverters

## *Transformerless vs. Isolated: What are the Differences? (2 of 2)*

- **Panel Choices**

- **-TL Inverters**

- Usable PV modules must be provisioned with **double insulated lead wire** per UL4703, or marked as “PV wire” per NEC & locking connectors
    - Cannot support panels requiring grounding , e.g., some Thin Film Technologies

- **Isolated Inverters**

- support all PV module types

- **Weight**

- -TL Inverters have no heavy transformer and weigh much less than Isolated Inverters utilizing line frequency (60 Hz) transformers
  - Lowers shipping and handling costs
  - Easier to install

# Why are –TL inverters Desirable?

## ***Benefits using -TL inverters:***

- ***Much safer*** from fire safety perspective:
  - Floating Array is Double Insulated
    - **PV Wire** required on PV modules and other PV source wiring
    - No HV DC referenced to Ground
  - Proven Two-Step GF Detection Technology is considered safer than arrays grounded via GFD Detector fuse (690.5)
    - See following slides
  - Eliminates the so-called ***GF blind spot*** issues – fire hazards due to ground faults in the grounded conductor that allow bypass of fault current around GFD fuse – can cause GFD system to fail
    - See following slides

# Transformer-less Inverter Operation

## Ground Fault Detection and Control in -TL Inverters

### Method 1: Pre-Start GF Test (Static $R_{ISO}$ )

- Any time conditions are suitable for the inverter to be connected to the grid prior to connection, internal circuitry measures the insulation resistance ( $R_{ISO}$ ) of the PV array conductors relative to ground
- If the result of this static insulation resistance test is less than the pre-programmed threshold value, the connection attempt is aborted and the inverter will display the error on its LCD screen and illuminate the (red) GF LED indicator on the inverter front panel
- *This test is conducted prior to any attempt to connect to the grid, i.e., at day break and any other time during the day where the inverter has been disconnected from the grid*

# Transformer-less Inverter Operation

## Ground Fault Detection and Control in -TL Inverters

### Method 2: Post Grid Connection: Dynamic Leakage Current

(1 of 3)

- Any time the inverter is connected to the grid, the inverter circuitry continuously checks for ground fault conditions using a differential measurement of the AC phase (2W or 3W) lines searching for any values that would indicate leakage of current to ground.
- Measurement of the ground leakage current is carried out simultaneously by two independent and redundant processors
- If either processor detects an unacceptable value as defined in the next slide:
  - The inverter will immediately be disconnected from the grid
  - An error will be displayed on the LCD screen
  - The red LED GF indicator on the inverter front panel will be lighted

# Transformer-less Inverter Operation

## Ground Fault Detection and Control in –TL Inverters

### Method 2: Post Grid Connection Dynamic Leakage Current

(2 of 3)

- The inverter disconnects from the grid depending upon the level and duration of leakage current detected.
- If any one of the following conditions is measured based on static values of differential current ( $I_{DIF}$ ) or a rapid change of  $I_{DIF}$  over time ( $\Delta I_{DIF}/\Delta t$ ), the inverter will automatically disconnect from the grid and the front panel GF indicator will be illuminated:
  - If  $I_{DIF} > 300$  mA for a period of 300 msec
  - If  $\Delta I_{DIF}/\Delta t > 30$  mA/sec for a duration of 300 msec
  - If  $\Delta I_{DIF}/\Delta t > 60$  mA/sec with duration of 150 msec
  - If  $\Delta I_{DIF}/\Delta t > 150$  mA/sec with duration of 40 msec

# Transformer-less Inverter Operation

## Ground Fault Detection and Control in –TL Inverters

### **Method 2: Post Grid Connection Dynamic Leakage Current**

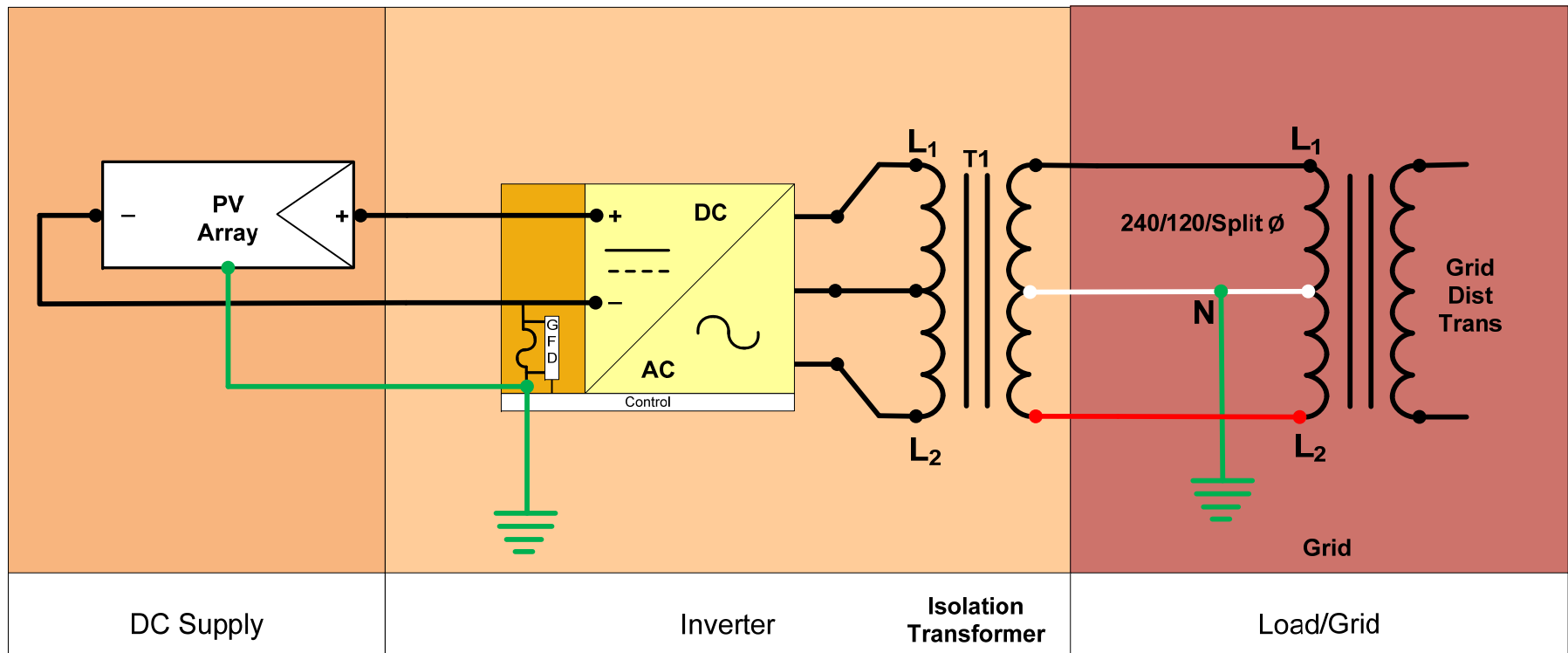
**(3 of 3)**

- As a further safety precaution, in compliance with UL1741 CRD 2010\*, the inverter conducts an isolation monitor interrupter self-test before connecting to the grid or every 24 hours, whichever is sooner. This test validates that the circuitry needed to perform the isolation test operates normally and has not been damaged.
- Errors generated when a ground fault is detected are permitted to occur 4 times within a 24 hour period before lockout
- Any ground fault error requires a manual reset of the inverter by a trained technician.

These steps are intended to ensure that equipment with a ground fault is not connected to the grid.

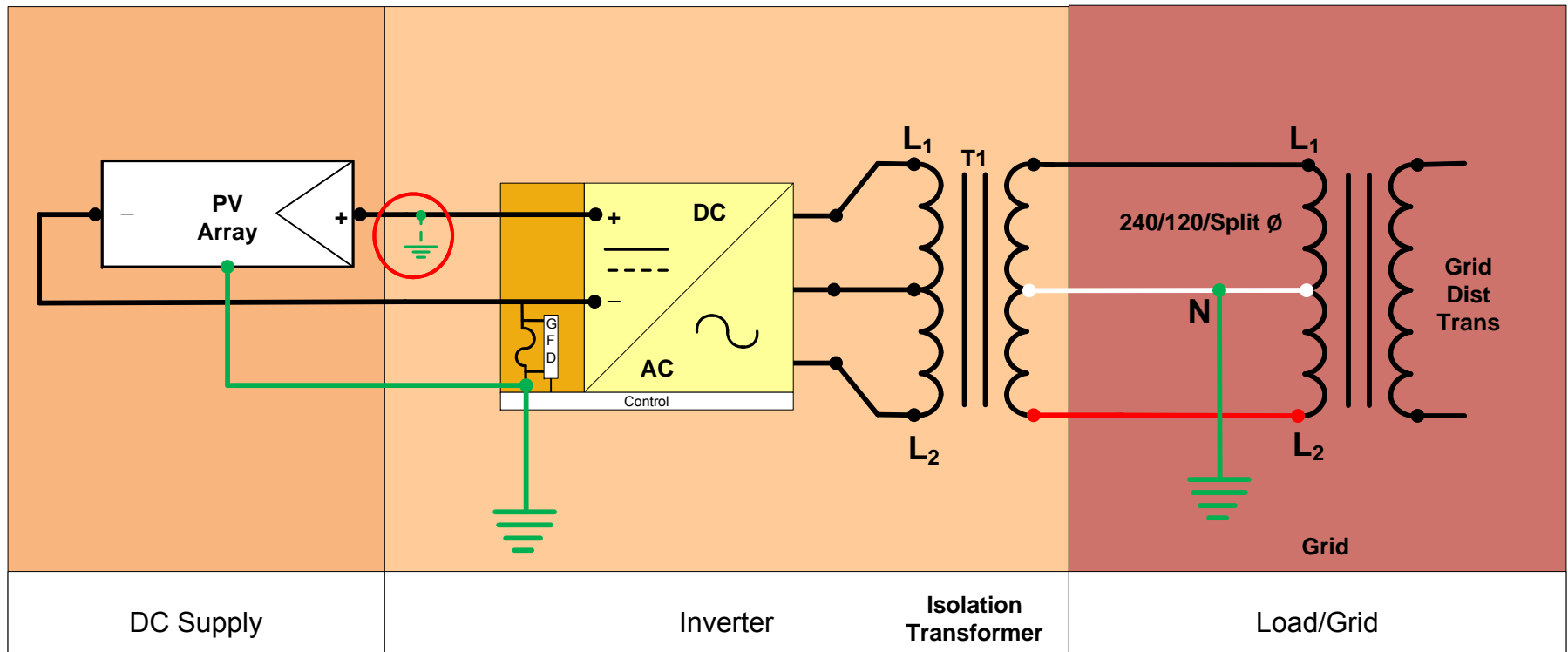
\**CRD = Certification Requirement Decision*

# Inverter Operation – GF Detection - Isolated



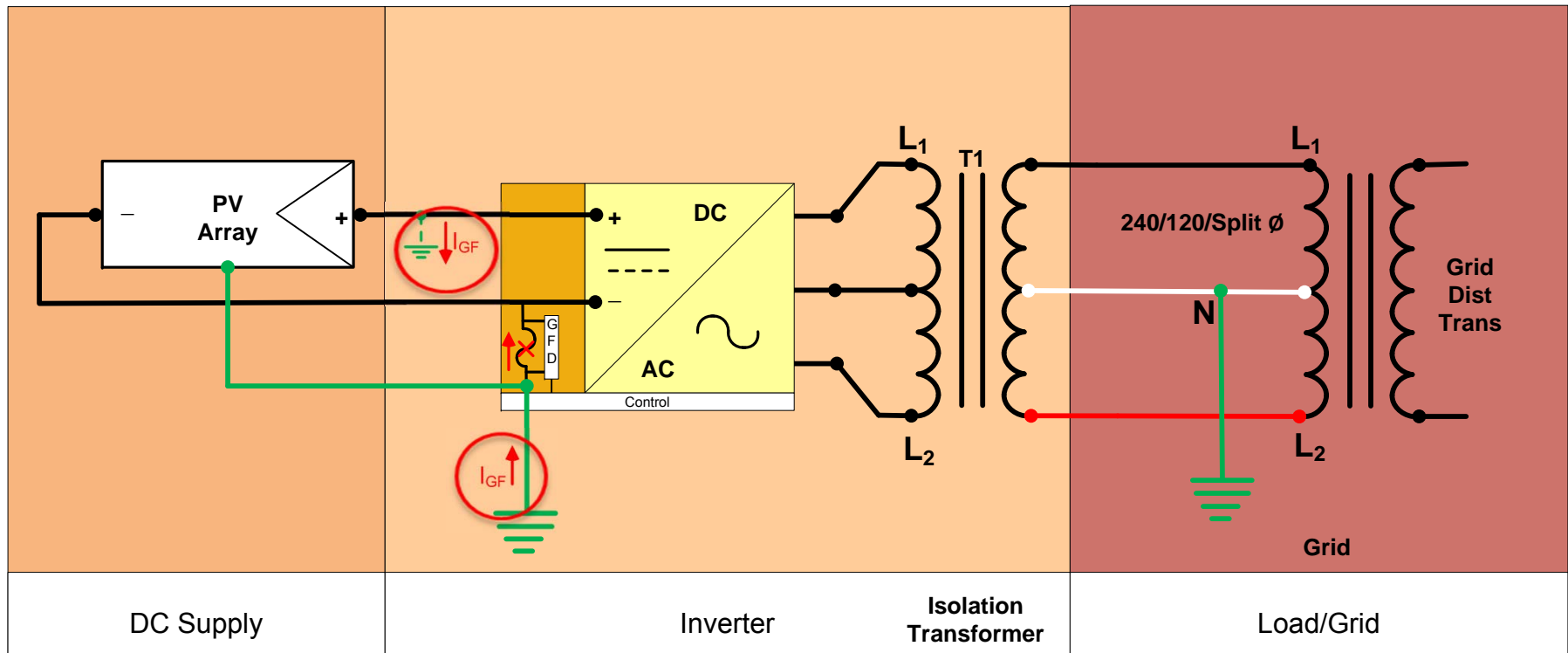
- Isolated inverter showing GF detector system that requires the connected PV array to be ground referenced (690.5)
- Typically this is done through a GFD fuse and sensing relay
- The fuse size is based on requirements of UL1741

# Inverter Operation – GF Detection - Isolated



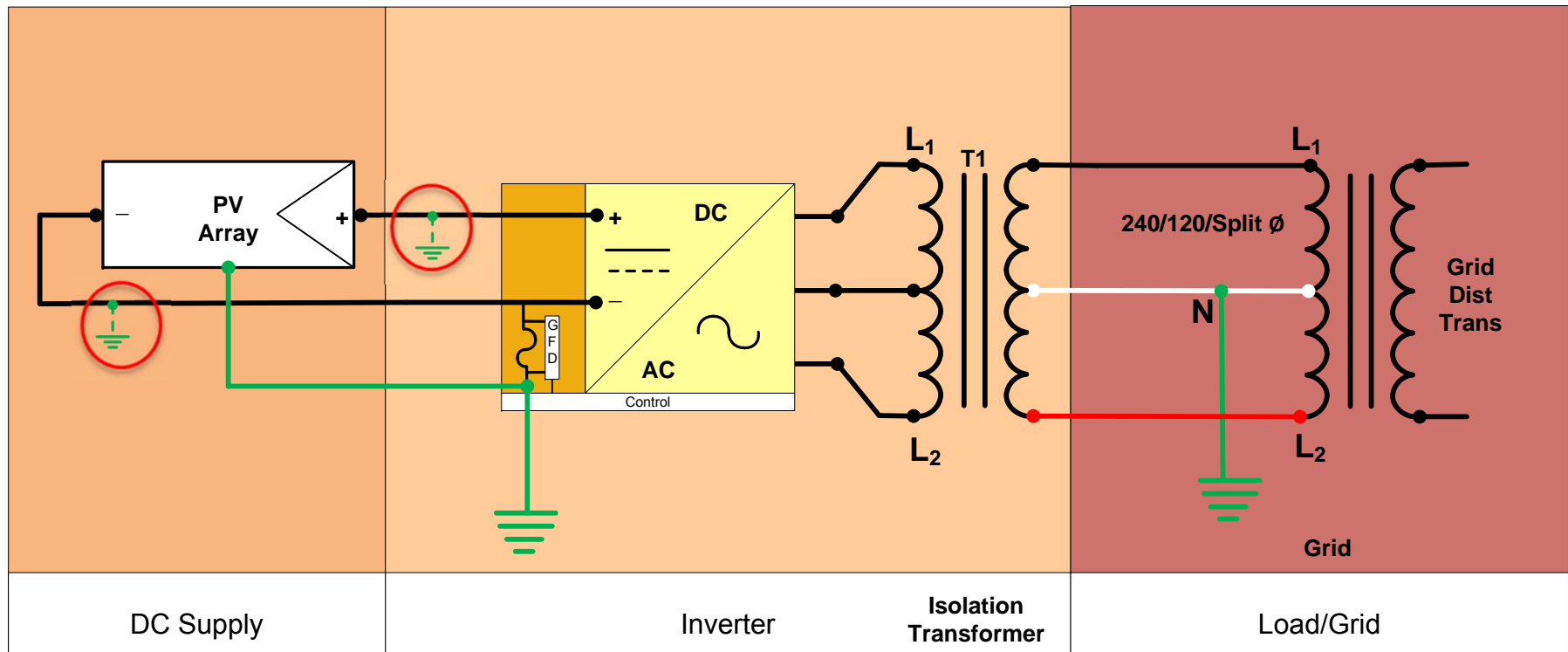
Assume a Ground Fault occurs on the POS lead as shown...

# Inverter Operation – GF Detection - Isolated



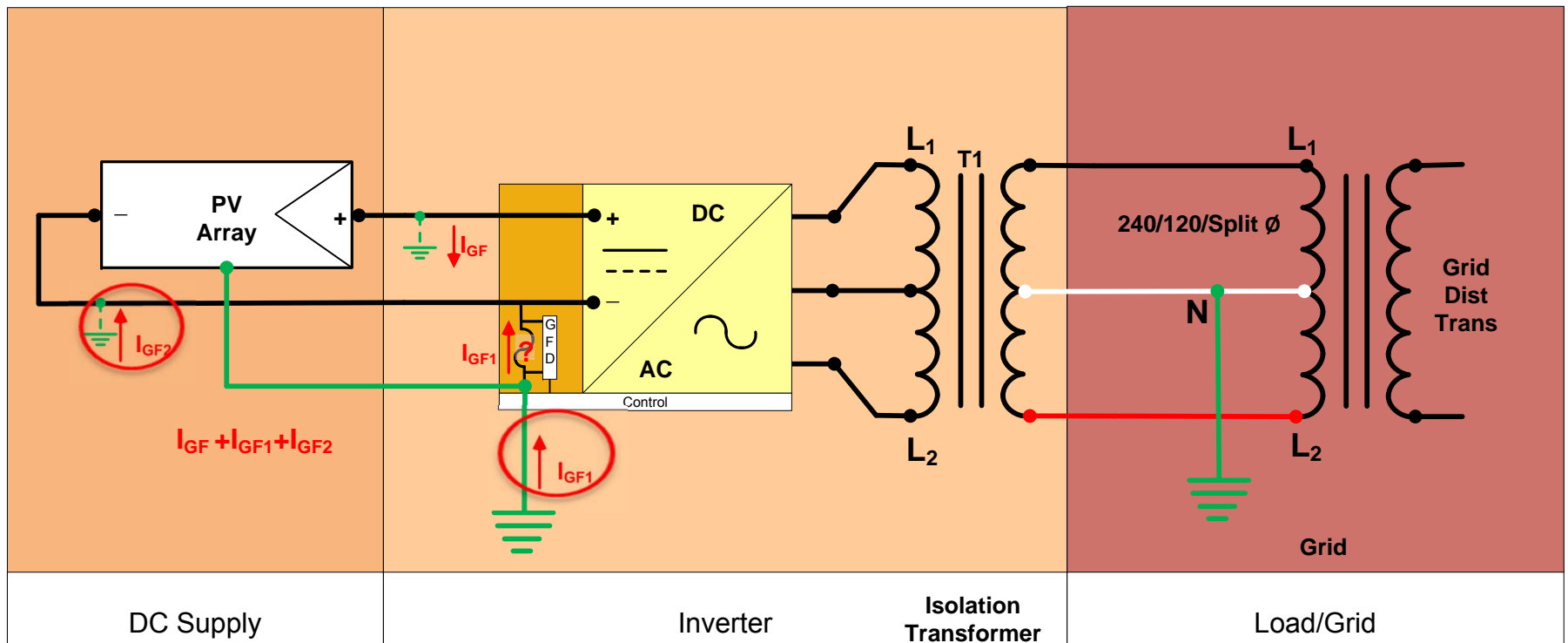
- A Ground Fault current,  $I_{GF}$ , flows through the fault to GND
- $I_{GF}$  is returned to the NEG side of the array via GFD fuse
- If magnitude of  $I_{GF}$  is sufficient, it will open fuse and relay will disconnect inverter and illuminate an indicator (LED)

# Inverter Operation – GF Detection - Isolated



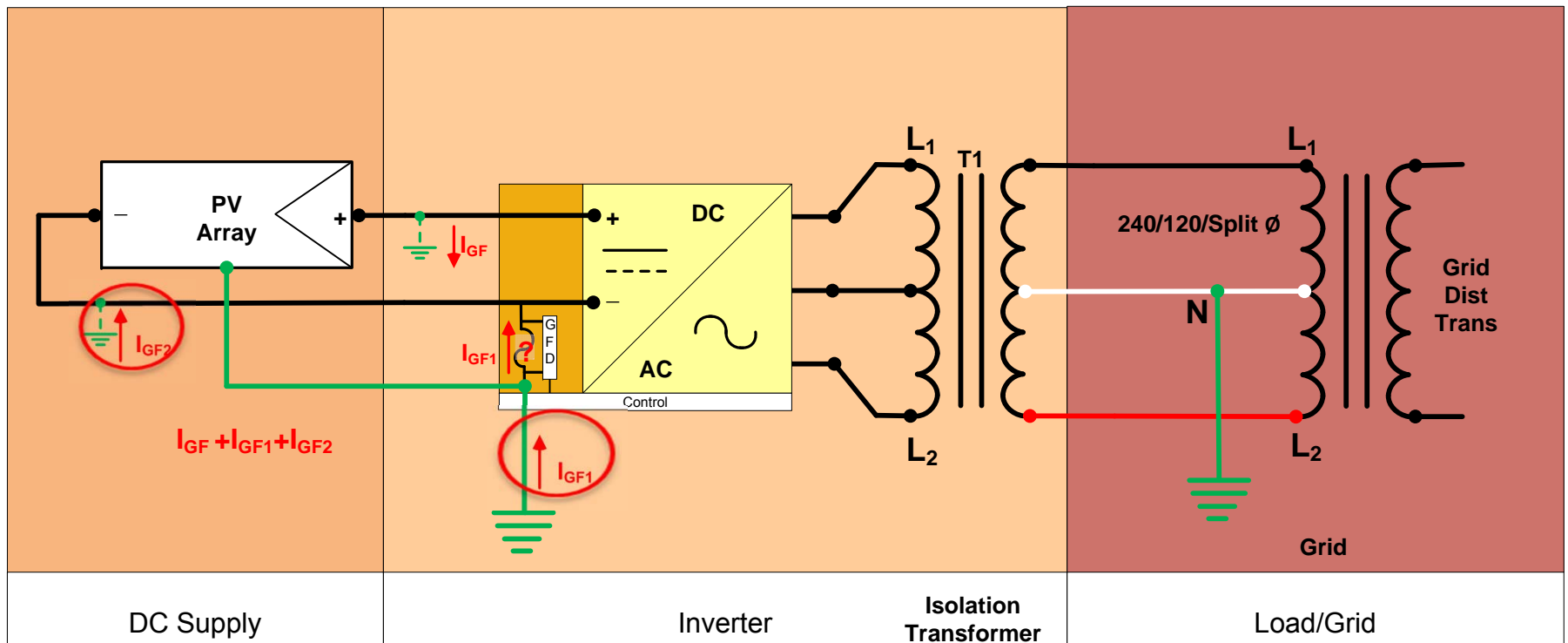
- Consider the case where there is also a fault in the **wiring of the grounded conductor** – this fault could have been created during installation, e.g., via a pinched wire
- **Now there are two current paths for GF current**

# Inverter Operation – GF Detection - Isolated



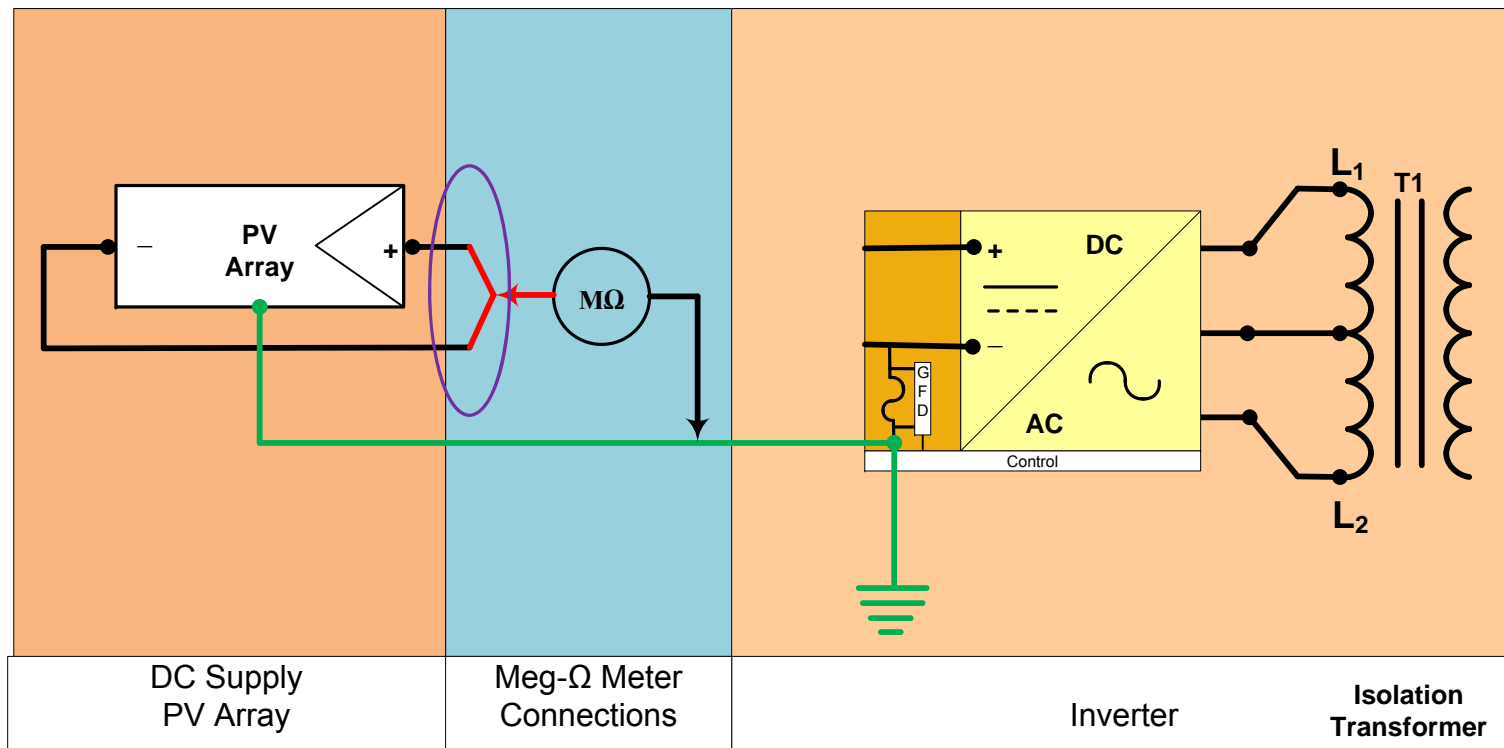
- Under this scenario, the fault current,  **$I_{FG}$** , from the POS conductor is returned to the NEG conductor via two paths
- **$I_{FG1}$** , is returned through the GFD fuse
- **$I_{FG2}$** , is returned through the ***grounded conductor fault***
- Thus, the GFD fuse may not see enough current to trip – this is called the “***GFD Blind Spot***” – it defeats this type (690.5) GFD

# Inverter Operation – GF Detection - Isolated



- This situation, i.e., the “**GFD Blind Spot**” – has been identified as having significant safety risk.
- In order to minimize occurrence, it is advisable to include (require?) a meg-ohm measurement of each string during commissioning (prior to connection to inverter) to assure the integrity of the array wiring

# Inverter Operation – Riso Measurement



- Connection for measuring Riso using meg-ohm meter
- Viable for single strings or multiple parallel strings
- ISC of array flows during Riso test between array conductors and ground
- Requires shorting and un-shortening the array

# Inverter Operation – DC Injection – TL Models

All certified models must meet the requirements of related safety standards relative to power quality, which includes **DC current injection**:

- ***IEEE1547 (referenced through UL1741):***  
Transformerless Designs must be qualified by testing to show DC current injection to the grid is limited to no more than 0.5% of full rated AC output current of the inverter

***ABB inverters meet this limit with large margins*** –  
Refer to test procedure from IEEE1547.1, Testing (see appendix)

# Inverter Operation – DC Injection – TL Models

**VDE V 0126-1-1**, is a European standard that addresses DC injection protection and requires the following:

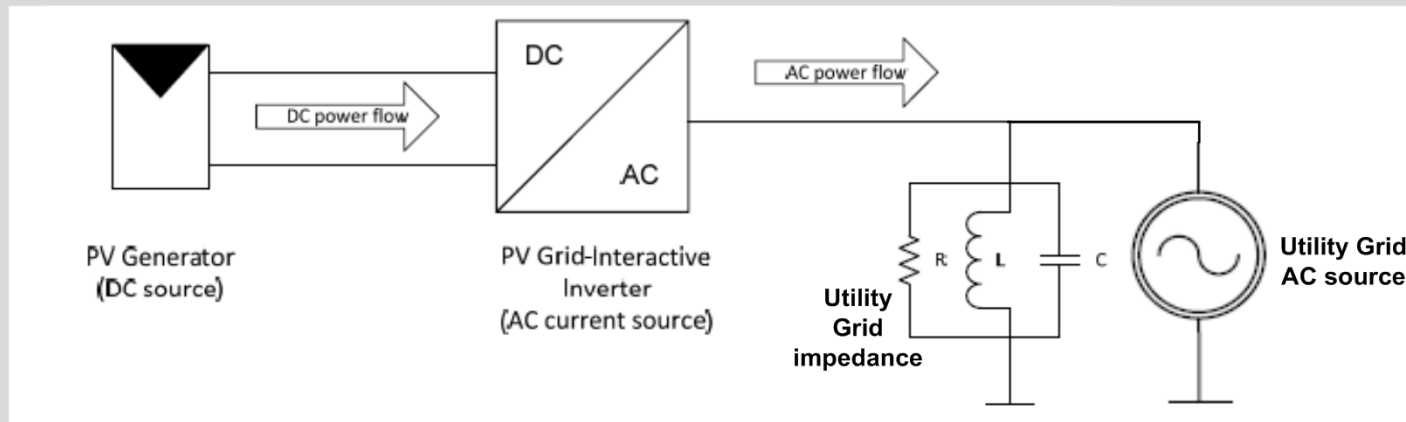
***DC Current Injection levels higher than 1A shall result in disconnection of the inverter from the grid in less than 200ms***

- For all ABB models the current limit is set at 900ma and a grid disconnect time of no greater than 160ms is utilized.
- This measurement is accomplished by use of electronic/ computing circuitry that calculates DC injection current on a cycle-by-cycle basis in real time, and uses the resulting measurement to control the grid interconnection.

# Inverter Operation – Anti-Islanding

## NORMAL OPERATION

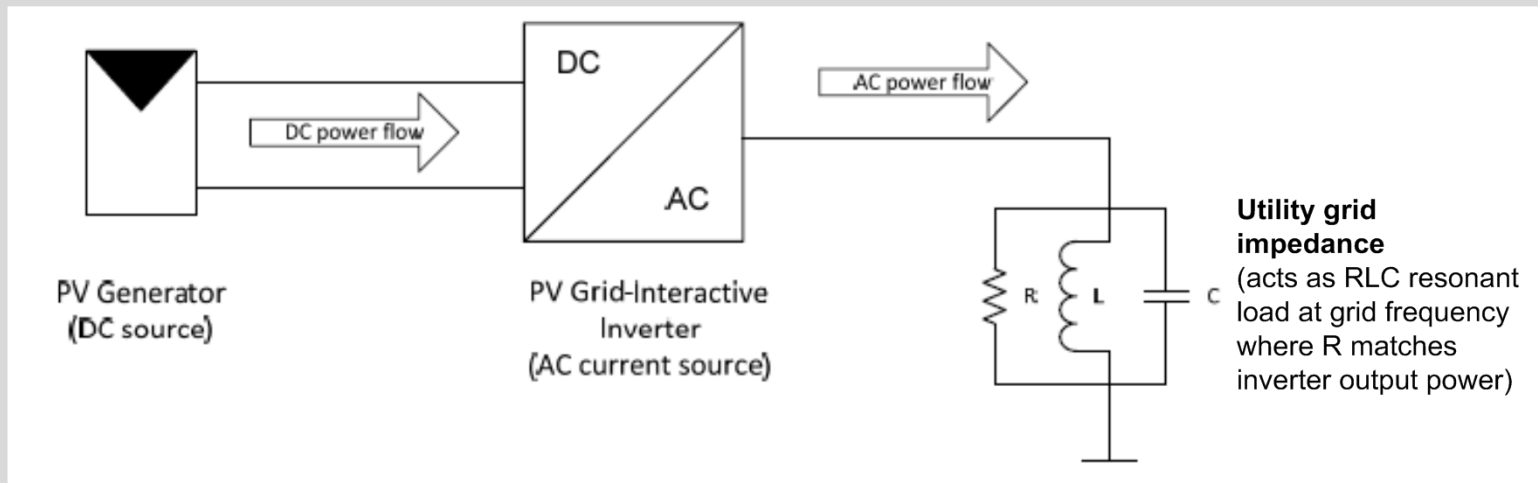
- Inverters utilized for grid-parallel operation (aka, “grid-tied” or grid-interactive inverters) operate as AC current sources that feed power into the utility grid.
- These inverters act as AC current sources, and cannot operate as voltage source, and therefore, this class of inverter is typically unable to supply the utility grid as a stand-alone generator.
- Grid-tied inverters feed power into the grid as AC current at the same frequency as the grid voltage.



**Grid-tied inverter normal operation**

# Inverter Operation – Anti-Islanding

An “island” condition (see figure below) arises when a grid-tied inverter continues to power the connected network even though voltage sources from the electric utility are no longer present



**Figure 2: Representation of an island condition**

# Inverter Operation – Anti-Islanding

An “island” (aka, “islanding”) condition can occur due to a fault condition within the grid or when the grid shows a resonant-load behavior.

In such conditions even if the voltage from the grid network is no longer present, the resonance between the reactive components (L-C) of the grid will maintain the voltage at the inverter’s output terminal. In this scenario a current source inverter cannot detect the absence of grid voltage, and if the resistive load matches the power produced by the inverter, the parallel operation is perpetuated creating an “island condition”

# Inverter Operation – Anti-Islanding

An island condition can be dangerous primarily due to the following reasons:

1. **Safety concerns**: if an island condition is present utility workers working on the grid may be encounter live conductors when expecting no voltage is present on the line.
2. **Equipment damage**: Damage to customer equipment could occur if operating parameters differ greatly from expected nominal values. In this case, the utility is liable for the damage.
3. **Reconnect to Grid**: Reclosing the grid onto an active island may result in problems with the utility's equipment, and/or cause automatic reclosing systems to fail to identify the problem.
4. **Inverter damage**: reclosing onto an active island may cause damage to connected inverters.

# Inverter Operation – Anti-Islanding

Differences in safety standards lead to different requirements for implementation of anti-islanding protection. Parameters shown below are typical of these variations:

- ***Time to detection interval*** (of an island condition) - how quickly does the system identify an island condition on the grid
- ***Time interval from detection to grid disconnection*** - once detected, how quickly must the inverter be disconnected from the grid
- ***Grid parameters such as a variation in the Q-factor*** used in the grid LC resonant load model

For a given inverter design, though a test methodology may be the same, these variations require capability of different settings of the anti-islanding circuit controls.

# Inverter Operation – Anti-Islanding

## ABB CENTRAL INVERTER ANTI-ISLANDING PROTECTION DESCRIPTION

Power-One inverters utilize the same detection mechanism and limits (re: detection time, disconnection time) and *are adjustable via controlled firmware changes* to accommodate all national standards.

The island condition detection is made observing the grid frequency variation respect the time.

- The inverter “induces” a frequency variation by a injecting capacitive reactive power into the grid periodically.
- The time period during which the reactive power is fed into the grid depends on the required detection time (grid standard).
- The amount of injected reactive power is typically 3-5% of the actual active power the inverter is converting.



**Thank You!**

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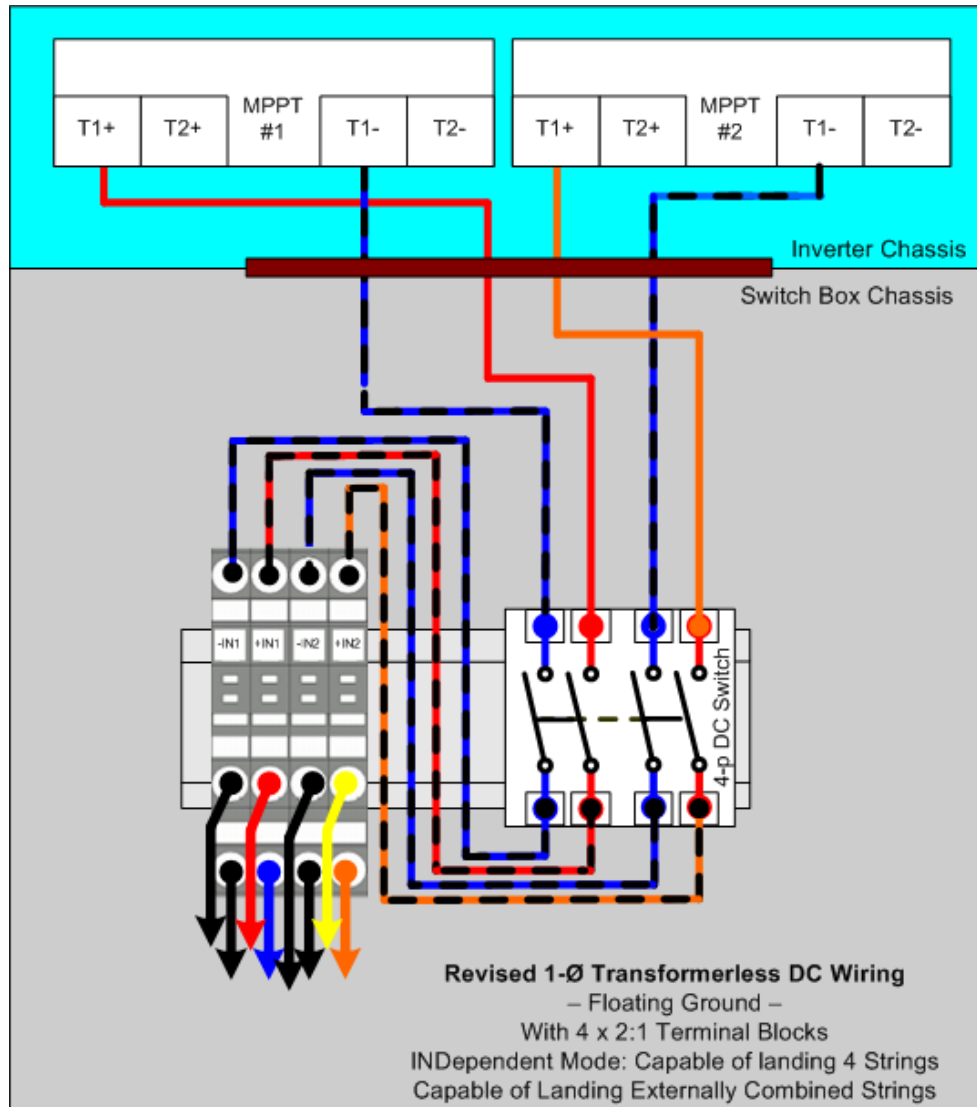
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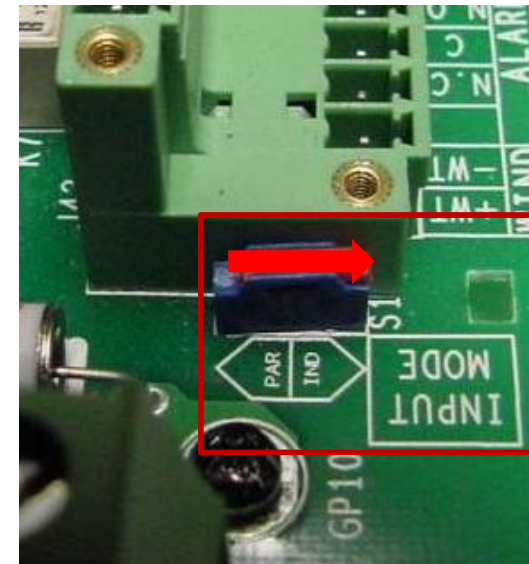
# Appendix

# Aurora PV String Inverters

## Dual MMPT DC Wiring Method – *IND*ependent Mode

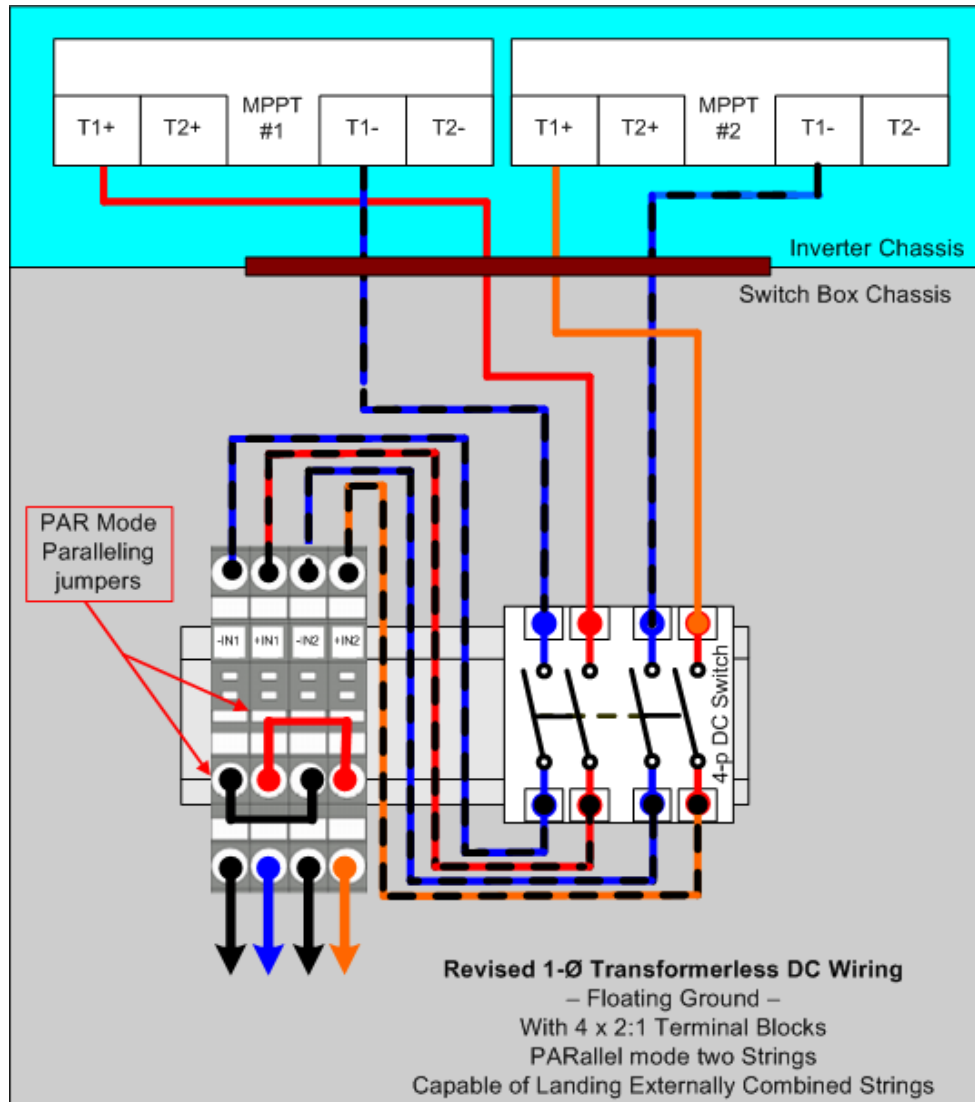


- **Connect DC Cables for up to four strings (two per input channel) at bottom clamps of input terminal block as shown**
- **Place switch S1 to *IND* selection**

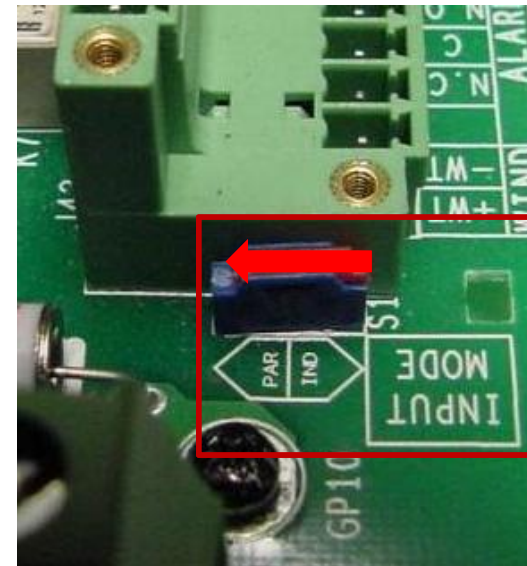


# Aurora PV String Inverters

## Single MMPT DC Wiring Method – *PAR*allel Mode



- Connect DC Cables for two strings at bottom clamps of input terminal block
- Connect two #10AWG wire jumpers as shown to parallel inputs
- Place switch S1 to *PAR* selection



# Inverter Operation – DC Injection – TL Models

## IEEE1547.1

### 5.6 Limitation of dc injection for inverters without interconnection transformers

#### 5.6.1 Purpose

The purpose of this test is to verify that an inverter that connects to the EPS complies with the dc injection limit specified in IEEE Std 1547, which ***states a [transformerless] inverter must not be capable of supplying DC current to a value exceeding 0.5% of its AC rating***

This test is conducted on inverters that connect to the EPS without the use of dc-isolation output transformers.

# Inverter Operation – DC Injection – TL Models

## 5.6.2 Procedure and data analysis

Operating power levels in this procedure have a tolerance of  $\pm 5\%$ .

- a) Connect the EUT according to the instructions and specifications provided by the manufacturer.
- b) Set all source parameters to the nominal operating conditions for the EUT.
- c) Set (or verify) all EUT parameters to the nominal operating settings.
- d) Record applicable settings.
- e) Operate the EUT at 33% of its continuous rated output current and at rated p.f. Allow the EUT to operate for at least 5 min prior to taking any test measurements (or until the EUT temperature stabilizes).

The EUT shall operate at the specified current and p.f. for the duration of the test.

# Inverter Operation –DC Injection – TL Models

## **5.6.2 Procedure and data analysis - continued**

f) At the EUT output, measure the rms voltage, rms current, and dc component (frequency less than 1 Hz) of current on all phases. The averaging window for all measurements shall be not less than one cycle and not more than 60 cycles.

g) Record all measurements at a sampling rate of not less than the reciprocal of the selected averaging window for a period of 5 min.

h) Repeat steps e) through g) with the DR operating at 66% and at a level as close to 100% of its rated output current as practical.

***For all output current levels tested, the following data analysis is required:***

a) Calculate average values of rms current and voltage on each phase. For each measurement, the average shall include every sample point recorded during the 5 min test period.

# Inverter Operation – DC Injection – TL Models

## ***5.6.2 Procedure and data analysis - continued***

- b) Verify that the average rms current on each phase is within 5% of the intended test point (33%, 66%, and 100%).
- c) Verify that the average rms voltage on each phase is within 5% of the nominal voltage.
- d) Calculate average values for the magnitude of the dc component of current on each phase. The average shall be taken of the absolute (unsigned) value of every sample point recorded during the 5 min test period.
- e) For each phase, divide the average dc component magnitude value by the rated output current of the EUT and multiply the result by 100. Record the final calculated values as the percent dc injection current for each phase.

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