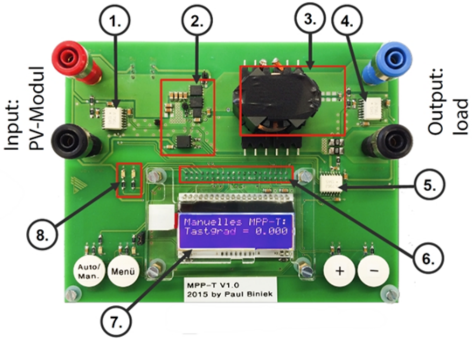
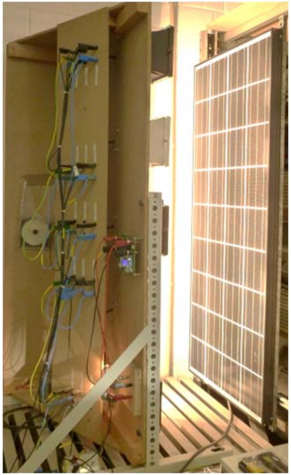


PV- MPP Tracking



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Übersicht

- MPP-Tracking – Overview
- MPP-Tracking Software
- MPP Tracking Showcase
- Expected Behavior with Buck Converter and Resistance
- Boost Converter feeding into a stiff DC-Link for feeding into the grid mains

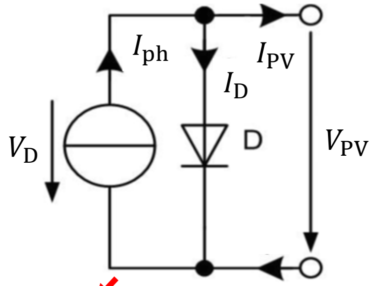
MPP-Tracking - Overview

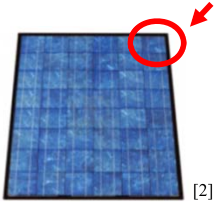
- Basic principles of the PV generator
  - Diode characteristic
  - MPP (cell coltage, current)
  - PV load impedance
  - Temperature
  - Efficiency
- Mains electrical specifications
  - EMI
  - Standards

Outline

- Converter: MPP tracker in the system
  - Impedance conversion
  - Buck or boost depending on voltage level
  - PV system concepts
- Special implications for DC mains

- First assumption: PV cell as diode equivalent circuit
- Current source: Photo current I_{ph} (short circuit current depending on irradiance α)
- Diode current I_{D}: Shockley model
  - $I_{\mathrm{D}} = I_{\mathrm{S}} \cdot (e^{\frac{V_{\mathrm{D}}}{n \cdot V_{\mathrm{T}}}} - 1)$
- Output current:
  - $I = I_{\mathrm{ph}} - I_{\mathrm{D}}$
- For a more accurate cell model see for example [1]





[2]

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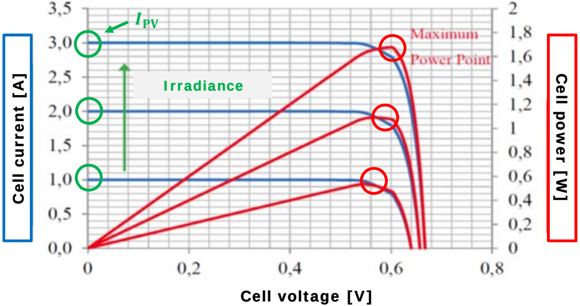
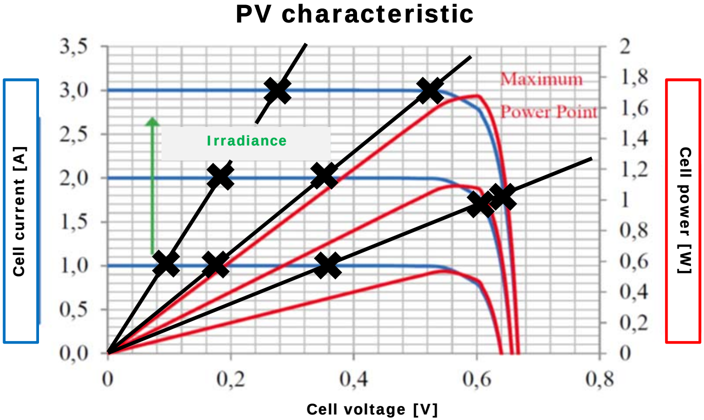
- Depending on solar irradiance α current I_{PV} in- or decreases
- Plotted over V_{PV} the current remains nearly constant
- Current drops to zero in the area of open circuit voltage $V_{\mathrm{PV_{OC}}}$
- Cell power has a maximum in the area of the current drop
- This point is called the maximum power point (MPP)
- MPP strongly depends on the irradiance α

PV characteristic

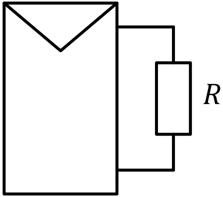


PV load impedance

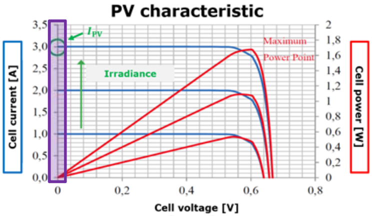
- The connected load impedance *R* determines the operating point

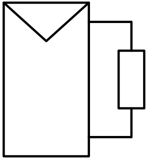


$$R = \frac{V}{I}$$

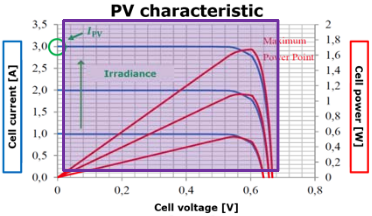


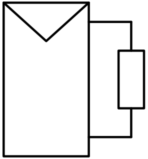
PV load impedance



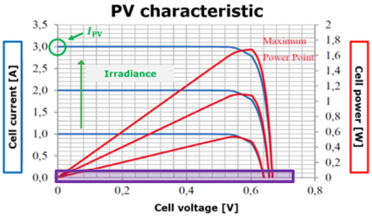


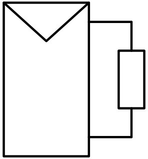
$R \to 0$





$0 < R < \infty$





$R \to \infty$

$$R = \frac{V}{I}$$

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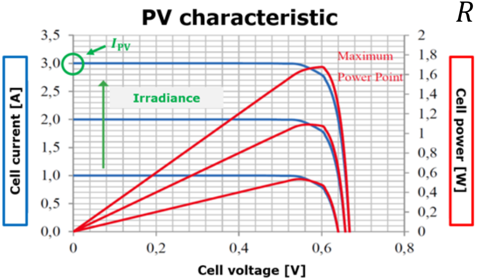
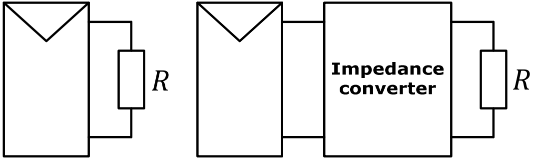
PV load impedance

- The connected load dependence determines the operating point
- To get maximum power of the PV source, the load impedance has to be adjusted
- This can be done by current or voltage conversion
- Power electronics are a common way for impedance conversion

$$R = \frac{V}{I}$$





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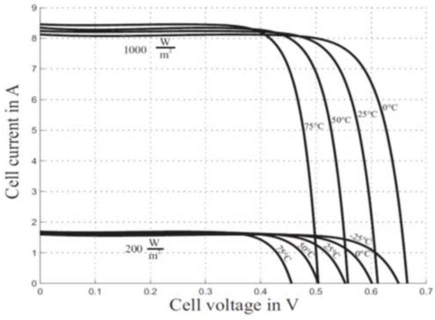
Temperature dependence

- Another important parameter is the temperature dependence of PV cells
- With increasing temperature, open circuit voltage V_{OC} drops
- Therefore PV power (MPP) decreases too
- So there is the need to track the MPP also at various temperatures



(a) $V-I$ characteristics [3]

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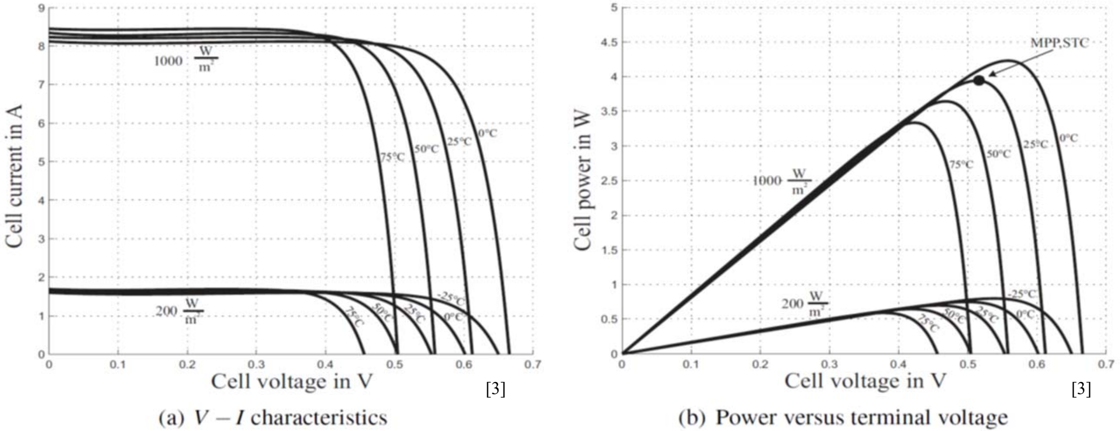
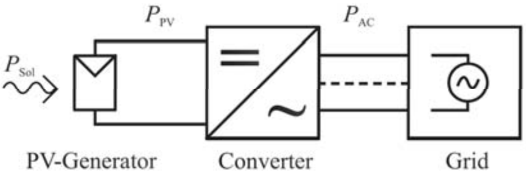
Temperature dependence



- Common PV efficiencies are calculated as follows:
  - $\eta_{PV_{Gen}} = \frac{P_{PV}}{P_{sol}}$
  - $\eta_{Conv} = \frac{P_{AC}}{P_{PV}}$
  - $\eta_{Sys} = \eta_{PV_{Gen}} \cdot \eta_{Conv}$
- As $\eta_{PV_{Gen}}$ is usually low and η_{Conv} very high, η_{Sys} will be slightly lower than $\eta_{PV_{Gen}}$



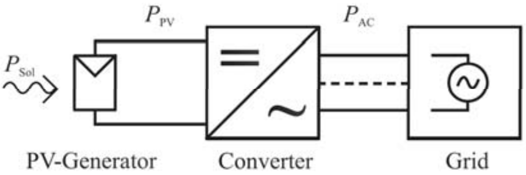
[3]

- For central Europe climate, the weighted euro efficiency η_{Euro} can be calculated: $\eta_{Euro} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%}$

($\eta_{x\%}$: Efficiency operating at x% of nominal load)

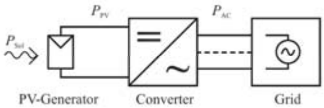
Mains EMI

- Electromagnetic interference (EMI) is a severe problem when connecting PV to the grid
- AC current has to be sinusoidal and AC voltage has to be stable without flicker etc.
- IEC 61000 deals with basic concepts, emission limits, measurement etc. @mains frequency
- It can be considered as the basic standard for AC mains EMI



[3]

- IEC 61000 deals with limits for frequencies between 0 and 2kHz and between 150kHz and 30MHz
- Todays power electronics (AC-DC converters) can easily provide sinusoidal waveforms @ mains frequency
- So they meet all the requirements of IEC 61000
- But: With switching frequencies between 2kHz and 150kHz IEC 61000 can't be considered anymore.



[3]

IEC 61000 [4]

Part 1: General
- Basic concepts (fundamental principles, definitions, terminology) - interference model
- Functional Safety (what a safety function does and approaches of its being performed satisfactorily)
- Measurement uncertainty

Part 2: Environment
- Description of the environment
- Classification of the environment
- Compatibility levels

Part 3: Limits
- Emission limits
- Immunity limits (insofar as they do not fall under the responsibility of product committees)

Part 4: Testing and measurement techniques
- Measurement techniques
- Testing techniques

Part 5: Installation and mitigation guidelines
- Installation guidelines
- Mitigation methods and devices

Part 6: Generic Standards
- Generic emission and immunity requirements in various environments

Part 9: Miscellaneous

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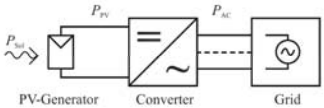
- Guidelines for these frequencies can be found in IEC 62578
- This standard is especially for so called "active-infeed-converters" (AIFs)
- It features design considerations for filters etc. with respect to newer studies about for example load impedance in European grid.
- DC-AC converters and their filter elements should be designed following the guidelines in IEC 62579



[3]

IEC 61000 [4]

Part 1: General
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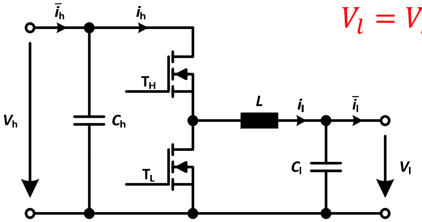
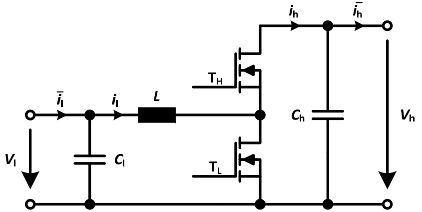
Impedance conversion

- The easiest way to realize the impedance conversion is using a buck or boost converter depending on the PV array voltage
- By changing the duty cycle, the input impedance of the converter changes while keeping a fixed output voltage
- In this case DC/AC conversion is not included
- Other converter topologies are also possible

$$V_l = V_h \cdot a_h$$





$$V_l = V_h \cdot a_h$$

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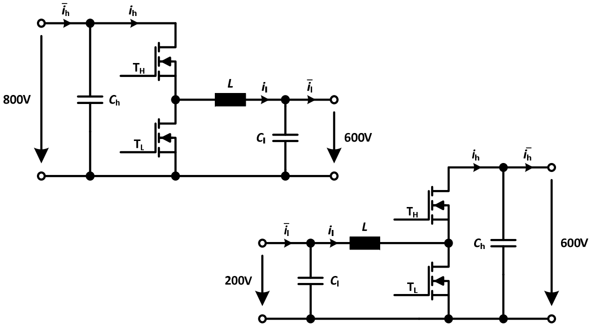
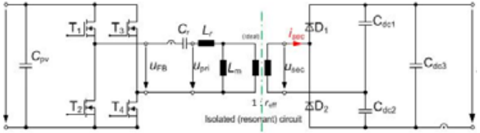
Buck or boost converter?

- Input voltage of the DC/AC converter has to be $> \sqrt{2} \cdot 400\text{V}$ in European grid
- Therefore the MPP tracker needs to boost the voltage depending on the PV input
- Maximum PV voltage is 1500V
- There exist also converter topologies (e.g. resonant converters) which can both boost and buck

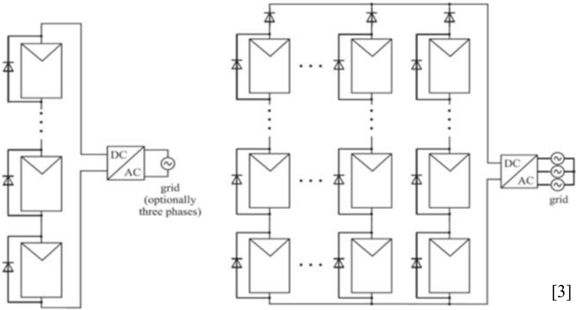




[2]

PV system concepts

- Different topologies can be considered for positioning the MPP tracker in the PV system
- Standard topologies have a DC-AC unit, which integrates the MPP tracker
- So there can be for example one MPP tracker per string
- Another system has a central converter
- String and central systems are the most widespread PV system concepts [3]



(a) System concept with string converter

(b) System concept with central converter

[3]

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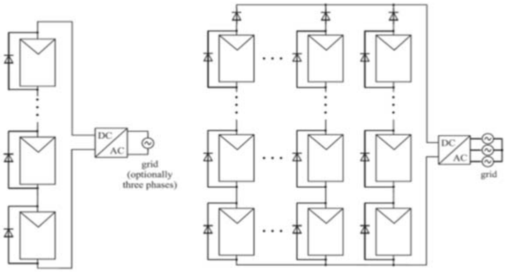
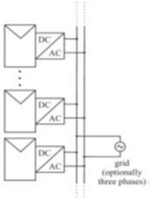
PV system concepts

- In string systems every module has a bypass diode to avoid losses and heat production in case of partial shading
- In central systems the modules are connected in a matrix installing one extra diode per string to avoid reverse current
- Also module integrated MPP trackers are possible:
  - Here no bypass-diodes are necessary and the converters can be connected in parallel
- The MPP of every module can be found individually

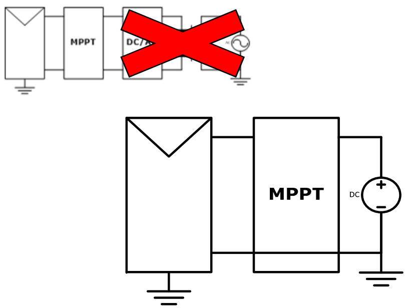


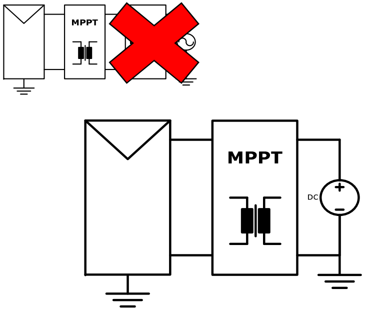
(a) System concept with string converter (b) System concept with central converter

[3]



- Advantage in DC mains:
  - DC-mains and PV can both be easily connected to GND/PE (protective earth)
  - No need for additional expensive components
  - No capacitive leakage currents (PV-potential same as grid potential)





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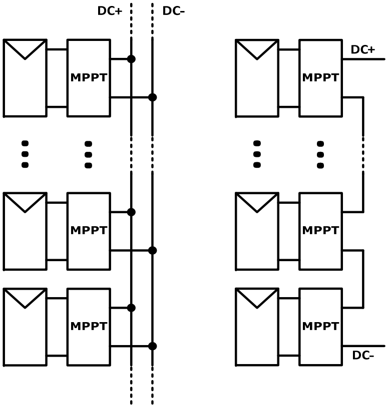
Special implications for DC mains

- Possibility to use local MPPTs for each module
  - Each module feeds the DC mains directly
  - 2 variations:
    - Parallel module-integrated converters
    - Cascaded module-integrated converters
  - The DC-DC converters do not need electrolytic capacitors (in a stable DC grid)
  - No need for transformers
  - Less hardware effort for the MPPTs
  - Better reliability



References

- [1]: Boeke, U.: *A simple model of photovoltaic module electric characteristics*, European Conference on Power Electronics and Applications, 2007
- [2]: Reuber, C.: *Konzeption, Aufbau und Inbetriebnahme eines isolierten, resonanten DC/DC Wandlers für eine Solaranwendung*, Bachelorthesis, 2013
- [3]: Dick, C.: *Multi-Resonant Converters as Photovoltaic Module-Integrated Maximum Power Point Tracker*, Dissertation, 2010
- [4]: *IEC information about IEC 61000 standard* https://www.iec.ch/emc/basic_emc/basic_61000.htm

MPP-Tracking Software

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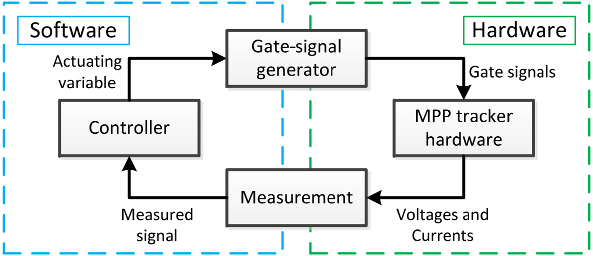
Outline

- How to control the MPP tracker using software?
  - Control circuit overview
  - Gate-signal generator
  - Measurement
  - Main control / interrupt routine
- Classic control strategies
  - Perturb & observe
  - Incremental conductance
  - etc
- Programming examples



- Control loop for the MPP tracker consists of 4 main parts
- Main control algorithms are done in software
- Gain-signal generator and measurement are the interface between hard- and software

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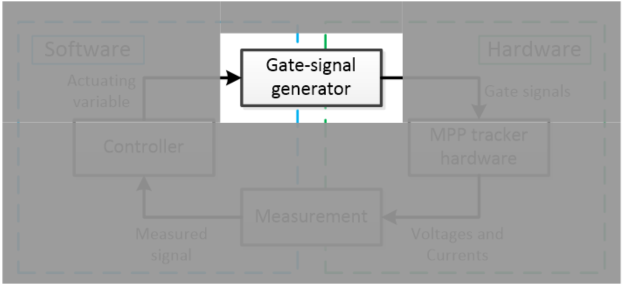
Control circuit



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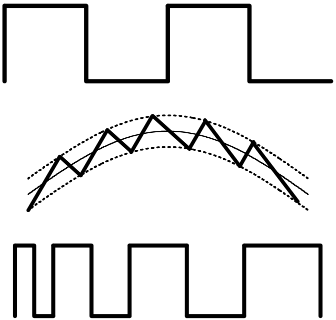
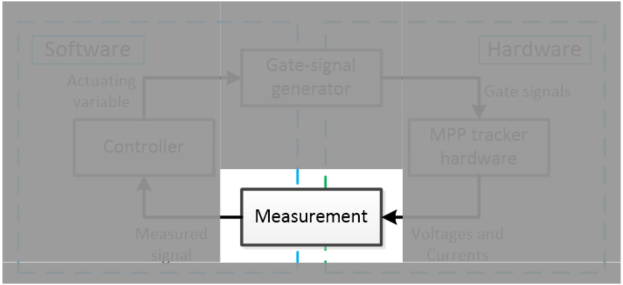
Gate-signal generator

- PWM modulator:
  - Actuating variable: duty cycle
- Bang bang control:
  - Actuating variable: tolerance band
- Resonant converter:
  - Actuating variable: frequency
- …
- All modulators can be designed on µCs or FPGA (also ICs available)



Control circuit



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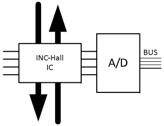
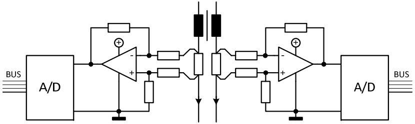
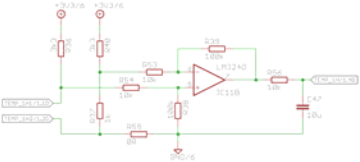
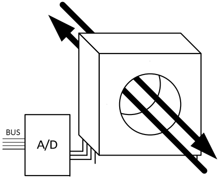
Measurement

- Current, Voltage, Temperature, …
- A/D- Conversion
  - Parallel
  - SAR
  - Delta-Sigma
  - …
- Filtering

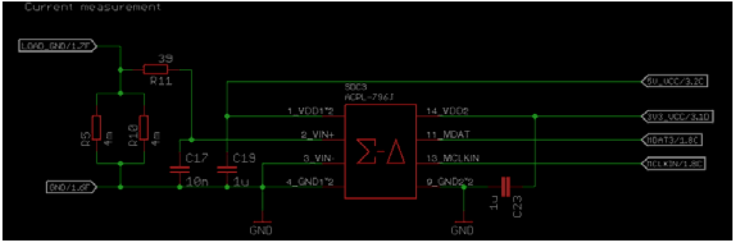




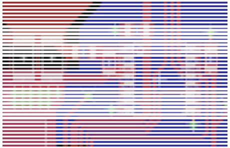




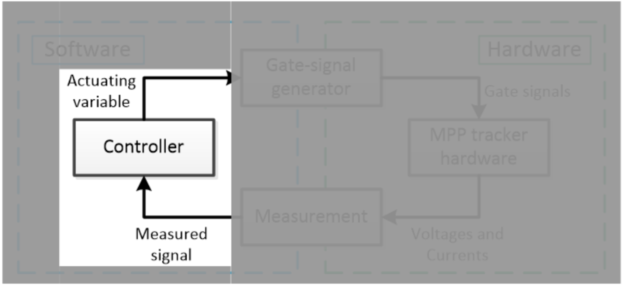
Measurement example



- Current measurement
- Shunt resistor
- Delta-Sigma A/D conversion



Control circuit



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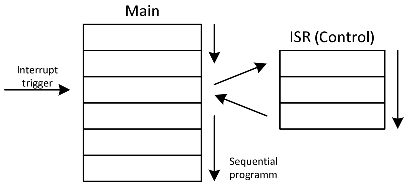
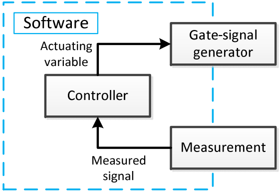
Interrupt concept

- Usually timer triggered code
  - Executed for example every 50µs
- Fixed sampling time
- Control algorithms are separated from other time variant code
- In hardware language:
  - Clocked process
  - State machine





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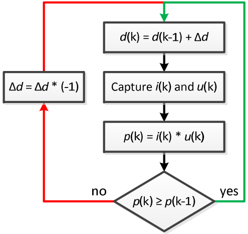
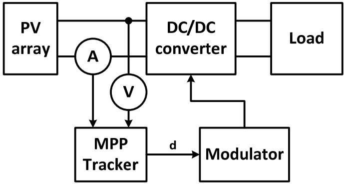
Perturb and Observe (P&O) (V1)

- Permanent change of duty cycle $d(k)$ (Perturb)
- Compare old power level with new power level (observe)
- Fixed absolute duty cycle change $|\Delta d|$
- Change direction of duty cycle change
- Only capable of finding local MPP





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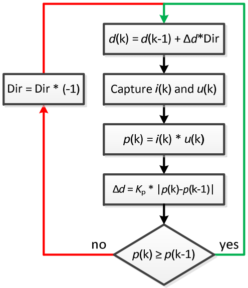
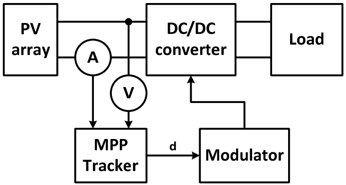
Perturb and Observe (P&O) (V2)

- Permanent change of duty cycle d (Perturb)
- Compare old power level with new power level (observe)
- Proportional duty cycle change:

$$\Delta d = K_\text{p} \cdot |\Delta p| = K_\text{p} \cdot |p(k) - p(k-1)|$$

- K_p depends on system power level
- Change direction of duty cycle change
- Only capable of finding local MPP





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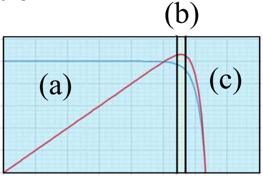
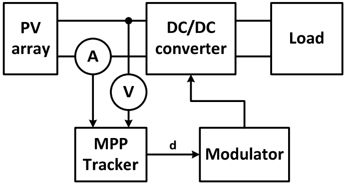
Incremental conductance

- Control depends on slope of the PV-characteristic
- $\frac{dP}{dU} = \frac{d(U \cdot I)}{dU} = I + U \cdot \frac{dI}{dU}$
- $\frac{dI}{dU} \approx \frac{\Delta I}{\Delta U} = \Delta G \begin{cases} > -\frac{I}{U} \text{ (a)} \\ = -\frac{I}{U} \text{ (b)} \\ < -\frac{I}{U} \text{ (c)} \end{cases}$
- $\frac{\Delta I}{\Delta U} = \Delta G$: Incremental conductance
- $\frac{I}{U} = G$: Conductance



$$\frac{dP}{dU} \begin{cases} > 0 \text{ (a)} \\ = 0 \text{ (b)} \\ < 0 \text{ (c)} \end{cases}$$



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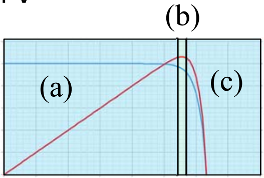
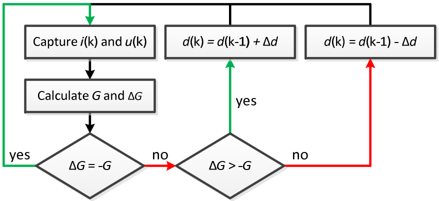
Incremental conductance

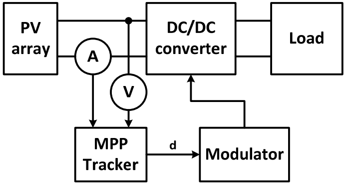
- Control depends on slope of the PV-characteristic

$$\frac{dI}{dU} \approx \frac{\Delta I}{\Delta U} = \Delta G \begin{cases} > -G \text{ (a)} \\ = -G \text{ (b)} \\ < -G \text{ (c)} \end{cases}$$



$$\frac{dP}{dU} \begin{cases} > 0 \text{ (a)} \\ = 0 \text{ (b)} \\ < 0 \text{ (c)} \end{cases}$$





Perturb & observe ISR (Overview 1)

```c
/****Timer Interrupt Service Routine (50us) & MPP-Tracker***********/

static void timer_50us_interrupt(void* context){

    IOWR_ALTERA_AVALON_PIO_DATA(ENABLE_OUTPUT_4BIT_BASE, enable_bit);
    IOWR_ALTERA_AVALON_PIO_DATA(DATA_OUTPUT_14BIT_1_BASE, duty_data);
    IOWR_ALTERA_AVALON_PIO_DATA(DATA_OUTPUT_8BIT_2_BASE, LED_MPP_Found<<3|LED_Spare<<2|LED_MPP_Auto<<1|LED_MPP_Man);
    //Read in measured values
    U_in_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_14BIT_0_BASE);  //Read in bit value U_in
    U_out_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_14BIT_1_BASE); //Read in bit value U_out
    I_out_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_14BIT_2_BASE); //Read in bit value I_out

    //Calculate physical values
    U_in = U_in_bit * K_U_IN;
    U_out = U_out_bit * K_U_OUT;
    I_out = I_out_bit * K_I_OUT;

    // Calculation of average values of U_in, U_out, I_out and P

    U_in_add += U_in;
    I_out_add += I_out;
    U_out_add += U_out;
    U_cnt ++;

    if(U_cnt >= NUMBER_AVERAGE){

        U_out_mittel_alt = U_out_mittel;            // Buffering old value of output voltage
        U_out_mittel = U_out_add/NUMBER_AVERAGE;    // Averaging output voltage
        U_out_add = 0.0;

        U_in_mittel_alt = U_in_mittel;           // Buffering old value of input voltage
        U_in_mittel = U_in_add/NUMBER_AVERAGE;      // Averaging input voltage
        U_in_add = 0.0;

        I_out_mittel = I_out_add/NUMBER_AVERAGE;    // Averaging current
        I_out_add = 0.0;

        P_alt = P;
        P = I_out_mittel * U_out_mittel;               // Power calculation

        // DELTA_U_calc = U_out_mittel_alt - U_out_mittel;  // Calculation of Delta U_in
        DELTA_U_calc = P_alt - P;
        if (DELTA_U_calc < 0) DELTA_U_calc *= (-1);    // Absolute value

        n = U_out_mittel / U_in_mittel;                // Ration Vout/Vin (= duty cycle)

    }
```

<- Output

<- Input

<- Calculate physical value from Bitvalue

<- Calculate average values (NUMBER_AVERAGE = 750)

<- Calculate power change and measured duty cycle

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Programming example

Perturb & observe ISR

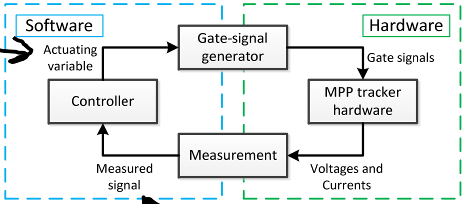
```
/****Timer Interrupt Service Routine (50us) & MPP-Tracker**********/

static void timer_50us_interrupt(void* context){

    IOWR_ALTERA_AVALON_PIO_DATA(ENABLE_OUTPUT_4BIT_BASE, enable_bit);
    IOWR_ALTERA_AVALON_PIO_DATA(DATA_OUTPUT_16BIT_1_BASE, duty_data);
    IOWR_ALTERA_AVALON_PIO_DATA(DATA_OUTPUT_8BIT_2_BASE, LED_MPP_Found<<3|LED_Spare<<2|LED_MPP_Auto<<1|LED_MPP_Man);
    //Read in measured values
    U_in_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_16BIT_0_BASE);  //Read in bit value U_in
    U_out_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_16BIT_1_BASE); //Read in bit value U_out
    I_out_bit = IORD_ALTERA_AVALON_PIO_DATA(DATA_INPUT_16BIT_2_BASE); //Read in bit value I_out
```

<- Enable

LED signals



Perturb & observe ISR

```
//Calculate physical values
U_in = U_in_bit * K_U_IN;
U_out = U_out_bit * K_U_OUT;
I_out = I_out_bit * K_I_OUT;

// Calculation of average values of U_in, U_out, I_out and P

U_in_add += U_in;
I_out_add += I_out;
U_out_add += U_out;
U_cnt ++;

if(U_cnt >= NUMBER_AVERAGE){

    U_out_mittel_alt = U_out_mittel;            // Buffering old value of output voltage
    U_out_mittel = U_out_add/NUMBER_AVERAGE;    // Averaging output voltage
    U_out_add = 0.0;

    U_in_mittel_alt = U_in_mittel;            // Buffering old value of input voltage
    U_in_mittel = U_in_add/NUMBER_AVERAGE;      // Averaging input voltage
    U_in_add = 0.0;

    I_out_mittel = I_out_add/NUMBER_AVERAGE;    // Averaging current
    I_out_add = 0.0;

    P_alt = P;
    P = I_out_mittel * U_out_mittel;                // Power calculation

    // DELTA_U_calc = U_out_mittel_alt - U_out_mittel;  // Calculation of Delta U_in
    DELTA_U_calc = P_alt - P;
    if (DELTA_U_calc < 0) DELTA_U_calc *= (-1);     // Absolute value

    n = U_out_mittel / U_in_mittel;                 // Ration Vout/Vin (= duty cycle)

}
```

<- Calculate physical value from Bitvalue

(e.g. K_U_IN is the translation factor)

<- Sum up all values until counter reaches NUMBER_AVERAGE

<- Calculate average values

(NUMBER_AVERAGE = e.g. 750)

<- Calculate power change

and measured duty cycle

Perturb & observe ISR (Overview 2)

```
if (MPP_Mode == 1){

    if(U_cnt >= NUMBER_AVERAGE){
        U_cnt = 0;
```

<- Reset average counter

```
    // If DELTA U_out lower than DELTA_U: Decrease duty cycle:

        if ((DELTA_U_calc <= DELTA_U) && (n > 0.1)){
            b = 1;
            LED_Spare = 1;
            LED_MPP_Found = 1;
            }
        else b = 1;
```

<- Possibility to reduce step size if needed (change b!)

```
        if (U_out_mittel < U_out_mittel_alt){
            k*= (-1);
            }
```

<- Change of direction (@ constant load resistance)

```
        // Calculate duty cycle
        a_f1 += (DELTA_A_auto*k*b);      // duty cycle = duty cycle + (Delta_A_auto * k * b)

        if (b == 1){
            if (k > 0) {
                LED_MPP_Found = 1;
                LED_Spare = 0;
            }
            else{
                LED_Spare = 1;
                LED_MPP_Found = 0;
                }
            }
}
```

<- Change duty cycle

k: direction

b: factor to reduce step size if needed

LED_Spare: decreasing duty cycle

LED_MPP_Found: increasing duty cycle

```
//Limit duty cycle (anti wind up)
if(a_f1 >= MAX_TASTGRAD) a_f1 = MAX_TASTGRAD;
else if (a_f1 <= MIN_TASTGRAD) a_f1 = MIN_TASTGRAD;
```

<- Anti Wind up

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Programming example

Perturb & observe ISR

```
if (MPP_Mode == 1){

    if(U_cnt >= NUMBER_AVERAGE){
        U_cnt = 0;


    // If DELTA U_out lower than DELTA_U: Decrease duty cycle;

        if ((DELTA_U_calc <= DELTA_U) && (n > 0.1)){
            b = 1;


            }
        else b = 1;


        if (U_out_mittel < U_out_mittel_alt){
            k*= (-1);
            }
```

<- Reset average counter

<- Possibility to reduce step size if needed (change b!)

<- Change of direction (@ constant load resistance)

Perturb & observe ISR

```
// Calculate duty cycle
a_fl += (DELTA_A_auto*k*b);      // duty cycle = duty cycle + (Delta_A_auto * k * b)

if (b == 1){
    if (k > 0) {
        LED_MPP_Found = 1;
        LED_Spare = 0;
    }
    else{
        LED_Spare = 1;
        LED_MPP_Found = 0;
        }
    }
}
```

<- Change duty cycle

DELTA_A_auto: Duty cycle change (e.g. 0.001 (0.1%))

k: direction

b: factor to reduce step size if needed

LED_Spare: decreasing duty cycle

LED_MPP_Found: increasing duty cycle

```
//Limit duty cycle (anti wind up)
if(a_fl >= MAX_TASTGRAD) a_fl = MAX_TASTGRAD;
else if (a_fl <= MIN_TASTGRAD) a_fl = MIN_TASTGRAD;
```

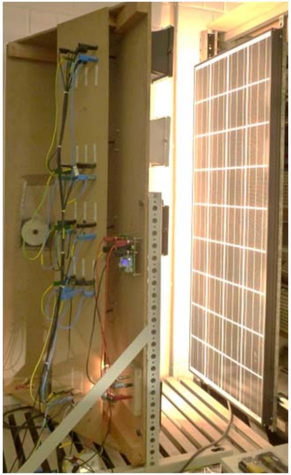
<- Anti Wind up

a_fl: duty cycle

MAX_TASTGRAD: maximum duty cycle (e.g. 0.98)

MIN_TASTGRAD: minimum duty cycle (e.g. 0.02)

MPP Tracking Showcase



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Outline

- System overview
  - Demonstration of the MPPT Showcase
  - Preparations (What you need)
- Showcase design tutorial
  - Parts assembly
  - Software How To
    - FPGA Flash tutorial
    - Detailed software tutorial

Outline

- System overview
  - Demonstration of the MPPT Showcase
    - Video
  - Preparations (What you need)
- Showcase design tutorial
  - Parts assembly
  - Software How To
    - FPGA Flash tutorial
    - Detailed software tutorial

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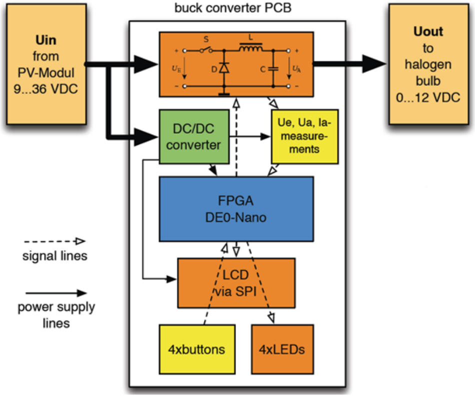
1. The showcase note (Note 4):

- ➢ contains all relevant information to build the showcase



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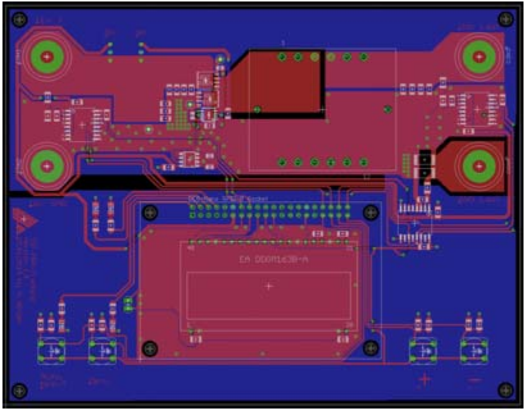
Preparations (What you need)

2. Printed Circuit Board produced using the EAGLE brd.-file in the showcase note (folder: PCB files\TST-MPP-Tracking V1.0.0.brd):



3. TERASIC DE0nano-FPGA evaluation board:

- https://www.terasic.com.tw/cgi-bin/page/archive.pl?Language=English&CategoryNo=165&No=593

Source: TERASIC.com

4. 3x16 DOG Characterdisplay EA-DOGM-163B-A:
   - https://shop.lcd-module.com/3x16-dog-characterdisplay.html

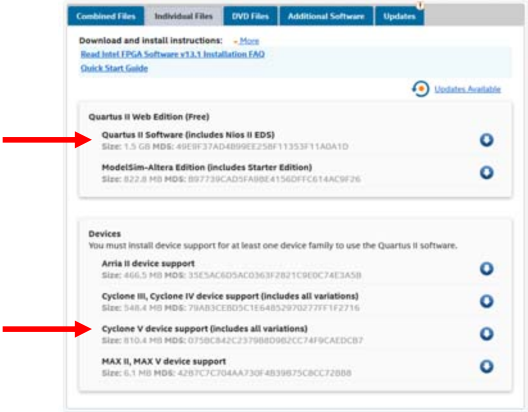
Source: lcd-module.com

5. LED backlit for EA DOGM EA LED55X31-W:
   - https://shop.lcd-module.com/led-backlit-for-ea-dogm-998.html

Source: lcd-module.com

6. Altera Quartus II web edition (free) V13.1 FPGA design software:

- ➢ https://fpgasoftware.intel.com/13.1/?edition=web



Source: intel.com

7. Inductance: $L \geq 120\mu\text{H}; \text{I}_{\text{sat}} \geq 7\text{A}$:
   - Bourns Inc. „1140-121K-RC"
     - (https://www.digikey.de/product-detail/de/bourns-inc/1140-121K-RC/M8378-ND/774918)
   - Würth Elektronik „7443742920315 1"
     - (https://www.digikey.de/product-detail/de/w%C3%BCrth-elektronik/7443742920315 1/732-11710-ND/8134284)
   - Self made inductance using for example:
     - Ferroxcube „RM12/I-3F3-A160" ferrite core
     - Litz-wire: 162x0.1mm / ACu = 1.27mm² / ∅ = 2mm

Source: digikey.com

Source: digikey.com

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8. The other parts of the part-list (folder: PCB files\Partlist\Partlist.xlsx):
   - ➢ Resistors, caps, optocouplers, LEDs
   - ➢ MOSFETs, drivers, delta-sigma-modulators, etc…

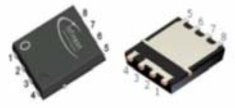
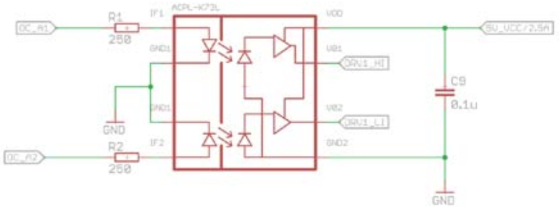
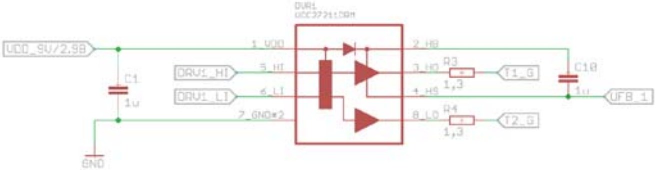


Figure 8: Power MOSFETs (Infineon, 2019)





Preparations (What you need)

9. PV generator:
   - ➢ Solar module with adjustable irradiance (lamps for example)
   - ➢ Similar characteristic

Output voltage level	9V...36V
Output MPP power	75W

Example PV generator characteristic:

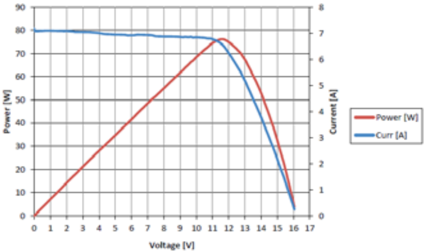


Figure 2: PV characteristic example (Brosig & Horstmann, 2014)

10. Load:

- ➢ Halogen lamps for example
- ➢ Two parallel 12V 35W
- ➢ Overall load resistance: 2.06Ω @ 70W

- ➢ … or similar load

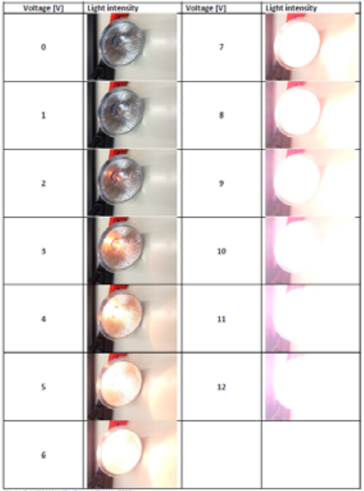


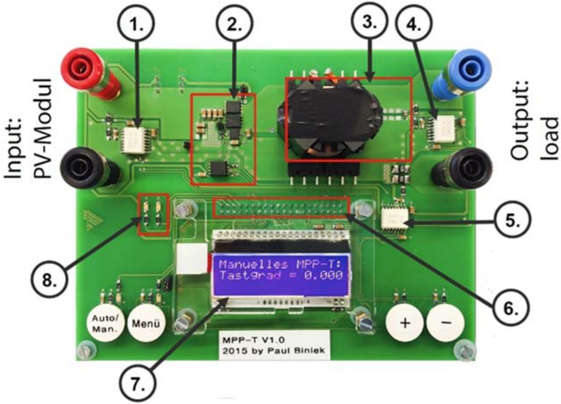
Figure 3: Light intensity change (Biniek, 2015)

Outline

- System overview
  - Demonstration of the MPPT Showcase
  - Preparations (What you need)
- Showcase design
  - Parts assembly
  - Software How To
    - Not in this lecture

Main parts of the PCB:

1. Input voltage measuring using a delta sigma modulator
2. Half-bridge including two power-MOSFETs, high frequency dual MOSFET driver and optocoupler
3. Self-made inductance of 127µH (low skin effect) and smoothing capacitor of 22µF
4. Output voltage measuring
5. Output current measuring
6. 2x20 Header for FPGA Terasic “DE0nano” evaluation board attached on bottom layer of PCB
7. LCD display showing MPP mode, duty cycle and measurements of in- and outputs
8. LED’s for status signalizing



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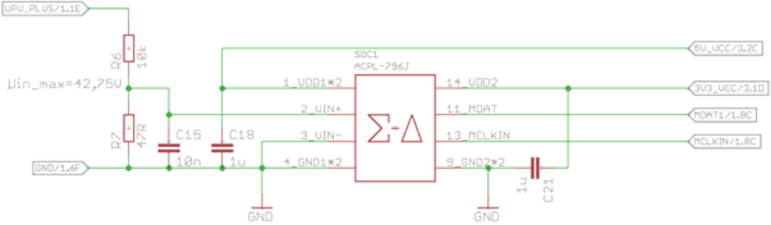
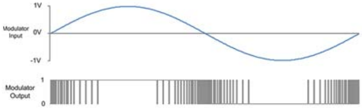
1. Input voltage measurement:

- Voltage divider
- Delta-sigma-modulator Broadcom „ACPL-796J"
  - Galvanic isolation
  - 2_VIN+ - 3_VIN-: 200mV linear input range
  - Output „11_MDAT": contains pulse-density modulated Bitstream
  - Input „13_MCLKIN": 20MHz Clock input from FPGA





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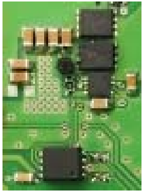
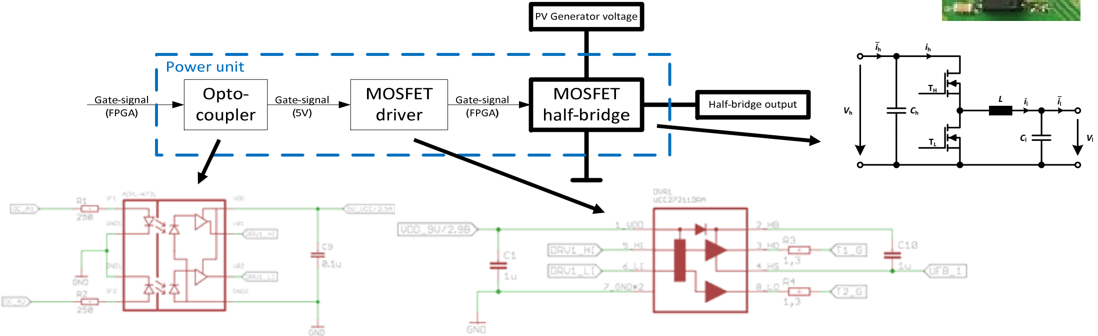
2. Power unit:

- Power MOSFETs Infineon „BSC016N06NS"
- MOSFET driver Texas Instruments „UCC27211DRM"
- Optocoupler Broadcom Inc. "ACPL-K73L"





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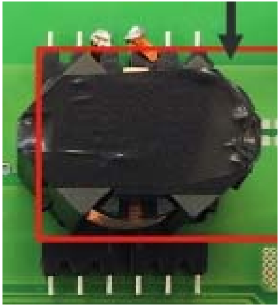
3. Inductance:

- $L \geq 120\mu\text{H}; \text{I}_{\text{sat}} \geq 7\text{A}$
- $L = \frac{1}{4} \cdot \frac{V_\text{h}}{f_\text{s} \cdot \Delta I_{\text{max}}} = \frac{1}{4} \cdot \frac{24\text{V}}{50\text{kHz} \cdot 1\text{A}} = 120\mu\text{H}$
- $N = \sqrt{\frac{L}{A_L}} = \sqrt{\frac{120\mu\text{H}}{160\text{nH (see Datasheet)}}} = 27.39 \approx 28$
- $i_{\text{max}} = \frac{B_{\text{max}} \cdot \text{Air Gap}}{N \cdot \mu_0} = \frac{0.35\text{T} \cdot 0.00157\text{m}}{28 \cdot 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}} = 15.62\text{A}$
- Ferroxcube “RM12/I-3F3-A160” with coil former
- Litz wire: 162x0.1mm / $A_{\text{Cu}} = 1.27\text{mm}^2$ / $\emptyset = 2\text{mm}$



- An inductance from distributor could also do the job (see slide 9)

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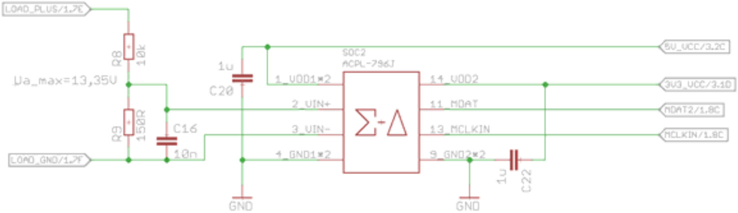
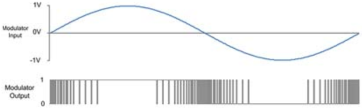
4. Output voltage measurement:

- Voltage divider
- Delta-sigma-modulator Broadcom „ACPL-796J“
  - Galvanic isolation
  - 2_VIN+ - 3_VIN-: 200mV linear input range
  - Output „11_MDAT“: contains pulse-density modulated Bitstream
  - Input „13_MCLKIN“: 20MHz Clock input from FPGA





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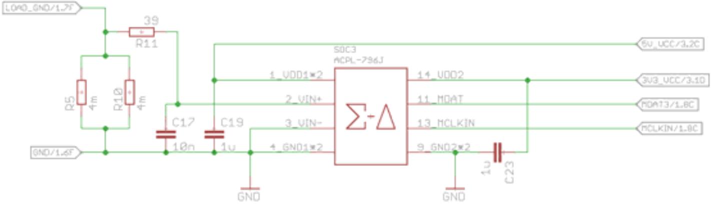
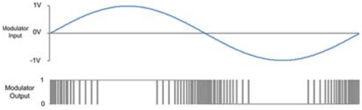
5. Output current measurement (in our case not needed):
   - Shunt measurement
   - Delta-sigma-modulator Broadcom „ACPL-796J"
     - Galvanic isolation
     - 2_VIN+ - 3_VIN-: 200mV linear input range
     - Output „11_MDAT": contains pulse-density modulated Bitstream
     - Input „13_MCLKIN": 20MHz Clock input from FPGA





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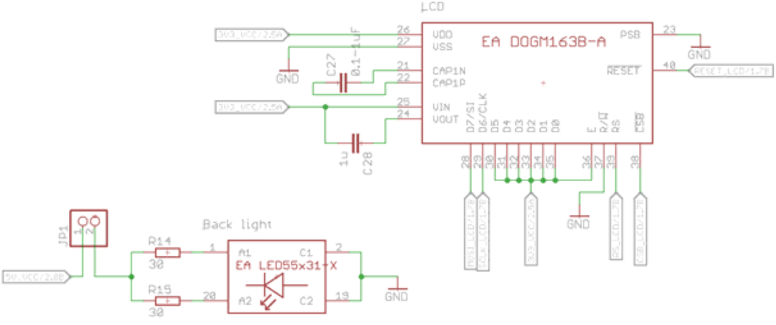
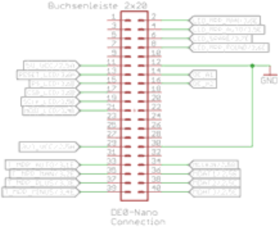
6. + 7. FPGA board header on bottom side and display:

- Data connection via SPI bus
- Display programmed via the FPGA





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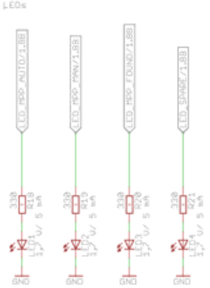
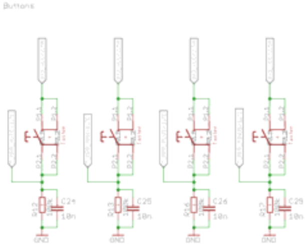
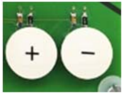
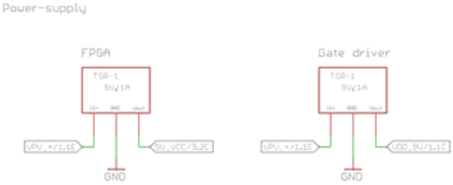
8. Status LEDs, buttons and auxiliary power:

- LEDs at I=5mA
- 9V level: gate-driver; 5V level: all other stuff
- Buttons are debounced with RC









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Übersicht

- MPP-Tracking – Overview
- MPP-Tracking Software
- MPP Tracking Showcase
- Expected Behavior with Buck Converter and resistance
  - Video Demonstration
- Boost Converter feeding into a stiff DC-Link for feeding into the grid mains

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Expected Behavior with Buck Converter and resistance

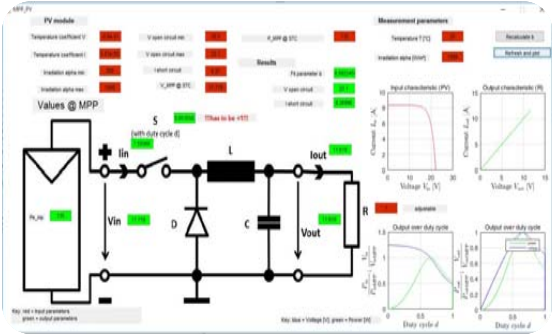
- PV Characteristic

$$I_{PV} = I_{in} = I_{\mathrm{ph}} - I_{\mathrm{S}} \cdot (e^{\frac{V_{\mathrm{in}}}{n \cdot V_{\mathrm{T}}}} - 1)$$

- Converter an load

$$V_{out} = V_{in} \cdot a$$
$$I_{in} = I_{out} \cdot a$$
$$R = \frac{V_{out}}{I_{out}}$$

- Common characteristics
  - Solved numerically



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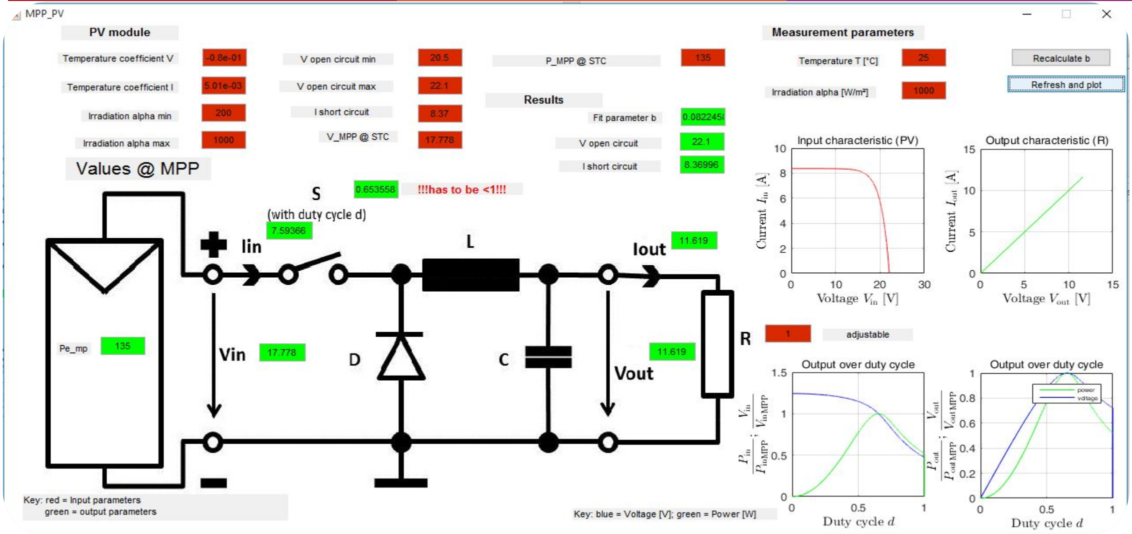
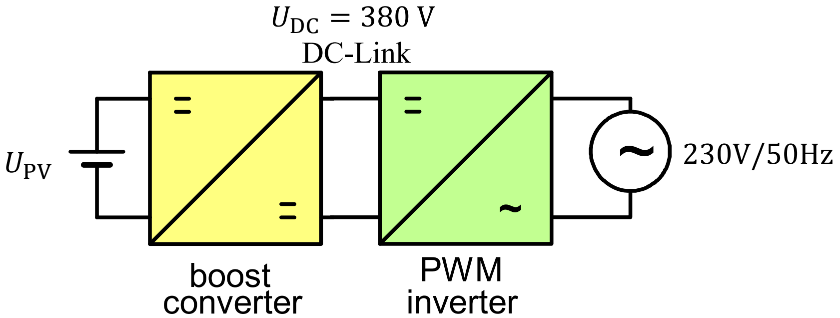
Expected Behavior with Buck Converter and resistance

Proof for being able for MPPT by varying duty cycle



- Mains converter controls output voltage to a constant level

- MPPT means maximizing DC-Link current



Boost Converter feeding into a stiff DC-Link for feeding into the grid mains

- In case PV-Generator voltage @ MPP exceeds DC-Link voltage
  - Then boost converter is bypassed ($U_{PV} = U_{DC}$)
  - PWM-Converter directly performs MPPT by varying dc-link voltage