Technical Overview:
Module Safety Disconnect

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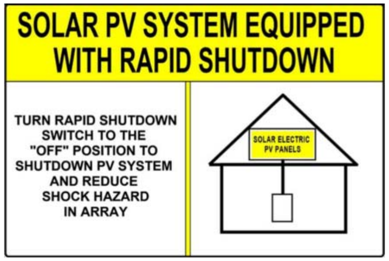
Issue and Opportunity



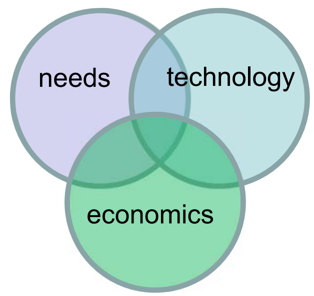
- Issue: PV strings must become safer for rescue personnel and installers
- NEC 2014 provided a set of rules (690.12, 690.56) to enforce "rapid shutdown" and control DC conductors beyond the array (10 seconds < 30V)
- NEC 2017 more narrowly defines the array zone as 12 inches from module, less than 80V within array, 30V outside array, 30 seconds
- Opportunity: a PV module with built in module-level power electronics (MLPE) rapid shutdown; lower system cost, easier to install than all other solutions, also make AFCI systems more potent

Images:NFPA Fire Fighter Safety and Emergency Response for Solar Power Systems, Bill Brooks

General Approach

Bring the modules down to a safe voltage: <u>break up the string</u>

<u>Basic technology:</u> add a *Distributed Module Disconnect* to each module, one that senses when it is safe for operation, when modules are off and exposed to light - short out the module leads (0V output)



A winning solution must be a <u>balance</u> between *needs*, *technology*, and *economics*

<u>Two primary objectives guiding this particular solution</u>:

1) simplicity (optimal MLPE reliability & cost)
2) minimal change to current PV industry (training & adoption)

Needs of the PV Industry

Module is safe (off) by default, allowing rapid shutdown in the safest way possible; provide maximum level of protection by shutting down at the module-level (NEC 2017)

Widespread industry adoption: The safety solution must be easy to standardize, solution must rapidly pass UL testing, simple to grasp by installers, able to withstand wiring errors, easy to install, simple to integrate with existing PV system elements, and low cost -> very little change, yet able to comply with NEC 2017 onward

Use only basic and easy to source building elements: transistors, optical isolators, transformer, low voltage signal wires -> simple, standard, reliable components that can be sourced from many vendors over long periods of time to keep costs low and reliability high

Ease of use: No need for computers, networking hardware and software, and complex instructions and training, and endless tech. support …

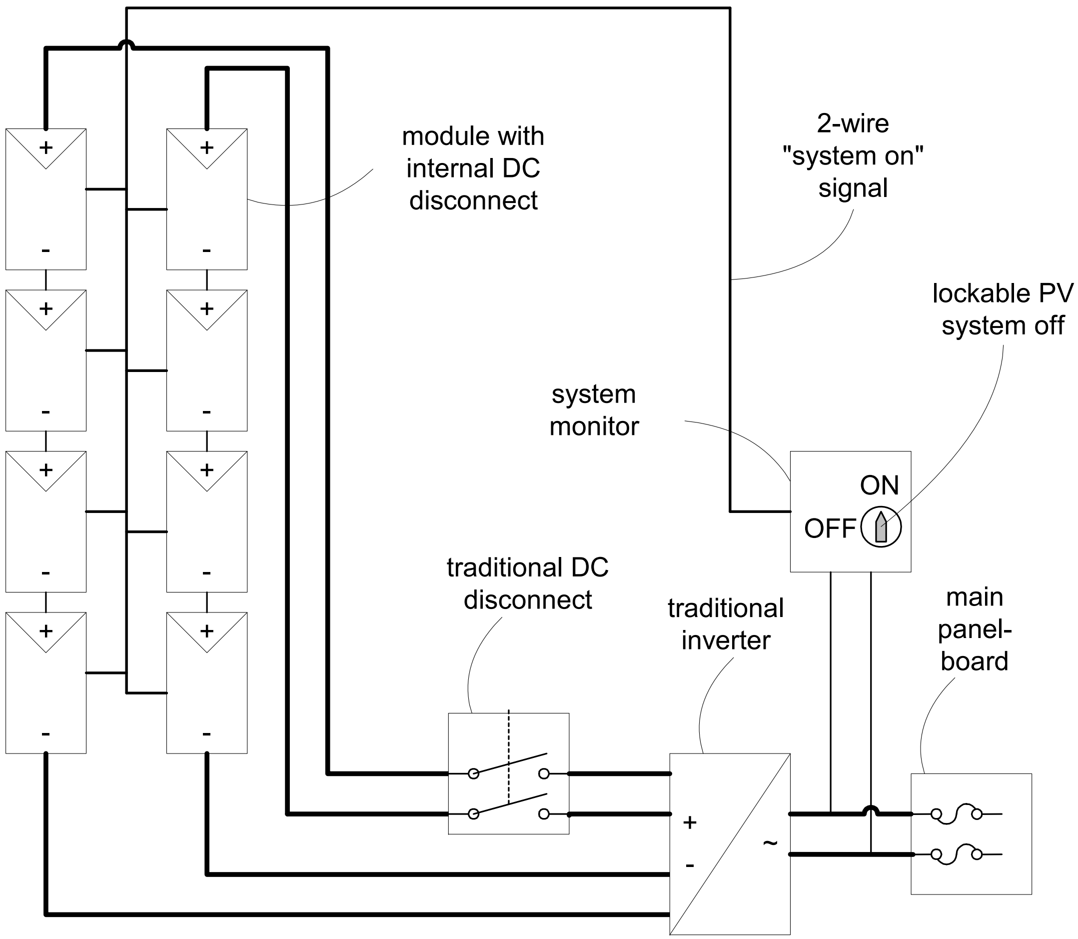
Scalable: No need to have multiple inventories of modules, e.g. residential commercial, and utility

Compatible: with today's existing system building blocks (inverters, DC combiners)

Minimal power to run safety system (a few mA per PV array)

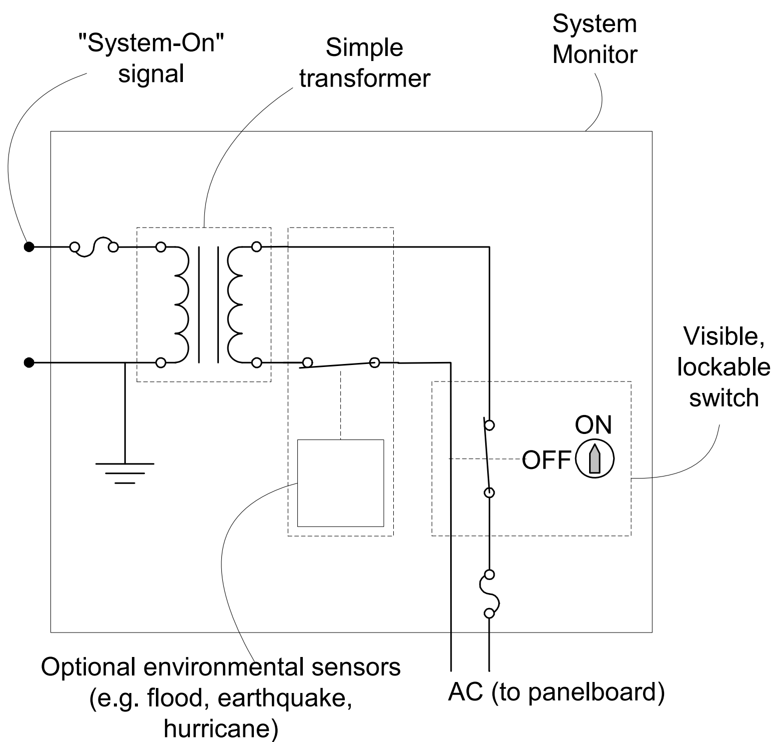
Offer additional value: allow all types of arc faults (series and parallel) to be extinguished by inverter ACFI. Much safer to install.

Approach Details 1)



- A *System Monitor* device provides an explicit signal to each module
- Each module is "off" by default and requires a "*System-On*" signal to operate
- System-On is generated only when it is safe to operate
  - *Home is powered (AC mains are on)*
  - *Lockable switch on (LOTO)*
  - *Can provide additional arc fault protection if inverter provides "system on" signal*

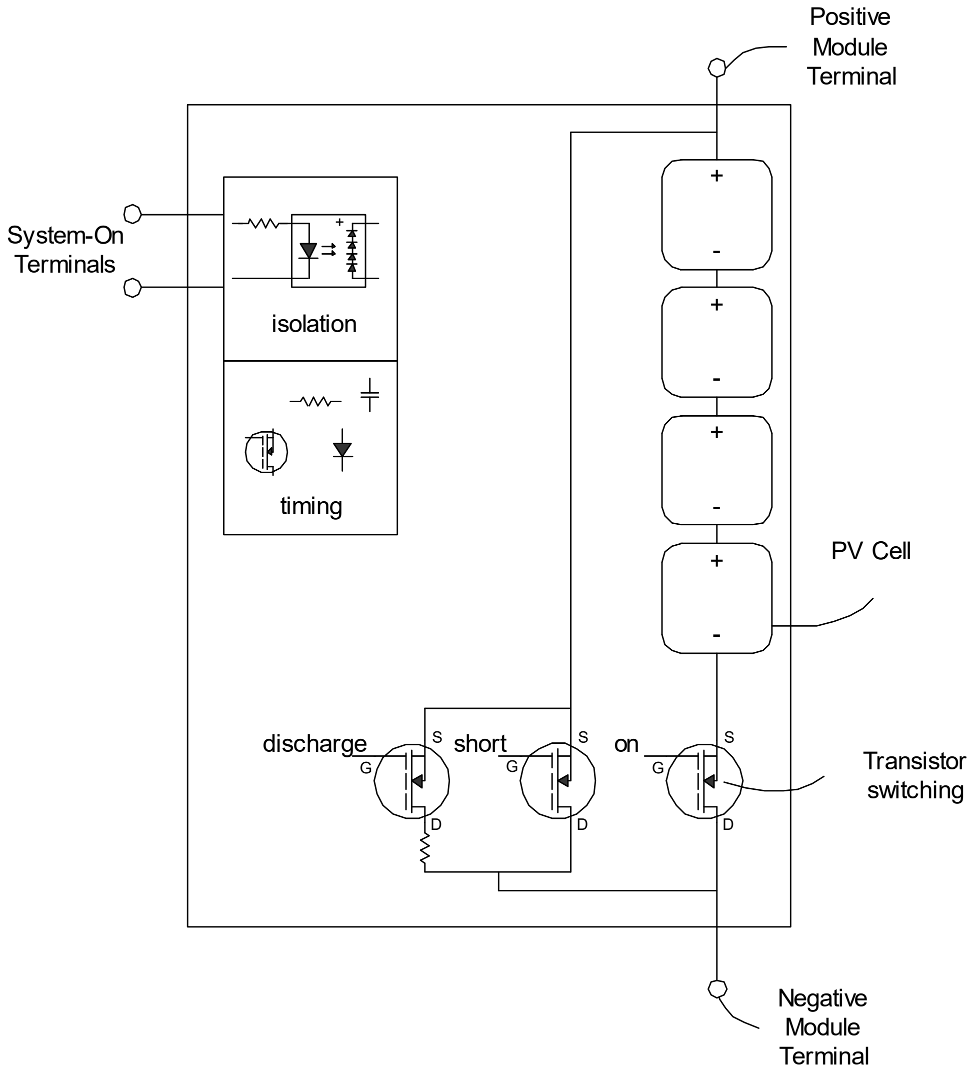
Approach Details 2)



- *Basic System Monitor* device is made from simple & reliable components
- Optional environmental sensors can add additional automatic safety (flood, hurricane, earthquake)
- Lockable visible switch to be used for technicians and rescue personnel
- Low voltage System-On signal can be either AC or DC (e.g. 12-24V)

Images: Hurricane Harvey Huston & Irma USVI 2017

Approach Details 3)



- Each PV Module has an individual DC-Disconnect implemented as a transistor switch
- As the module is turned off it opens up the module circuit
- Next it discharges the array and inverter (module-level piece-wise)
- When fully “off” the module is in a low impedance state (shorted)
- System-On signal is electrically isolated from module DC-circuits
- Timing and control is based on simple RTL logic

Approach Details 4)

simple low cost components:

- All components are very common, well characterized, and available from multiple sources

- Cost breakdown Module assembly with off the shelf parts, not optimized (~10K qty.)
  - (3) MOSFET Transistor $2.5 (total) [1)]
  - (2) FET Driver $1.8 (total) [2)]
  - (1) Two-layer PCB/FPC $0.1 (1.5 in^2) [3)]
  - Resistors, diode, capacitor $0.03 (total)
  - Optoisolator $0.2
  - Signal transistor $0.01
  - Wires and connectors (TBD, est.at ~$2)
  - Total cost ~$6 or ~2 cents/W (300W module)

- Cost breakdown System Monitor (integrated in inverter)
  - Basic transformer (12V, 0.5A, 6W) $4.7 (1K qty.)
  - Lockable Switch (part of DC disconnect)
  - System monitor is also controlled by inverter AFCI circuit

Notes:
1) SUD50N06
2) Toshiba TLP190B
3) http://e-teknet.com/PCB%20Promotion.htm

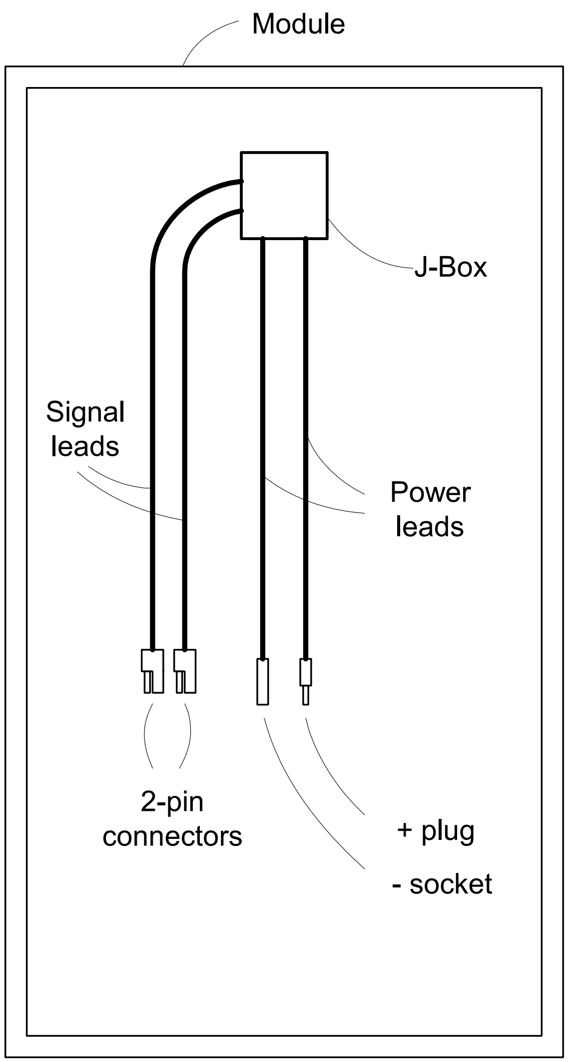
Approach Details 5)

simple reliable components that can outlast the module:

- MOSFET Transistors of this type are rated for junction temperatures between –55C to 175C [1)]
- PVI circuits operate from –40C to 85C [2)]
  - UL recognized (UL1577)
- Reliability:
  - PV system goal: 30 years continuous = ~270'000 hours
  - FET Transistor
    - Life expectancy (FIT) 55C [3)] : 1'422 or ~700'000h
  - PVI FET Driver: in production since 1972 [4)]
    - Life expectancy 75C [5)] : ~ 800'000h

1) STB140NF55
2) Toshiba TLP190B
3) SUM75N06-09L http://www.vishay.com/docs/72537/72537.pdf
4) Dionics Inc.
5) TLP190B at 10mA, 75C, AC dual PVI circuit used ½ the time, see backup

Approach Details 6)

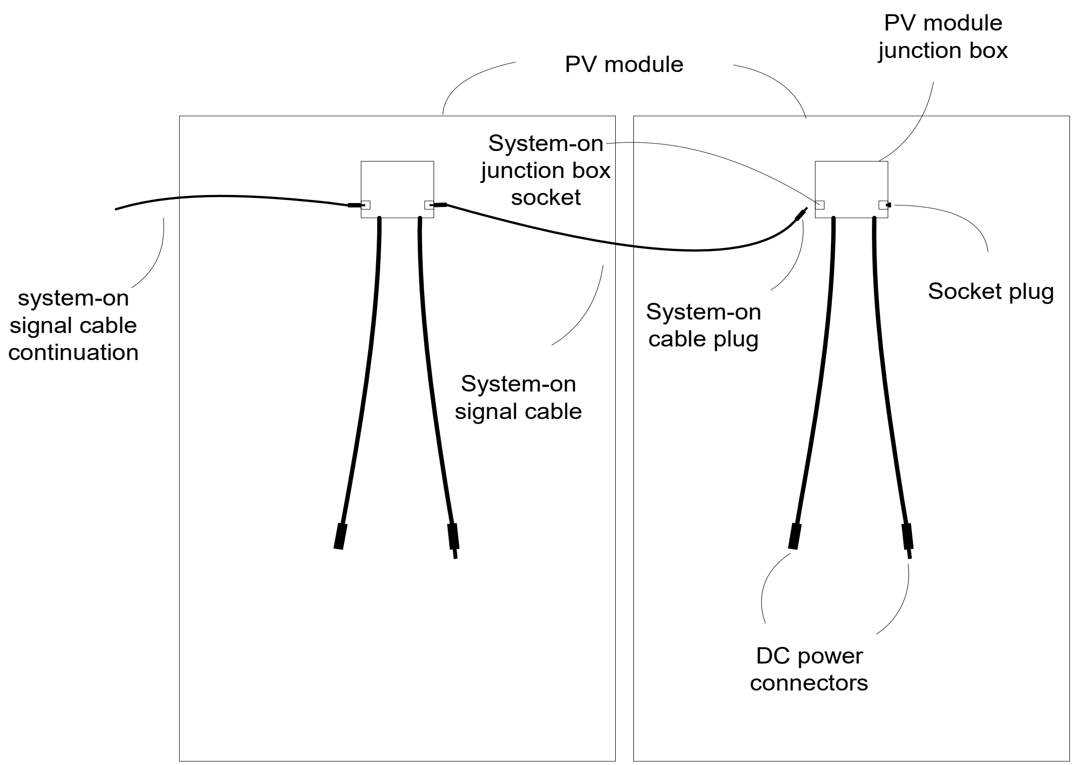


Two ways to wire up system:

Option A

- In addition to the traditional J-box and power leads, an additional pair of signal lead cables are fed from the J-box for the System-On signal
- Two signal lead cables are provided to connect to the neighboring modules
- Polarity is not important for the System-On signal, it can be DC or AC
- Simple to field install; the home run wiring for the signal needs to be field installed, just like the power leads
- Easy to field test a module: use 9V battery based supply to act as "system on" signal

Approach Details 7)

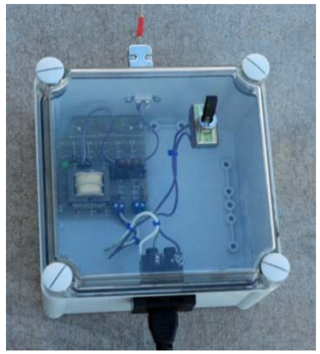
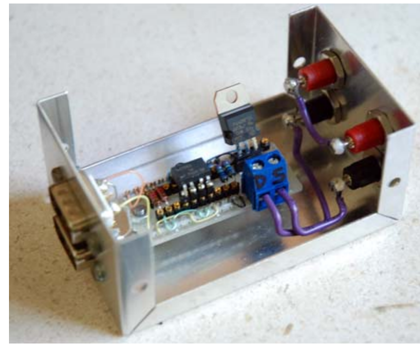


Two ways to wire up system:

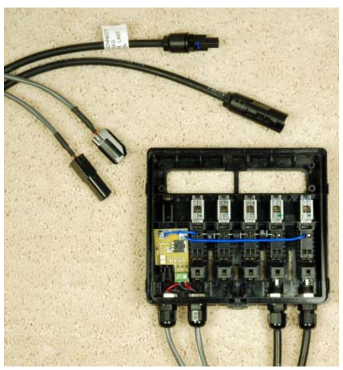
Option B

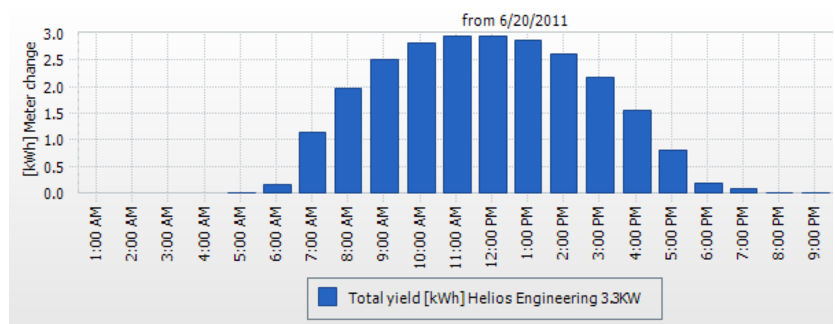
- In addition to the traditional J-box and power leads, an additional pair (signal) plugs are provided on the J-box
- One cable is provided with each module to connect to the neighboring module

Approach Details 7)

- 1st generation prototype operating in AZ in 2009



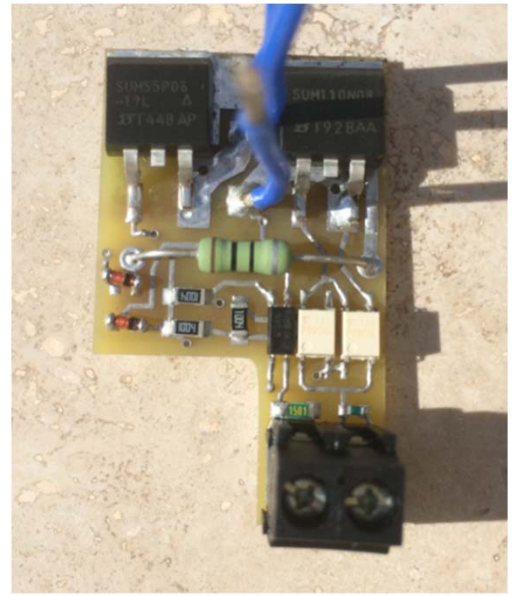


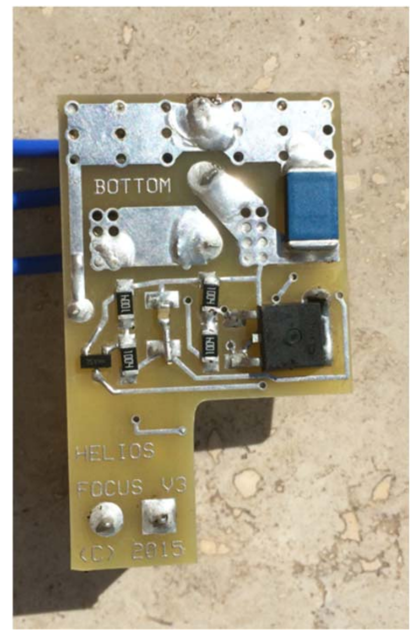
- 2nd generation prototype (w. system off switch) testing began in summer of 2010
- 2nd generation prototype installed on Arizona residence early 2011 (18 modules)
- 3rd generation prototype installed in 2015 (improved high capacity discharge circuit)

Approach Details 8)

3rd generation prototype (current) operating in summer of 2015

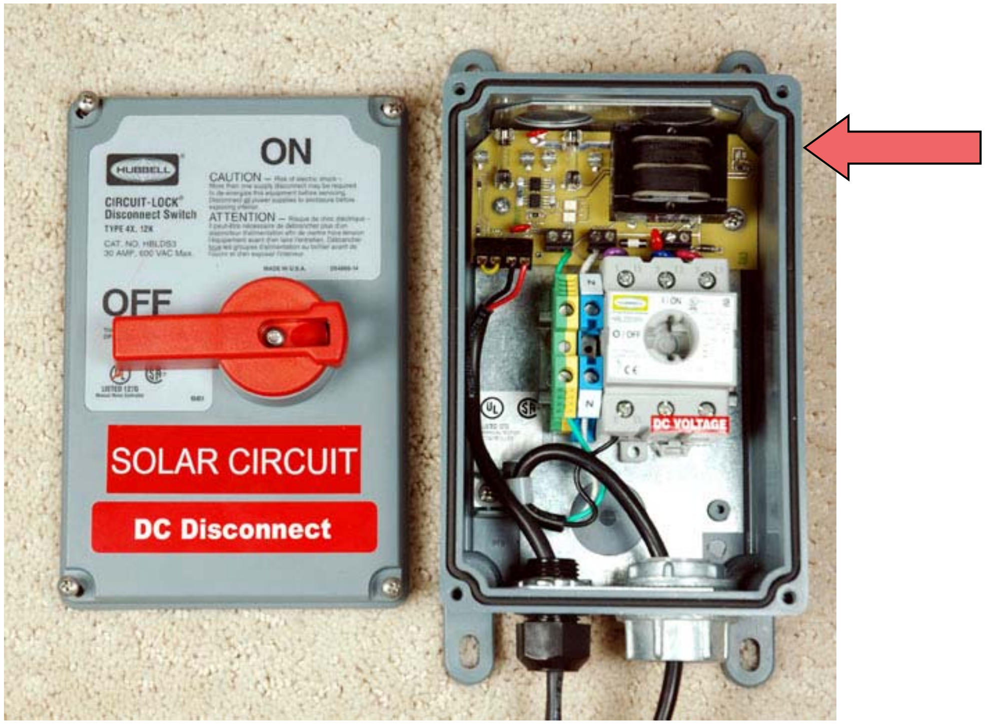
- Module disconnect can easily fit inside most existing module junction boxes
- Prototype utilized an existing J-box from TE connectivity (Tyco)
- 3rd generation complied with NEC 2014, requiring the inverter to be discharged in 10 seconds





Approach Details 9)

- “system on” signal is best performed by PV inverter of PV battery charge controller
- External (optional) switch is very simple to manufacture:
  - Prototype easily fit inside existing AC disconnect box (Hubbell HBLDS3)



Benefits and Costs

- Benefits of solution:
  - Simple solution, with low costs and short development effort
  - Field Tested in Arizona heat for over 6 years
  - Licensable patented technology, further patents pending
  - Reliable by design: low risks
  - Works at 1500V DC (current opto-isolators limited to ~2000V)
  - Minimal number of barriers to overcome due to architecture
    - minimal change to: system, installer's know-how or skills, module J-box and other BOS equipment
  - Low technical and investment risk due to simplicity, ease of integration, ease of training for installers
  - Independent system; does not in any way depend on BOS, inverter, scalable to all sizes
  - Future proof and compatible: current and past modules can coexist with Helios Focus based system
  - Further cost reduction possible: more tailored parts, integration with inverter (signal)
  - Enables series and *parallel* arc fault shut down (inverter generated signal)
  - Discharges inverters without any changes required to inverters; discharge at safe levels

- Cost of solution:
  - New standard required for reliable signal connections (2-pin connector)
  - Product development
  - Product testing & certification
  - New product marketing & adoption
  - ~2 cents per watt parts-cost adder to module to start (further cost reductions possible)

<u>Competition & Alternatives</u>

- <u>Comparable alternative</u> solutions for module shutdown are considerably more complex and cost considerably more - less reliable, shorter MTBF
- These solutions require an entire change in the PV systems architecture, components playing a major role are fundamentally altered, and they introduce software and network technology
- PV integrators and installers do not want complexity
  - A failed single unit must be replaced with the same solution (otherwise incompatible)
  - Networking and PC skills not common among PV installers, minimize training
  - Networking components not as reliable, and hard to debug
  - Fragile tools (laptop, network diagnostics, etc.)

- Lack of generally available training for new and complex systems poses a barrier for these solutions to become accepted
  - 28 page manual for micro inverter, 28 page manual for network elements
  - ~2.5 year average turnover for solar installers -> constant training -> complexity is not good

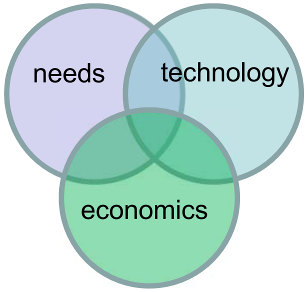
- <u>Alternative: Do nothing is not an option</u>

Left: Tigo Energy Maximizer integrated junction box; Right: modular DC buck-boost box from SolarEdge. The circuit boards are meant to give readers a chance to compare electronic component count of a Tigo Energy Junction Box and a SolarEdge PowerBox

Summary

- The Helios Focus *Module Disconnect* provides a straightforward, compatible, and lowest cost solution to reduce the hazards of PV electrocution and comply with NEC 2017
- Basic Module Disconnect is the quickest path to a *pragmatic* product that can be adopted quickly by the whole solar industry (for any scale power plant)
- additional arc fault protection possible
- Relatively low risk and high gain strategy

- A balanced approach between: needs, technology, and economics



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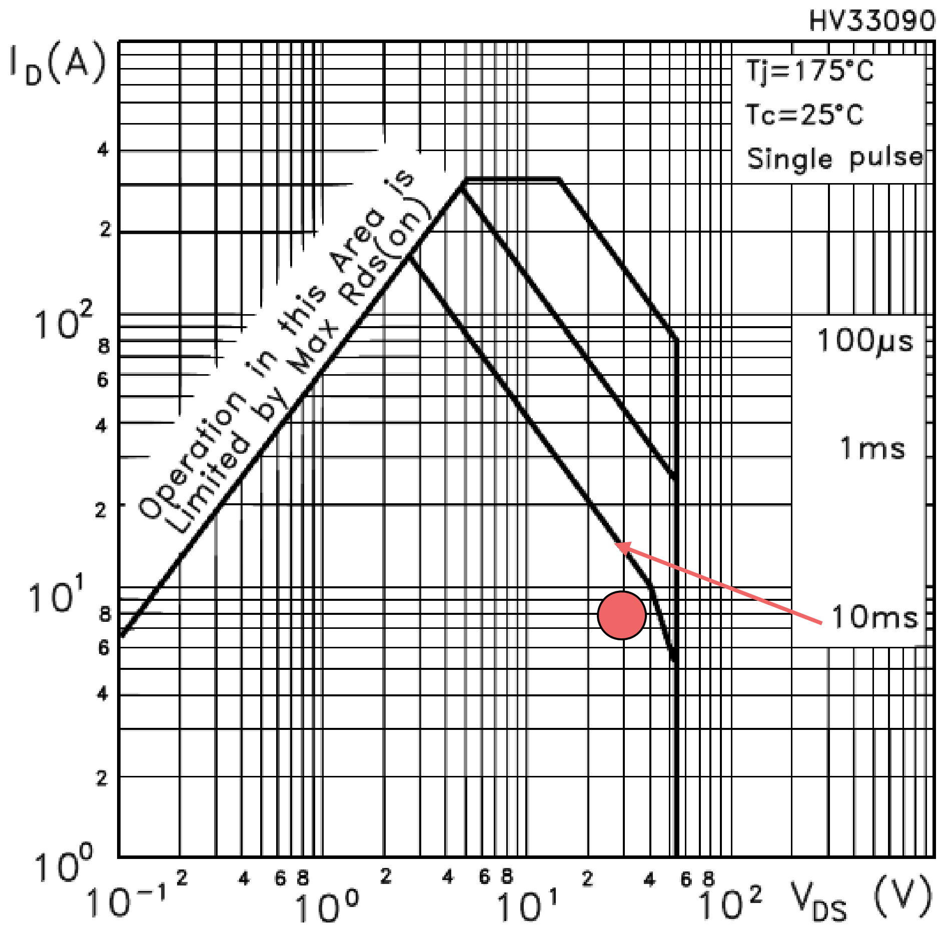
Backup

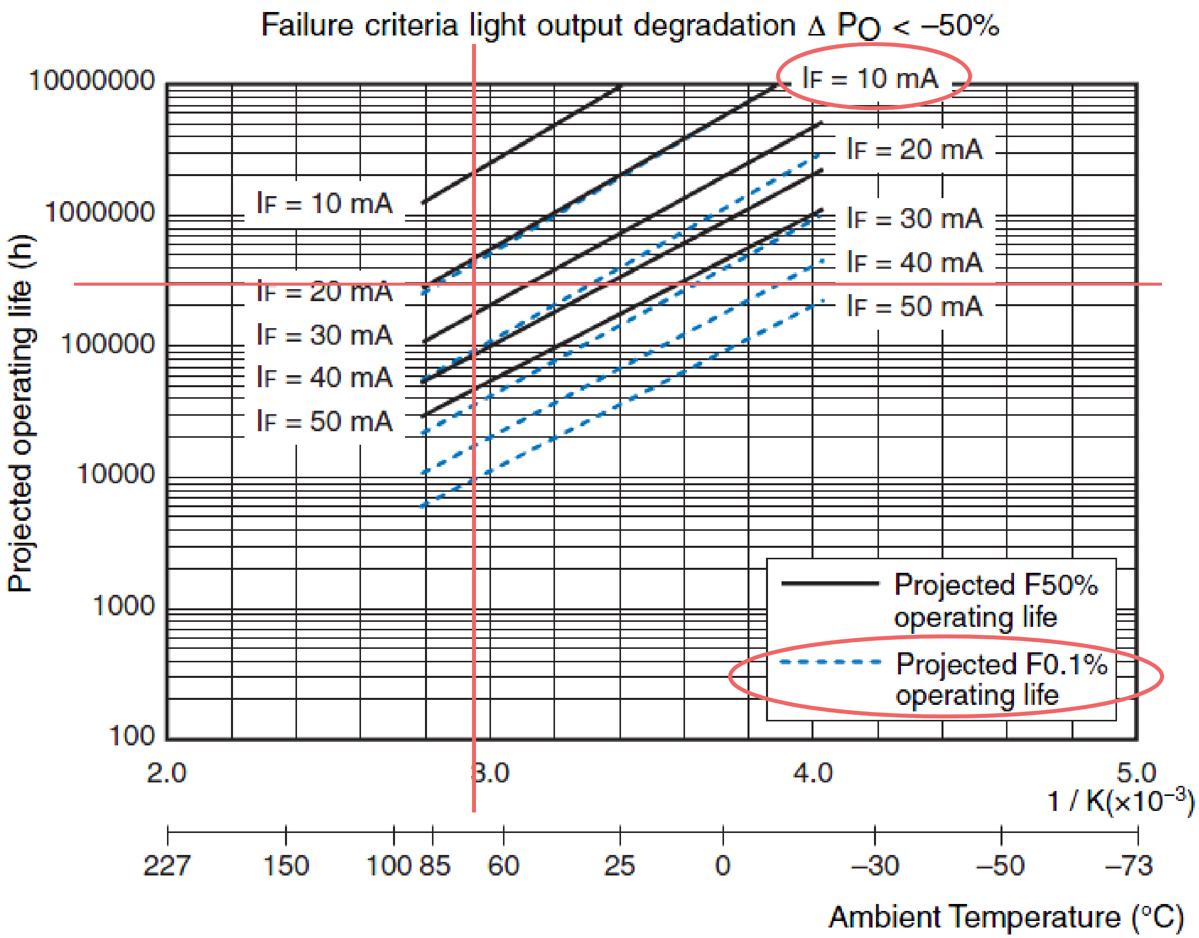
Safe operating range



- The safe operating range for the FET (single pulse) is a function of the current and voltage and switching times
- E.g. 240W module at 30V 8A, and a switching time of ~10mS

1) STB140NF55

Life expectancy of TL190 photo-coupler

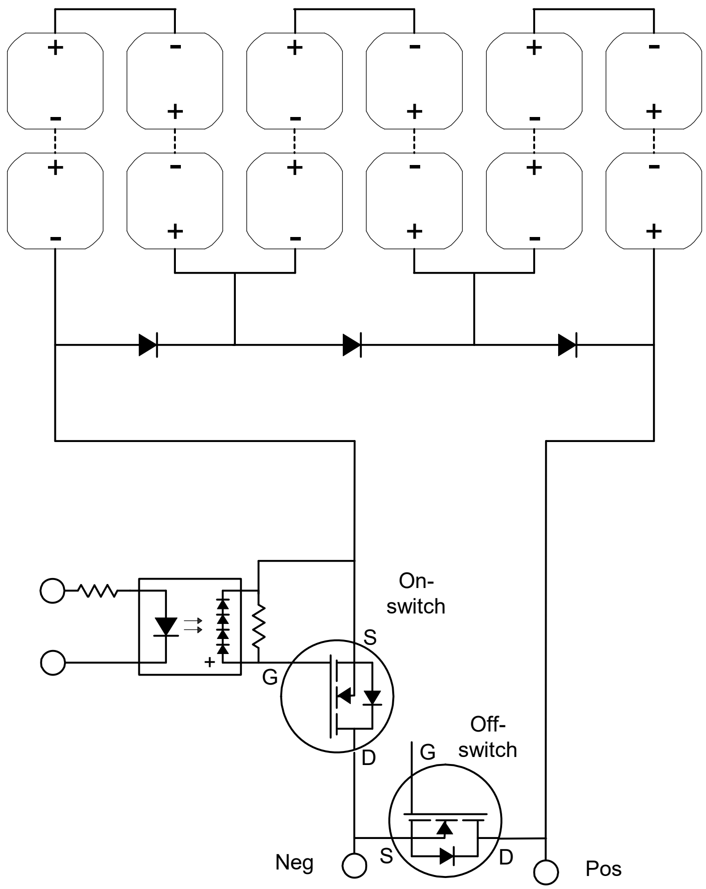


1) Toshiba Product Guide Photocouplers and Photorelays

- Projected operating life (Toshiba) [1)]
- Forward current (I_F) will be at 10mA
- Worst case ambient ~75C (not average)
- Goal is around 300’000h (30+ years)
- 0.1% cumulative failure rate (F0.1%) at ~450’000+h

- Conclusion: if the circuit were to be at a maximum temperature it’s entire life, be supplied by a DC circuit (only one LED on), the life expectancy should exceed 30 years, or 0.1% of the units will fail
- Recommendation: Using dual PVI and accounting for lower average temperatures will provide design margin

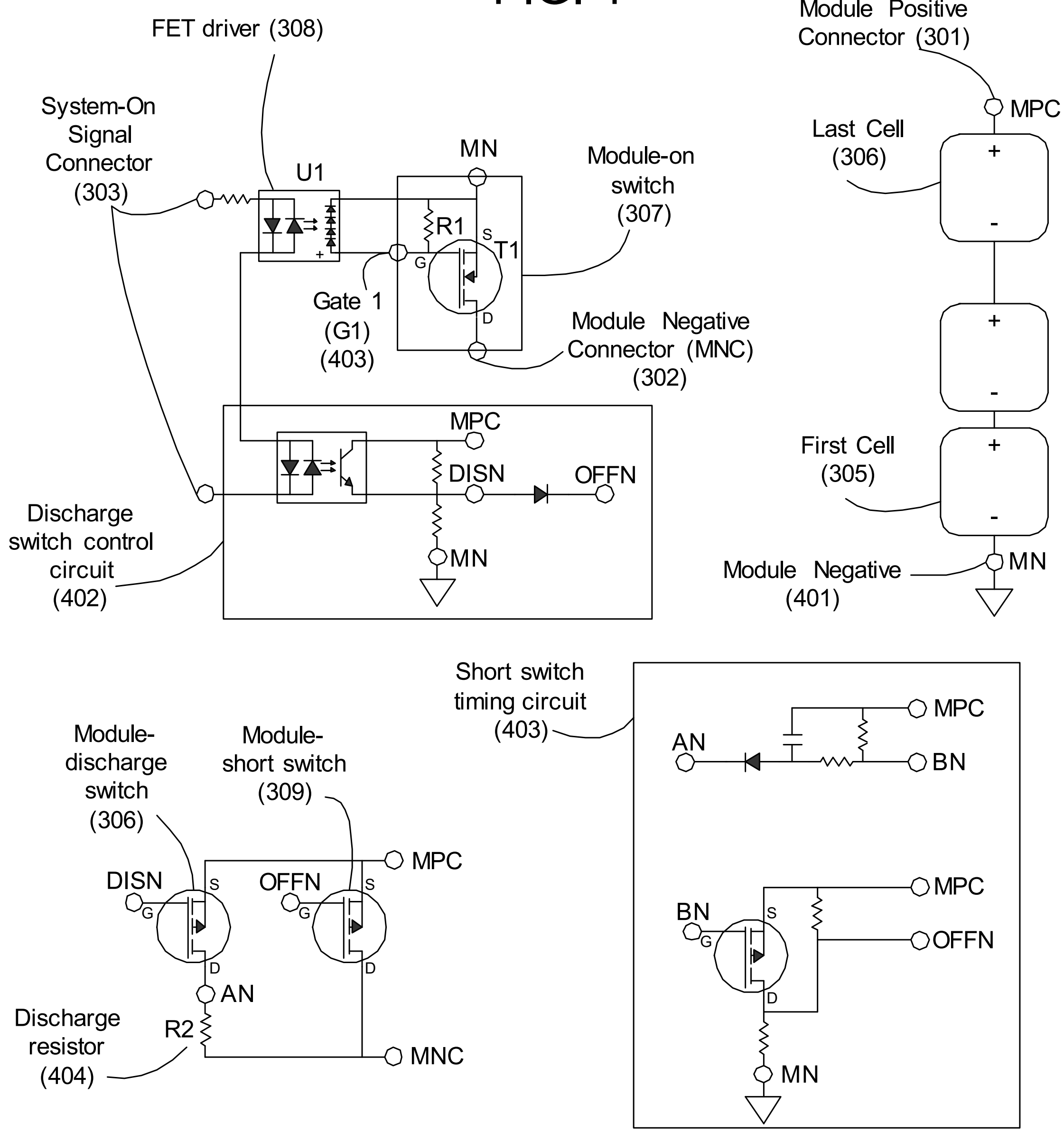
Module wiring diagram (detailed)



- Bypass diodes remain as is
- One terminal is interrupted with “On switch” -> low impedance when on
- “Off switch” provides low impedance path when module is off

Module circuit diagram (detailed)

FIG. 4



- T1 is the “on” switch connecting the module negative to the connector lead
- “discharge switch” dissipates charge of array in R2
- “short switch” shortly after will completely short out the leads to the module
- Timing circuit is a basic RC circuit with a single transistor amplifier
- At any time when the “system on” signal is present the module immediately turns on

Patent information

Solar Photovoltaic Module Safety Shutdown System

patents

8,859,884	issued 10-14-2014
9,369,126	issued 06-14-2016

Solar Photovoltaic Module Safety Shutdown System

Applications

US14532883

US14922123