

# Energy and Power

## Energy Harvesting, Solar Cell Characteristics and Maximum Power Point Tracking, Application Control

### Exercise class 8

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*In cooperation with:*

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*Based on the lecture of:*

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# Gliederung

Organisation

Overview

Task 1

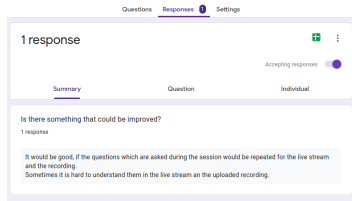
Task 2

Task 3

# Organisation

# Organisation I

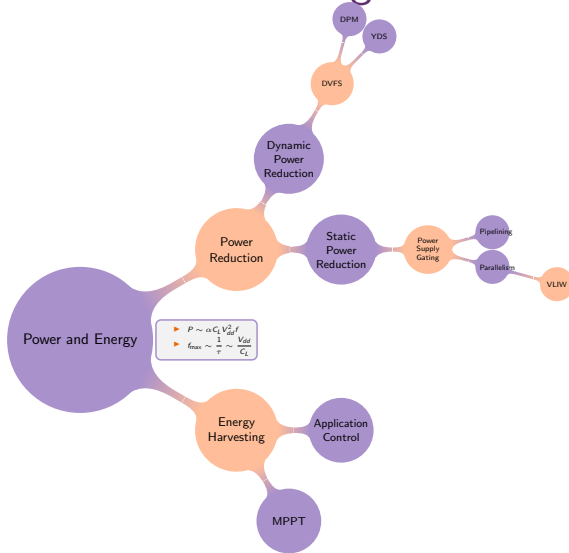
► feedback for me: <https://forms.gle/f3YN8EFrZ1vsfPoC6>



The screenshot displays a Google Forms interface with three tabs at the top: 'Questions', 'Responses' (which is active and has a notification icon), and 'Settings'. Below the tabs, the text '1 response' is shown next to a green plus icon and a vertical ellipsis. A toggle switch for 'Accepting responses' is visible and is currently turned on. Below this, there are three sub-tabs: 'Summary', 'Question', and 'Individual'. The 'Summary' tab is selected. The main content area shows the question 'Is there something that could be improved?' with '1 response' listed below it. The response text is: 'It would be good, if the questions which are asked during the session would be repeated for the live stream and the recording. Sometimes it is hard to understand them in the live stream an the uploaded recording.'

# Overview

# Overview Scheduling



# Task 1

# Task 1 I

## Task 1.1:



<i>Task</i>	$\tau_1$	$\tau_2$	$\tau_3$
<i>Arrival Time</i> [ms]	0	0	0
<i>Period</i> [ms]	6	4	12
<i>Relative Deadline</i> [ms]	6	4	12
<i>Cycles</i> [ $\times 10^3$ ]	2	1	2

$$P_{\text{dynamic}}(f) = \left( \frac{f}{1 \text{ MHz}} \right)^3 \text{ mW}$$



# Task 1 II

## Solution 1.1:



- ▶ The execution times  $C_i$  of tasks  $\tau_i$  are:  $C_1 = \frac{1 \cdot 10^3 \text{ Cycles}}{1 \cdot 10^6 \frac{\text{Cycles}}{\text{s}}} = 2\text{ms}$ ,  
 $C_2 = \frac{1 \cdot 10^3 \text{ Cycles}}{1 \cdot 10^6 \frac{\text{Cycles}}{\text{s}}} = 1\text{ms}$ , and  $C_3 = \frac{1 \cdot 10^3 \text{ Cycles}}{1 \cdot 10^6 \frac{\text{Cycles}}{\text{s}}} = 2\text{ms}$  ( $T = \frac{N}{f}$ ).
- ▶ Applying EDF schedule, the processor is busy in  $[0\text{ms}, 9\text{ms}]$
- ▶ constant input power:  $P_{in} = 0.5\mu\text{J}$
- ▶ We use 1MHz for processing tasks, leading to  $P_{dynamic}(1\text{MHz}) = 1\text{mW}$
- ▶ This means we consume  $1\text{mW} \cdot 1\text{ms} = 1\mu\text{J}$  per millisecond.
- ▶ Since all our tasks take a multiple of 1ms, we know that while processing tasks, our battery empties with  $0.5\mu\text{J}/\text{ms} - 1\mu\text{J}/\text{ms} = -0.5\mu\text{J}/\text{ms}$

# Task 1 III

## Solution 1.1:

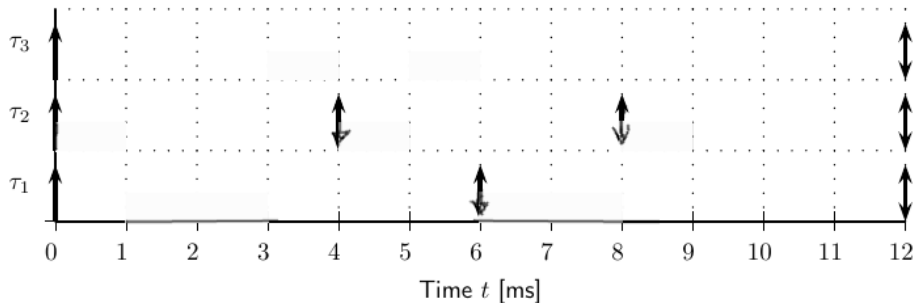


Figure 1: The resulting schedule for tasks  $\tau_i$  when applying EDF algorithm.

# Task 1 IV

## Solution 1.1:

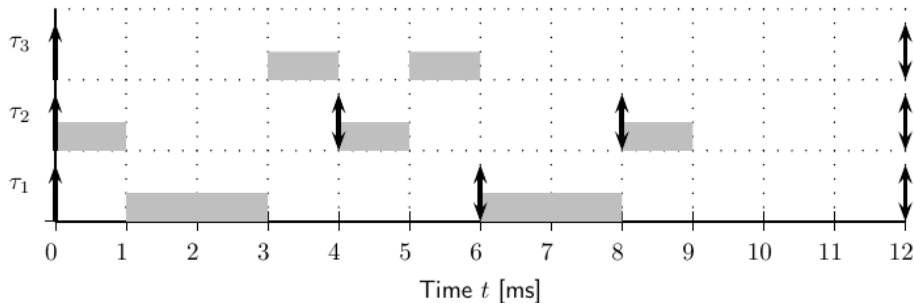


Figure 1: The resulting schedule for tasks  $\tau_i$  when applying EDF algorithm.

# Task 1 V

## Solution 1.1:

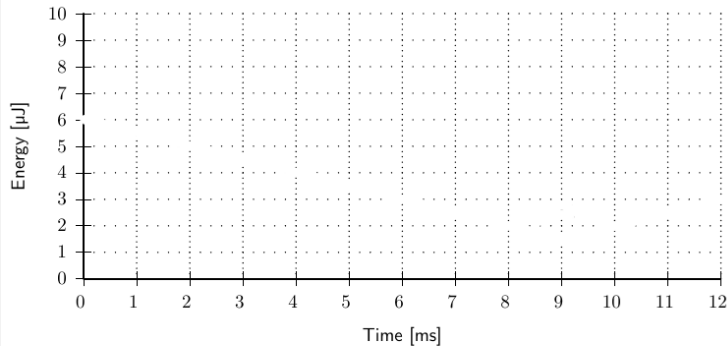


Figure 2: The resulting evolution of the battery charge state  $E_{\text{bat}}(t)$ .

# Task 1 VI

## Solution 1.1:

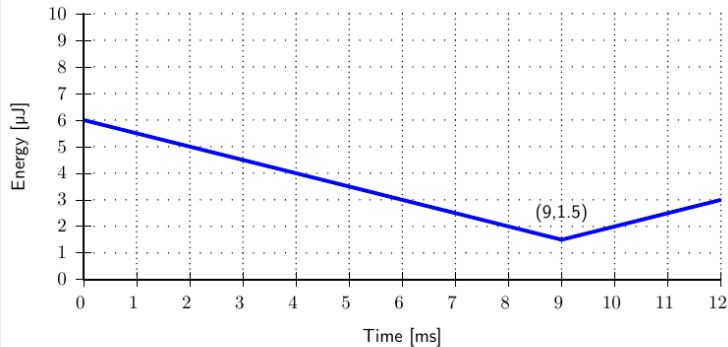


Figure 2: The resulting evolution of the battery charge state  $E_{\text{bat}}(t)$ .

# Task 1 VII

## Task 1.2:



- ▶ To maximize the energy stored in the battery at the end of each hyper-period ( $12ms$ ), all tasks  $\tau_i$  have to be executed at the same frequency and this frequency leads to a utilization of 1.0

# Task 1 VIII

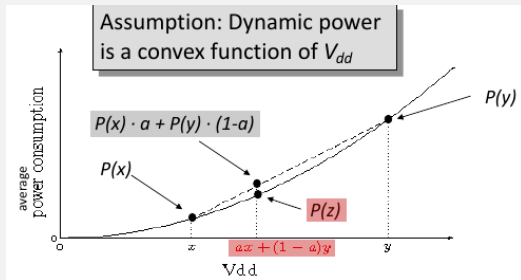
## Requirements 1.2:



- ▶ *processor utilization*  $U_p = \sum_{i=1}^n \frac{C_i}{T_i}$
- ▶ the given power consumption  $P_{\text{dynamic}}(f)$  is a *strictly convex* function ( $f(\theta x + (1 - \theta)y) \leq \theta f(x) + (1 - \theta)f(y)$ ) of the frequency  $f$
- ▶ The EDF scheduling algorithm where deadlines of tasks equal their periods guarantees a feasible schedule as long as the utilization of the processor is  $U \leq 1.0$ 
  - ▶ this schedulability test is *necessary* and *sufficient*, i.e. if one reaches a utilization of exactly  $U = 1.0$ , then it has to be schedulable

# Task 1 IX

## Requirements 1.2:



- The same argument applies if the power is a convex function of the **frequency**!



# Task 1 X

## Solution 1.2:

- ▶ The execution of all tasks with a constant frequency allows for a schedule where the utilization satisfies  $U = 1.0$ , i.e., the processor is constantly busy
  - ▶ determine right frequency by calculation:
    - ▶  $1 = \frac{\frac{2kCycles}{f}}{6ms} + \frac{\frac{1kCycles}{f}}{4ms} + \frac{\frac{2kCycles}{f}}{12ms} = \frac{4kCycles+3kCycles+2kCycles}{12ms} \Leftrightarrow f = \frac{9 \cdot 10^3 Cycles}{12 \cdot 10^{-3}s} = 0.75 \cdot 10^{3+3} \cdot \frac{1}{s} = 0.75MHz$
- ▶ the optimality of processing at a constant frequency during the whole time follows the same argumentation used to derive the optimal Dynamic Voltage and Frequency Scaling (DVFS).
  - ▶ Due to the strict convexity of the power consumption  $P_{dynamic}(f)$  the increase in the average power consumption of the higher frequency task always dominates the savings in the average power consumption of the lower frequency task execution.

# Task 1 XI

## Solution 1.2:



- ▶ *the above conditions (constant frequency during execution, processor executing all the time) lead to a schedule, where the maximum frequency of task execution can not be further reduced as the whole time interval where tasks can be executed is filled with execution and all tasks are executed with the same frequency.*

# Task 1 XII

## Sidenote 🔍

- ▶ Power is **polynomial** if you plot over voltage or frequency. So tasks with high frequency will consume polynomially more power than those with low frequency.
- ▶ The example from the lecture assumes only **two** different frequencies, but with more different frequencies the principle is similar.
- ▶ The line we see is caused by the fact that there is a certain time share of tasks with the low frequency, namely  $\alpha$ , and a certain time share of tasks with the high frequency, namely  $(1 - \alpha)$ . Depending on how the time share  $\alpha$  is composed, more or less time units of the tasks with the high or low frequency flow into the averaged total power.

# Task 1 XIII

## Sidenote 🔍

- ▶ If you leave the frequency constant, you don't have this situation with a certain time share of tasks with the high or low frequency, but you lie somewhere on this polynomial power curve, depending on how high or low the selected frequency is.
- ▶ If, on the other hand, you have a mixture with a certain time share of the task with the high frequency and the task with the low frequency, then the time share of tasks with the high frequency dominates, which then ensures that you end up somewhere on this line between the task with the high frequency  $y$  and the task with the low frequency  $x$ , i.e.:

$$\alpha \cdot P(x) + (1 - \alpha) \cdot P(y)$$

# Task 2



# Task 2 I

## Power Point Tracking Algorithm

### Requirements 2.1:

- ▶  $I(U) = G \cdot 1 \text{ A} - \left( \exp\left(\frac{U}{0.1 \text{ V}}\right) - 1 \right) \cdot 0.01 \text{ mA}$
- ▶  $P = I \cdot U$

# Task 2 II

## Power Point Tracking Algorithm

### Solution 2.1:



Relative Irradiance $G$	0.1	0.2	0.5	1.0
Voltage $V$ [V]	0.7	0.7	0.7	0.7
Current $I$ [mA]				
Power $P$ [mW]				

# Task 2 III

## Power Point Tracking Algorithm

### Solution 2.1:



Relative Irradiance $G$	0.1	0.2	0.5	1.0
Voltage $V$ [V]	0.7	0.7	0.7	0.7
Current $I$ [mA]	89.0	189.0	489.0	989.0
Power $P$ [mW]	62.3	132.3	342.3	692.3



# Task 2 I

## Task 2.2:

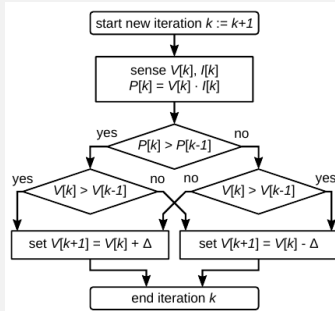


- ▶ for  $G = 0.1$  and  $G = 1.0$
- ▶  $\Delta = 0.05V$
- ▶ iteration  $k = 1$ ,  $V[0] = 0.7V$  and  $V[1] = 0.75V$

# Task 2 II

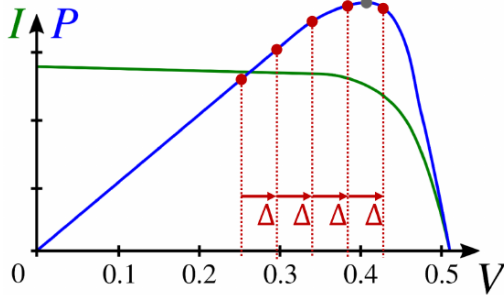
## Requirements 2.2:

- ▶  $I(U) = G \cdot 1 \text{ A} - \left( \exp\left(\frac{U}{0.1 \text{ V}}\right) - 1 \right) \cdot 0.01 \text{ mA}$
- ▶  $P = I \cdot U$



# Task 2 III

## Requirements 2.2:



## Task 2 IV

### Requirements 2.2:



- ▶  $P(V) = V \cdot I(V) = V \cdot G - V \cdot (\exp(\frac{V}{0.1V}) - 1) \cdot 10^{-5}$
- ▶ *the power  $P$  extracted at a given operating point  $V$ , calculated as is a concave function of that  $V$*
- ▶ *As the algorithm adjusts the operating point in discrete voltage steps  $\Delta$ , the maximum of the power  $P[k]$  observed by the algorithm presents a lower bound of the actual maximum power point  $P^*$ .*
  - ▶ *Only in the special case where the voltage of the maximum power point is a multiple of  $\Delta$ , it is matched exactly by the algorithm.*

# Task 2 V

## Solution 2.2:



$G = 0.1$ :

Iteration $k$	0	1	2	3	4	5	...
Voltage $V[k]$ [V]	0.7	0.75					...
Current $I[k]$ [mA]	89.0						...
Power $P[k]$ [mW]	62.3						...

# Task 2 VI

## Solution 2.2:



$G = 0.1$ :

Iteration $k$	0	1	2	3	4	5	...
Voltage $V[k]$ [V]	0.7	0.75	0.7	0.65	0.7	0.75	...
Current $I[k]$ [mA]	89.0	81.9	89.0	93.4	89.0	81.9	...
Power $P[k]$ [mW]	62.3	61.4	62.3	60.7	62.3	61.4	...

# Task 2 VII

## Solution 2.2:

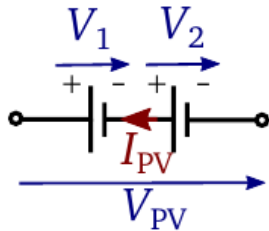


$G = 1.0$ :

Iteration $k$	0	1	2	3	4	5	...
Voltage $V[k]$ [V]	0.7	0.75	0.8	0.85	0.9	0.95	...
Current $I[k]$ [mA]	989.0	981.9	970.2	950.9	919.0	866.4	...
Power $P[k]$ [mW]	692.3	736.4	776.2	808.2	827.1	823.1	...

# Task 2 VIII

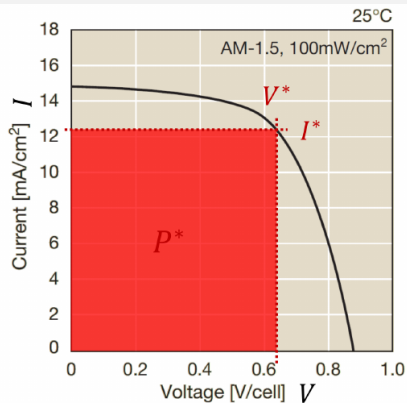
## Task 2.3:





# Task 2 IX

## Requirements 2.3:



# Task 2 X

## Solution 2.3:



- ▶ find the **voltage**  $V_1^*$  of the **maximum power point**  $P_1^*$  by numerically solving:  

$$\frac{d}{dU_1} P_1(U_1) = \frac{d}{dU_1} U_1 \cdot I_1(U_1) = 0$$
- ▶ cell 1 with  $G = 1.0$ : voltage at the maximum power point:  $U_1^* \approx 0.919 \text{ V}$  and the maximum power generated:  $P_1^* = U_1^* \cdot I_1(U_1^*) \approx 829 \text{ mW}$
- ▶ cell 2 with  $G = 0.1$ :  $U_2^* = 0.712 \text{ V}$  and  $P_2^* = 62.4 \text{ mW}$
- ▶ we determine an upper bound, i.e., a value which is larger than what can be generated by the partly shaded photovoltaic panel
- ▶ conditions:  $U_{PV} = U_1 + U_2$  and  $I_{PV} = I_1 = I_2$

# Task 2 XI

## Solution 2.3:



$$\blacktriangleright G_1 - \left( \exp\left(\frac{U_1}{0.1}\right) - 1 \right) \cdot 10^{-5} = G_2 - \left( \exp\left(\frac{U_2}{0.1}\right) - 1 \right) \cdot 10^{-5}$$

$$\Leftrightarrow (G_1 - G_2) \cdot 10^5 = \exp\left(\frac{U_1}{0.1}\right) - \exp\left(\frac{U_2}{0.1}\right)$$

$$\Leftrightarrow \exp\left(\frac{U_1}{0.1}\right) = (G_1 - G_2) \cdot 10^5 + \exp\left(\frac{U_2}{0.1}\right)$$

$\blacktriangleright$  Note that an increase in  $U_2$  leads to an increasing  $U_1$ ! First we assume  $U_2 = 0$ :

$$\blacktriangleright U_1 = 0.1 \cdot \log\left((G_1 - G_2) \cdot 10^5 + \exp(0)\right) \approx 1.14 \text{ V}$$

$$\blacktriangleright P_{PV} = I_{PV} \cdot (U_1 + U_2) \approx 114.1 \text{ mW} = 0.1 \text{ A} \cdot (1.14 \text{ V} + 0 \text{ V}) \approx 0.1141 \text{ W} = 114.1 \text{ mW}$$

## Task 2 XII

### Solution 2.3:



- ▶ The voltage  $U_1 \approx 1.14V$  at this operating point is already above  $U_1^* \approx 0.919V$  the maximum power point of cell 1. Therefore, an increase in  $U_1$  (and  $U_2$ ) results in a decrease in the output power for cell 1.
- ▶ safe upper bound:  $P_{PV}^* \leq 176.5 \text{ mW} = 114.1 \text{ mW} + 62.4 \text{ mW}$
- ▶ We note that this is significantly lower than  $P_1^* \approx 829.0 \text{ mW}$  that can be generated with a single cell 1 at the same operating point. In addition, it is only slightly better than a situation, where both cells receive the low irradiance, namely  $125\text{mW}$

# Task 3

# Task 3

## Application control

### Task 3.1:

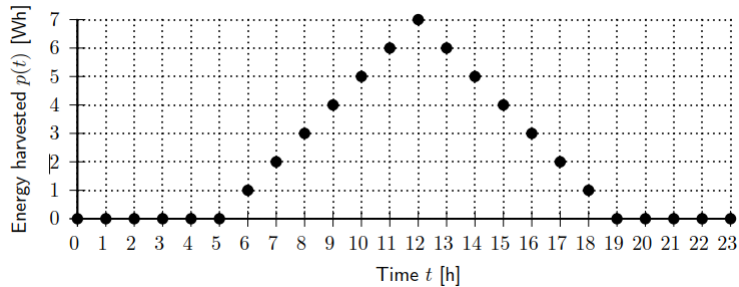


Consider the energy harvesting profile  $p(t)$  given in Figure 4 that repeats daily. What is the maximum average power  $u_{max}$  that can be used by the system?

# Task 3

## Application control

### Solution 3.1:



# Task 3

## Application control

### Solution 3.1:



- ▶ *The daily harvested energy is calculated by:*  
$$(1Wh + 2Wh + 3Wh + 4Wh + 5H + 6Wh) * 2 + 7Wh = 49Wh$$
- ▶ *This results in the following maximum average harvesting power:*  
$$u_{max} = \frac{49Wh}{24h} = 2.04W$$



# Task 3

## Application control

### Task 3.2:



Given the knowledge of the daily energy input profile  $p(t)$  in Figure 5, calculate the minimal battery size  $B_{min}$  such that the used energy satisfies  $u(t) = 2$  for every time interval during a day. Complete the diagram in Figure 6 with the daily evolution of the used energy  $u(t)$  and the battery charge state  $b(t)$  at the beginning of the interval for the found battery size  $B_{min}$ .

# Task 3

## Application control

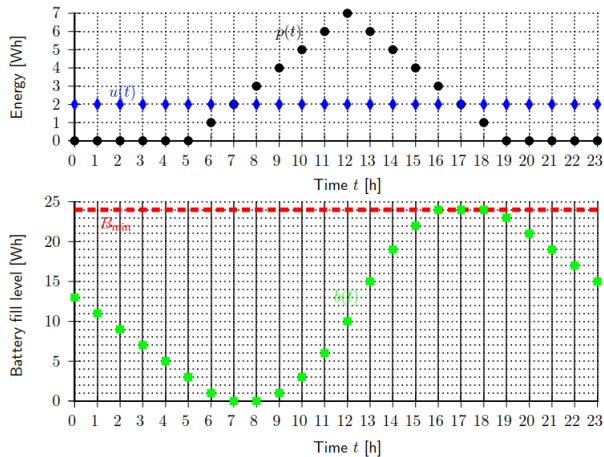
### Solution 3.2:



- ▶ The energy used during night, where the harvested energy is *lower* than the consumed energy, is:  $1\text{Wh} + 11 \cdot 2\text{Wh} + 1\text{Wh} = 24\text{Wh}$
- ▶ We need at least this much energy in our battery to compensate this deficit, meaning  $B \geq 24\text{Wh} \Rightarrow B_{\min} = 24\text{Wh}$ .

# Task 3 I

## Application control



# Task 3 II

## Application control

### Sidenote 🔍

- ▶ We observe that in intervals  $t \in [0, 6]$  and  $t \in [18, 23]$  of a day  $u(t) > p(t)$  and therefore energy is used from the battery. In intervals  $t \in [7, 17]$  the battery is not used and the extra input power of intervals  $t \in [8, 16]$  is stored to the battery, with the battery overflowing in interval  $t = 16$ .