EASY-RES

SUMMER SCHOOL
"ENABLING DRES TO OFFER ANCILLARY SERVICES"
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THE ROLE OF FRR FOR THE MITIGATION OF POWER IMBALANCES AND THE NEED FOR RRL AS A PREVENTIVE ACTION IN DISTRIBUTION GRIDS

Kyriaki – Nefeli Malamaki // Tuesday, September 21st

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Presentation Outline

- Ramp-Rate Limitation (RRL) as an Ancillary Service (AS) – Preventive action towards the commitment of FCR and FRR in weak and stiff networks.
- RRL Grid Codes and Need for proper Definition
- The EASY-RES approach for RRL at DRES and distribution grid level using Ultracapacitors and Battery ESS.
  - ✓ Experimental Results
  - ✓ Comparison with State-of-the art power smoothing control approaches and Energy Storage System (ESS) sizing via simulations
  - ✓ RRL activation

Variability of Wind and PV Power

- Renewable Energy Sources (RES) like the PVs or Wind Turbines depend on primary energy sources (renewable “fuel”: sun, wind), which are highly variable, due to their stochastic nature.
- This causes intermittent RES production.
- Both Wind and PV power are variable (or non-dispatchable) because they are available not upon demand, but upon natural and uncontrollable forces.
- Both of them have LOW capacity value.

Variability of Wind and PV Power

- Currently, due to new forecasting models, wind generation and solar PV generation can be predicted with really good accuracy.
- However, predictable variation is still…variable … posing several instability issues to the electric power systems.

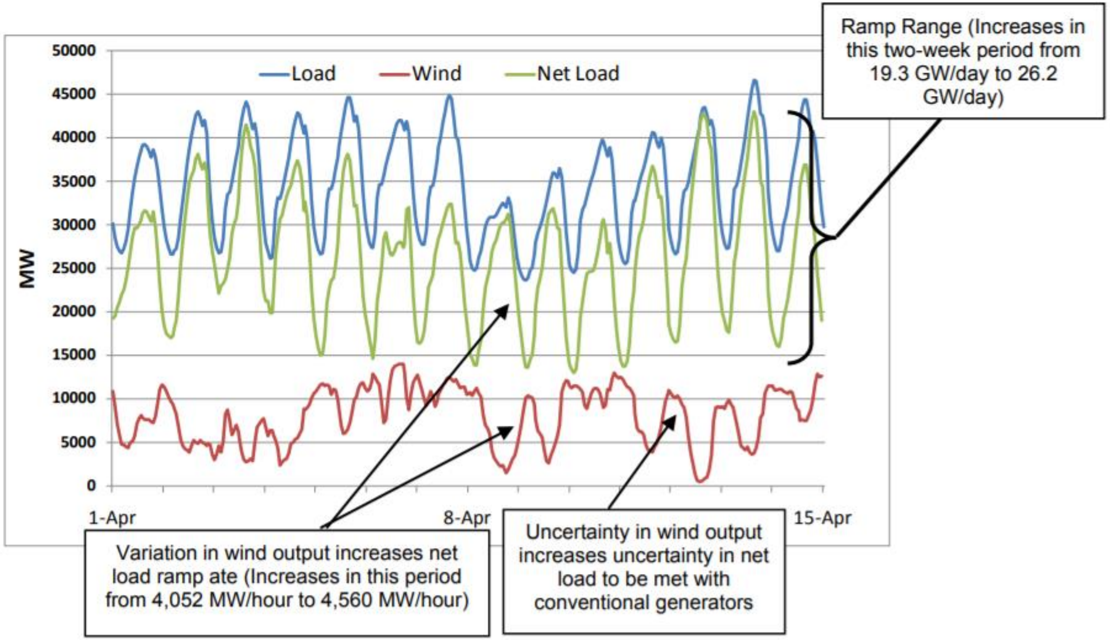


Figure: Impact of net load from increased use of renewable energy **[1]**

Variability of Wind and PV Power

- The increased RES intermittency (variability) and the decrease of the base load lead the System Operators to commit conventional rotating resources in their systems and greater investment in flexible ramping resources is required

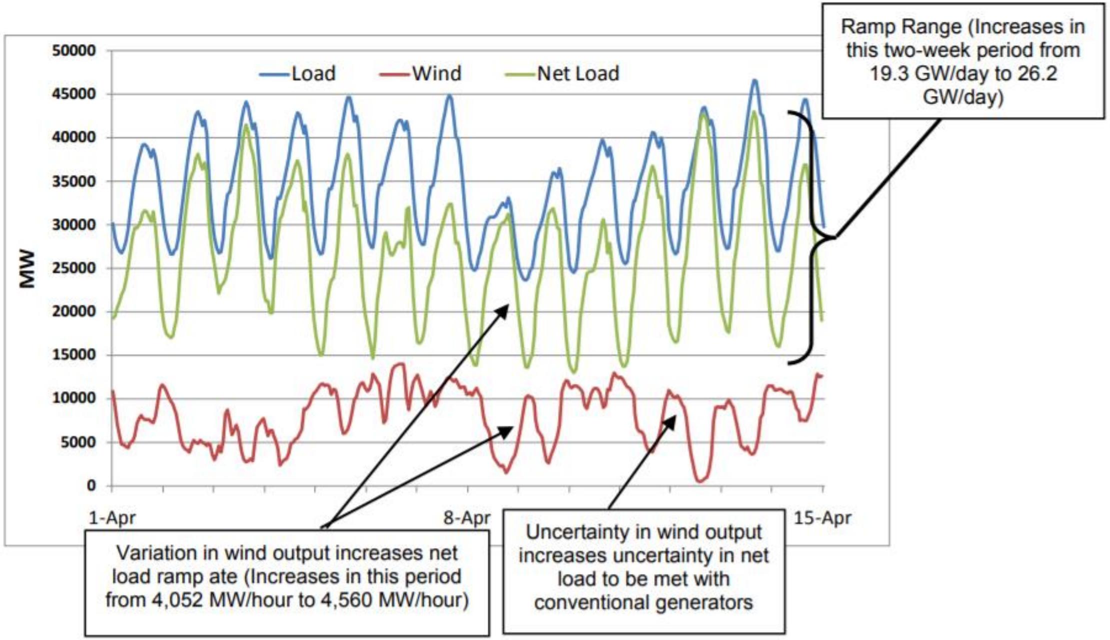


Figure: Impact of net load from increased use of renewable energy **[1]**

Why is RRL needed?

- The intermittent RES with high, unpredicted short-term ramp rates can become more "grid-friendly" by providing "flexible ramping".
- Ramp Ups can be easily mitigated by RES with Active Power Curtailment. This is undesired … due to revenue loss.
- A system consisting of an intermittent RES and an Energy Storage System (ESS) can provide flexible ramping: based on the RES+ESS size, the injected grid power can increase or decrease with a specific predefined ramp-rate → provide flexible ramping!
- Such systems do not only provide flexible ramping … The ESS action can eliminate any day-ahead or intra-day forecast error of the RES generation!
- Why is this important? … The load and RES variability affects the day-ahead scheduling of FCR and FRR (especially aFRR)

Why is RRL needed?

The TSOs in each country schedule the committed FCR and FRR for the day-ahead and in some countries within the day (intra-day).

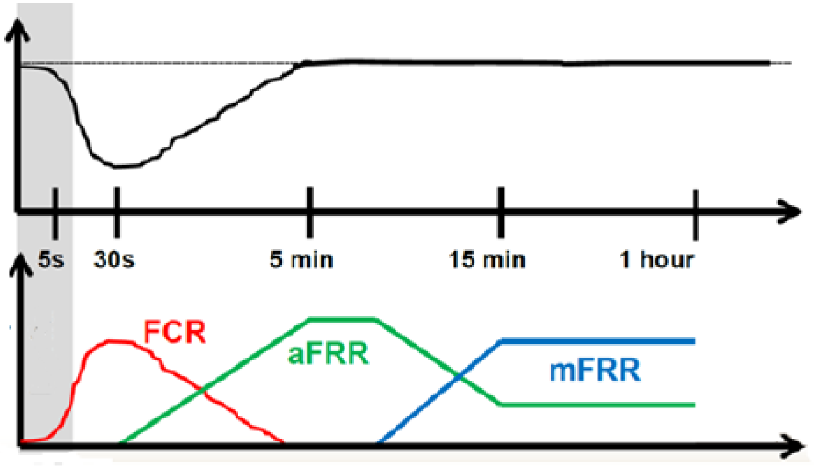


Figure: Activation of operating reserves after a frequency disturbance, **[3]**

Why is RRL needed?

In cases of high RoCoFs, the FCR committed units take action, leading the frequency to stabilize to a value higher or lower than the nominal frequency.

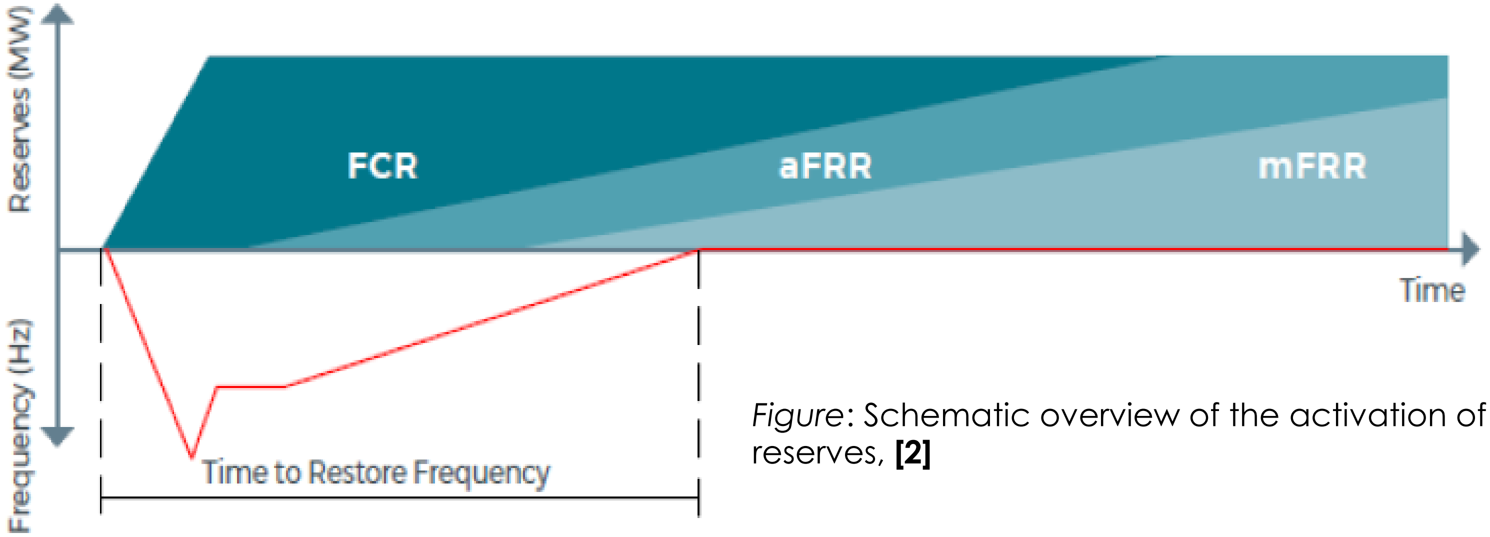
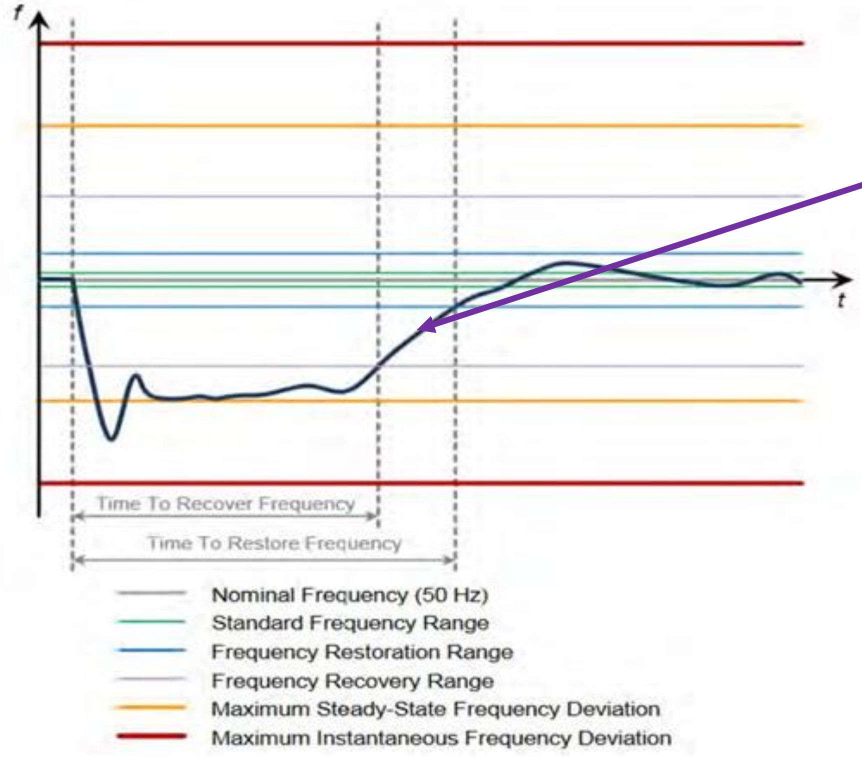


Figure: Schematic overview of the activation of operating reserves, **[2]**



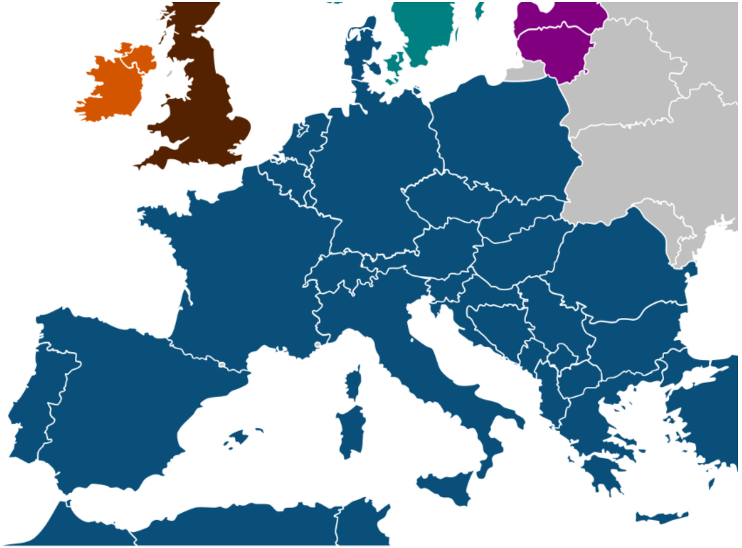
FRR is distinguished in automatic (aFRR) and manually (mFRR) activated. The mixture of aFRR/mFRR is determined by each TSO for his control area/block so that the frequency quality criteria are fulfilled.

After a major frequency event, the FRR not only restores the frequency within the restoration range but also restores the FCR that have exhausted and finally restores the cross-border power flows of the relevant control area to its pre-fault values.
This is depicted in the two terms of the ACE.

$$ACE_i = \sum_j \Delta P_{i,j} + \beta_i \cdot \Delta f$$

RRL in Stiff Networks

- In stiff transmission systems, the equivalent system inertia (**Part 1**) is large, hence, a power imbalance **ΔP** between generation and demand, as well as short-term (in terms of 5-10 seconds) variations of RES hardly affect the global frequency and the RoCoF.
- In emergency conditions FCR units are needed to support the stiff networks



- FRR units are committed to reduce the error between the nominal frequency and the new stable frequency. The units which take action first are the aFRR committed units (with flexible ramping) within 30 seconds.
- However, high RoCoFs and huge disturbances are rare within stiff networks …

During steady-state operation within a synchronous area, Δf is practically zero. Therefore, the ACE (thereby the FRR) has to do with the restoration of the power interchanges among areas to predefined and agreed values.

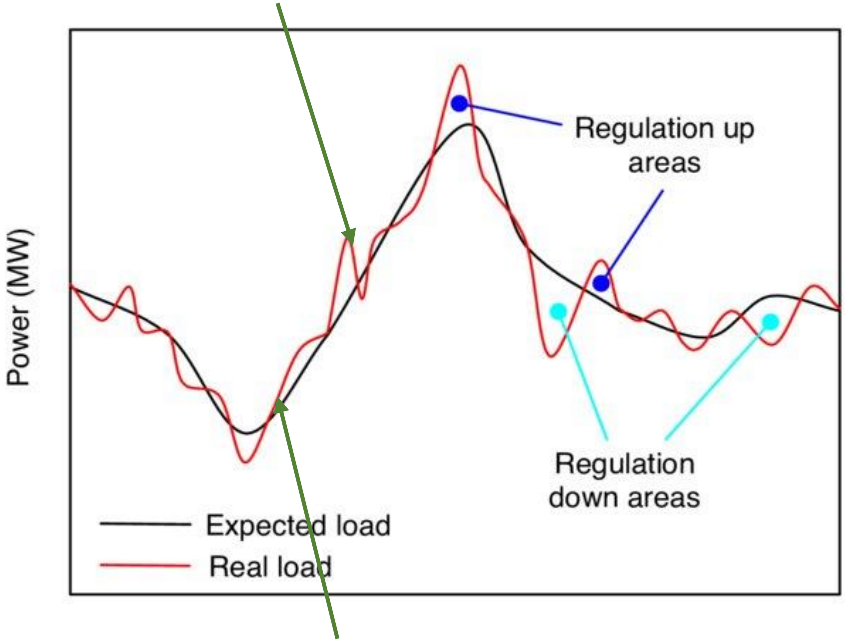
The power interchanges deviate due to errors in forecasting of

- Load
- Power generated by RES

and also, by probable faults like loss of a local generating unit, or of a tie line.

$$ACE_i = \sum_j \Delta P_{i,j} + \beta_i \cdot \Delta f$$

aFRR is used to deal with the fast variations in the scheduled load/generation



mFRR is used to deal with the slower variations in the scheduled load/generation

RRL in Stiff Networks

- The usual case is that low RoCoFs happen every day and there are small oscillations around the nominal frequency, due to errors in the short-term forecast.
- These short-term variations usually activate the aFRR units, which are more expensive than mFRR.

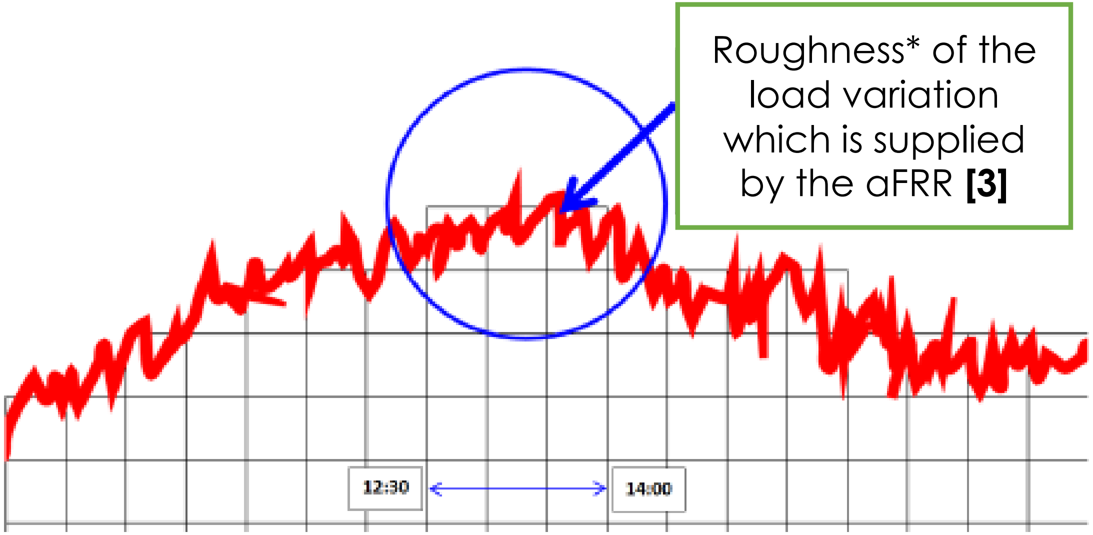
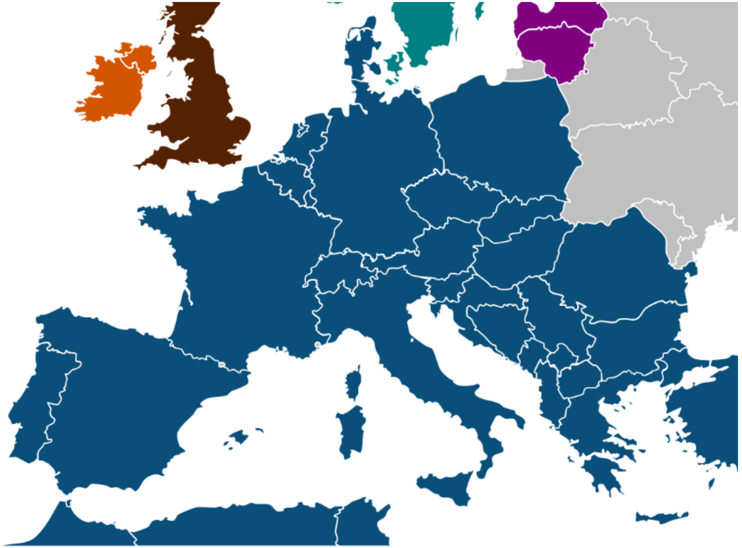


Figure: Real Variation Of Load Demand, **[3]**

*The term "roughness" describes the continuous random load variation that resembles white noise

RRL in Stiff Networks

- By having a coordinated RES+ESS RRL control action, the flexible ramping generation is assured while any short-term forecast error can be easily mitigated!
- In this way, short-term frequency oscillations and the aFRR activation can be avoided →
- This in turn would lead to fewer costs in the scheduling for the conventional unit commitment.



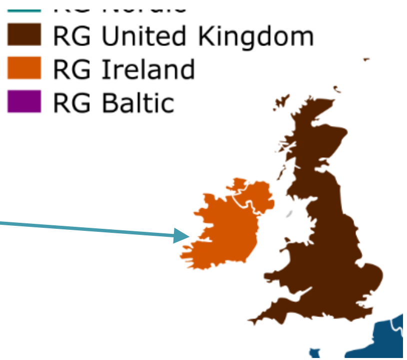
RRL in Weak Networks

- Weak systems suffer from low equivalent system inertia (**Part 1**) and a power imbalance **ΔP** between load and generation or an error in the RES forecast together with the high penetration of intermittent RES with high **dP/dt** could cause large frequency disturbances – high RoCoF
- In turn, cause huge commitment of both FCR and FRR → FCR in order to avoid large RoCoFs in the short-term mismatch forecast errors
- This is why it is an already established requirement for the installation of new RES plants

RRL in Weak Networks - Examples

- **Puerto Rico** has set the Minimum Technical Requirements (MTR) **[4]**

- EirGrid and SONI (**Irish** TSOs) have also defined RRL in their mutual interconnections **[5]**



RRL in the Grid Codes and Identified Gaps

System Operators: Specifications for the limitation of the Ramp-Rate (RR) at the Point of Common Coupling (PCC) of the DRES with the grid

- for DRES with nominal Power >1MW
- Especially in weak Transmission Systems

Identified Gaps:

- currently only ramp-ups can be mitigated efficiently by individual RES plants (without ESS) by performing Active Power Curtailment
- there is **no unified definition** of RR considering either the time-interval Δt or the power variation ΔP, **[6]**
- No specifications for RES with nominal power below 1MW → The RR Limitation (RRL) is currently vague at distribution level, **[6]**

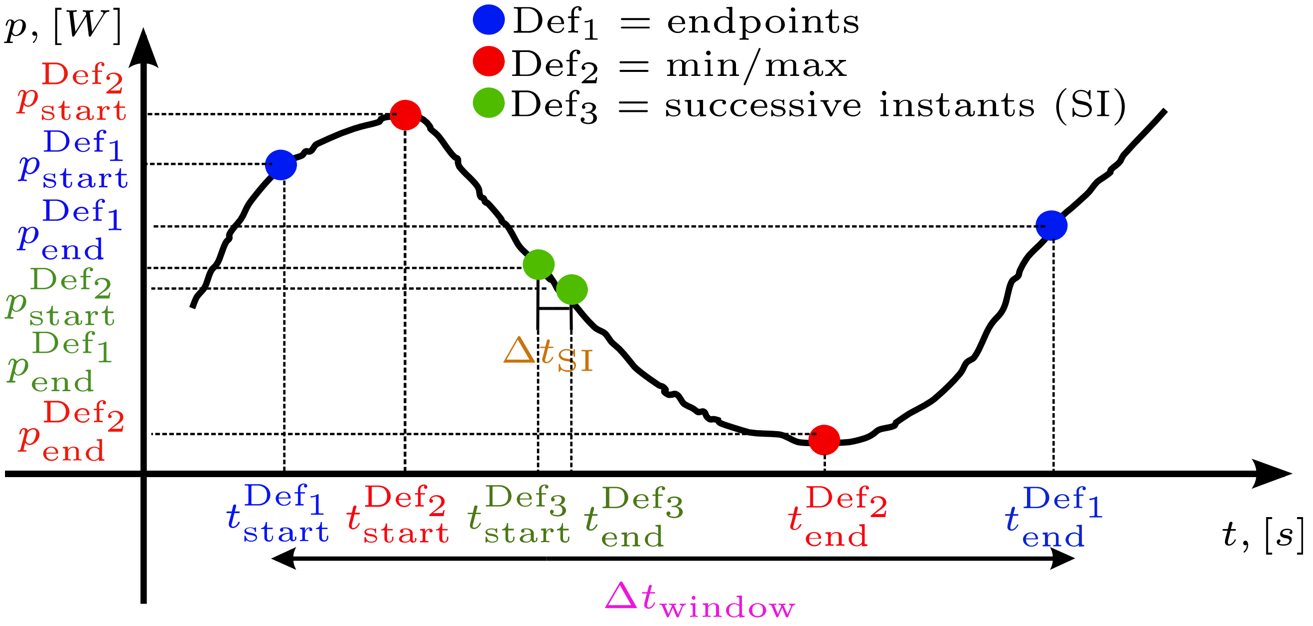
Country/TSO	RRL Requirements
HECO (Hawaii)	2 MW/min, 1 MW/2sec (inst.)
PREPA (Puerto Rico) Germany Romania	10%/min
EIRGRID (Ireland)	1-30 MW/min (1min average) 1-30 MW/min (10min average)
England & Wales NGC	*A*. No limit for ΔP of up to 300MW *B*. 50MW/min for ΔP between 300-1000MW *C*. 40MW/min for ΔP > 1000MW
Scotland	*A*. No limit for a change of up to 15MW *B*. 15MW to 150MW: *i*) 20% of the rated power/min (1-min average) *ii*) 7% of the rated power/min (10-min average) *C*. Over 150MW: *i*) 30MW/min (1-min average) *ii*) 10MW/min (10-min average)
Australia (AEMO)	Set by the TSO, at least 3MW/min or 3%
Australia (WP)	Set by the TSO, not less than 5%/min
Denmark (Energinet)	Set by the TSO, 10-100%/min
China SGCC	*A*. For WF capacity below 30MW *i*) 2MW/min (10-min average) *ii*) 6MW/minute (1-minute average) *B*. For WF capacity between 30 to 150MW: *i*) $P_{rated}/1.5$ (10-min average) *ii*) $P_{rated}/5$ (1-min average) *C* For WF capacity over 150MW *i*) 100MW/min (10-min average) *ii*) 30MW/min (1-min average)
India	*A*. No limit for a change of up to 50MW *B*. For WF capacity between 50 to 150MW: *i*) $P_{rated}/1.5$ (10-min average) *ii*) $P_{rated}/5$ (1-min average) *C*. For WF capacity over 150MW *i*) 100MW/min (10-min average) *ii*) 30MW/min (1-min average)

[6] EASY-RES Deliverable 1.1; Available online:

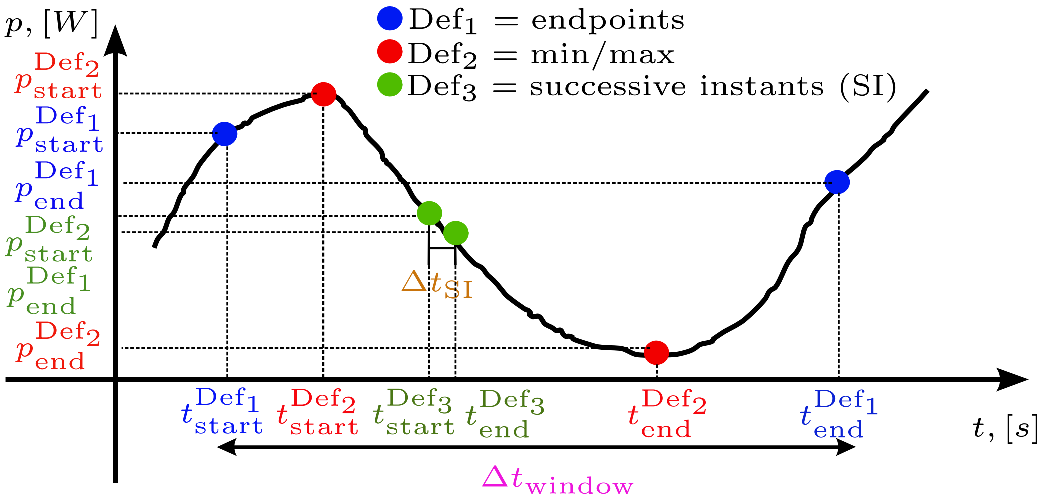
State-of-the-Art RRL Definitions 1

Key Characteristics:

- ✓ Direction: upward and downward
- ✓ Magnitude
- ✓ Duration → Need for the proper definition of past and current instants



State-of-the-Art RRL Definitions 2 **[7]**



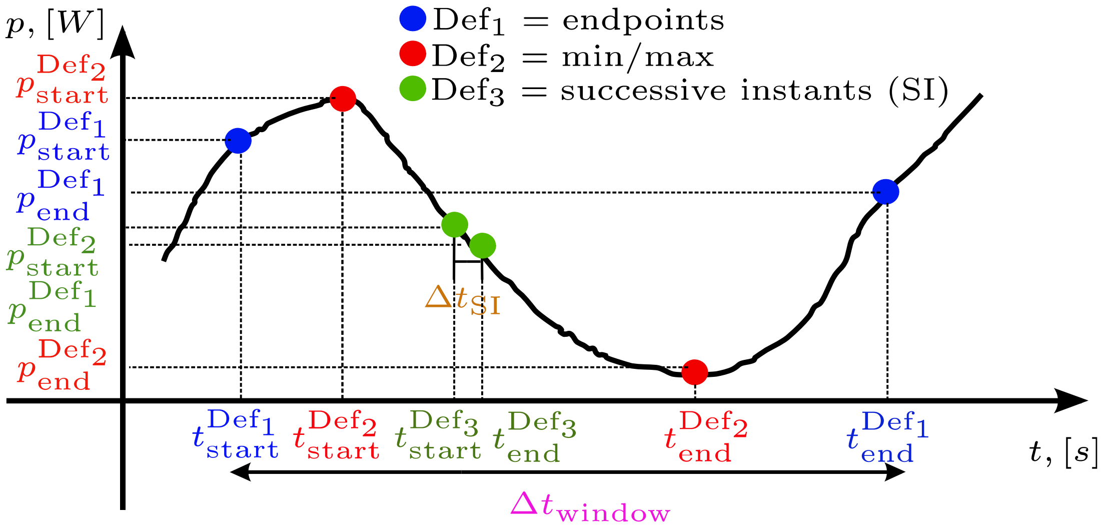
Definition 1: difference between two endpoints of a $\Delta t_{\mathrm{window}}$ interval (typical values 1 minute or 10 minutes)

$$RR_{\mathrm{Def}_1}[t] = \frac{p_{\mathrm{out}}[t + \Delta t_{\mathrm{window}}] - p_{\mathrm{out}}[t]}{\Delta t_{\mathrm{window}}}$$

Definition 2: difference between the maximum and minimum values within a $\Delta t_{\mathrm{window}}$ interval

$$RR_{\mathrm{Def2}}[t] = \frac{\max_{p_{\mathrm{out}}[t+\Delta t_{\mathrm{window}}],p_{\mathrm{out}}[t]} - \min_{p_{\mathrm{out}}[t+\Delta t_{\mathrm{window}}],p_{\mathrm{out}}[t]}}{t_{\max} - t_{\min}}$$

State-of-the-Art RRL Definitions 3 **[7]**



Definition 3: difference between two successive measurements (instants Δt_{SI}) – usually 1 second

$$RR_{\mathrm{Def}_3}[t] = \frac{p_{\mathrm{out}}[t + \Delta t_{\mathrm{SI}}] - p_{\mathrm{out}}[t]}{\Delta t_{\mathrm{SI}}}$$

RRL Definitions 4 - Example

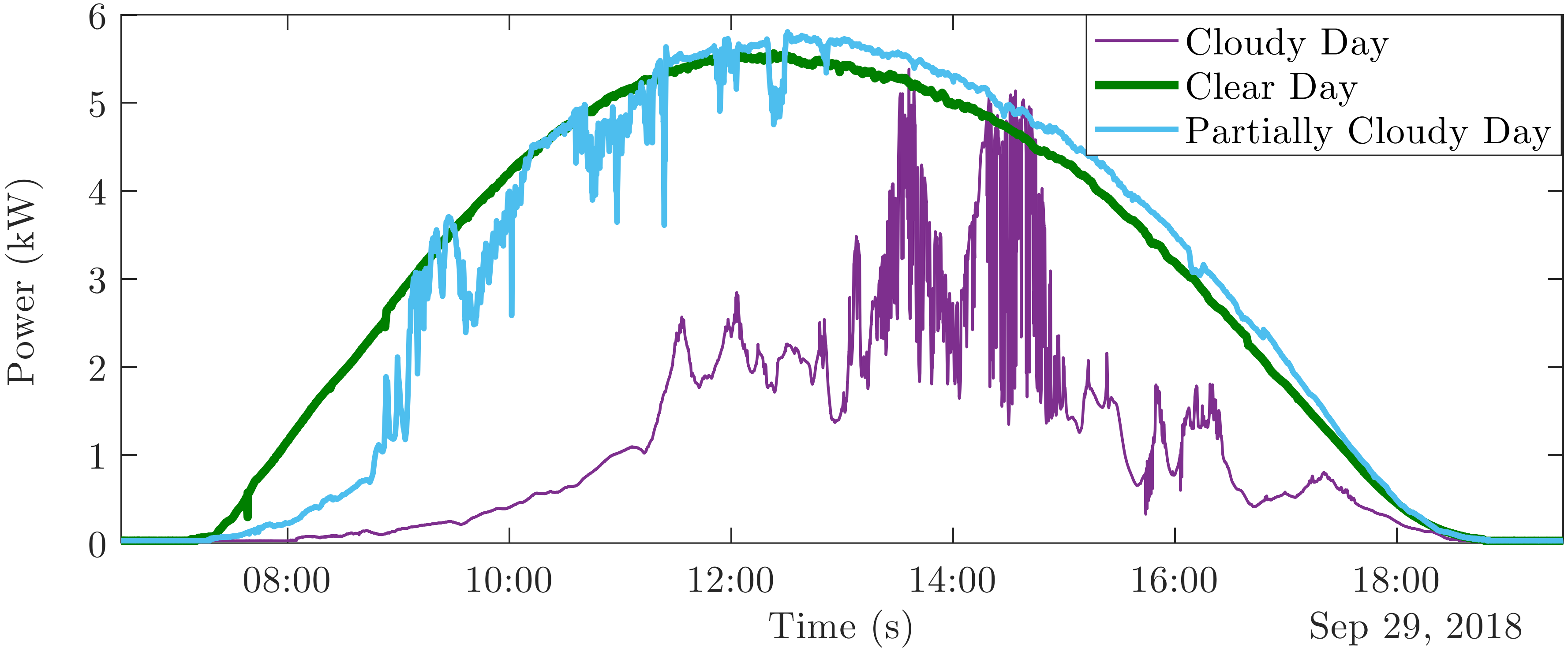
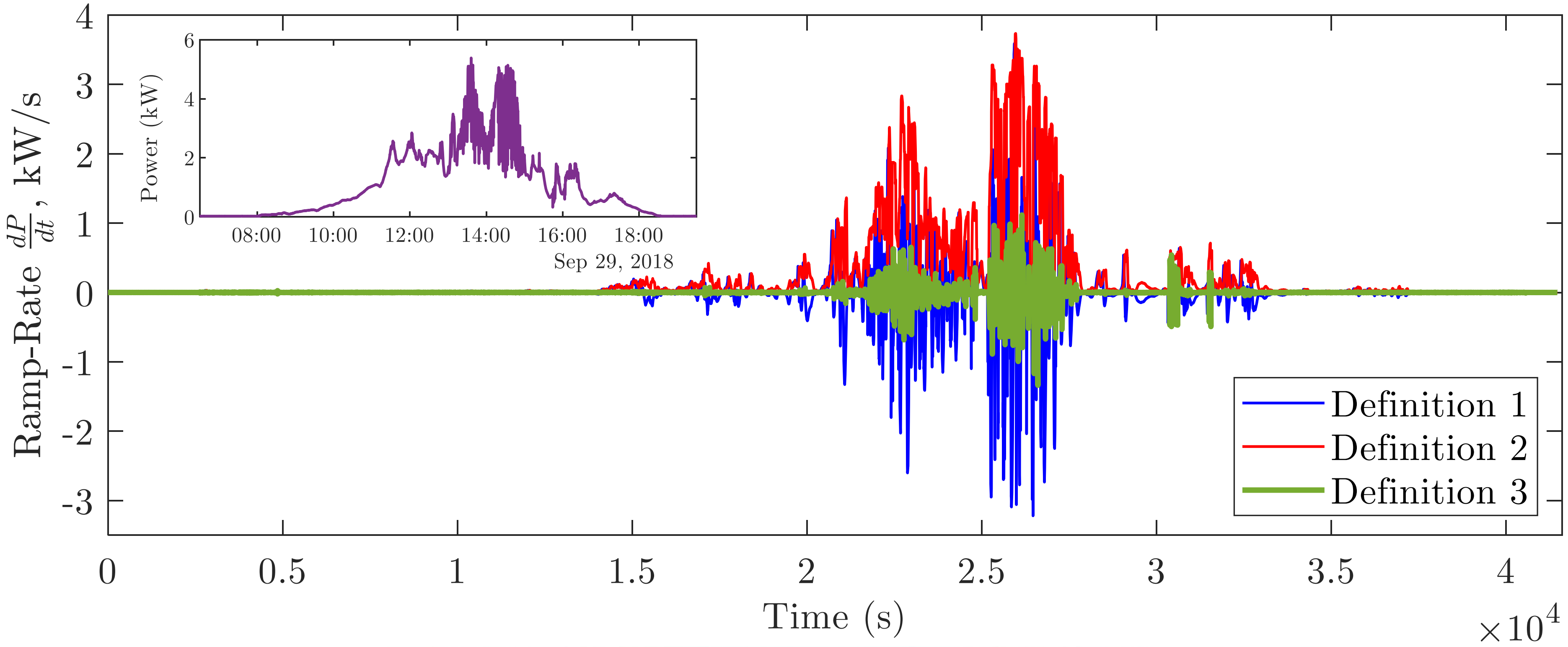
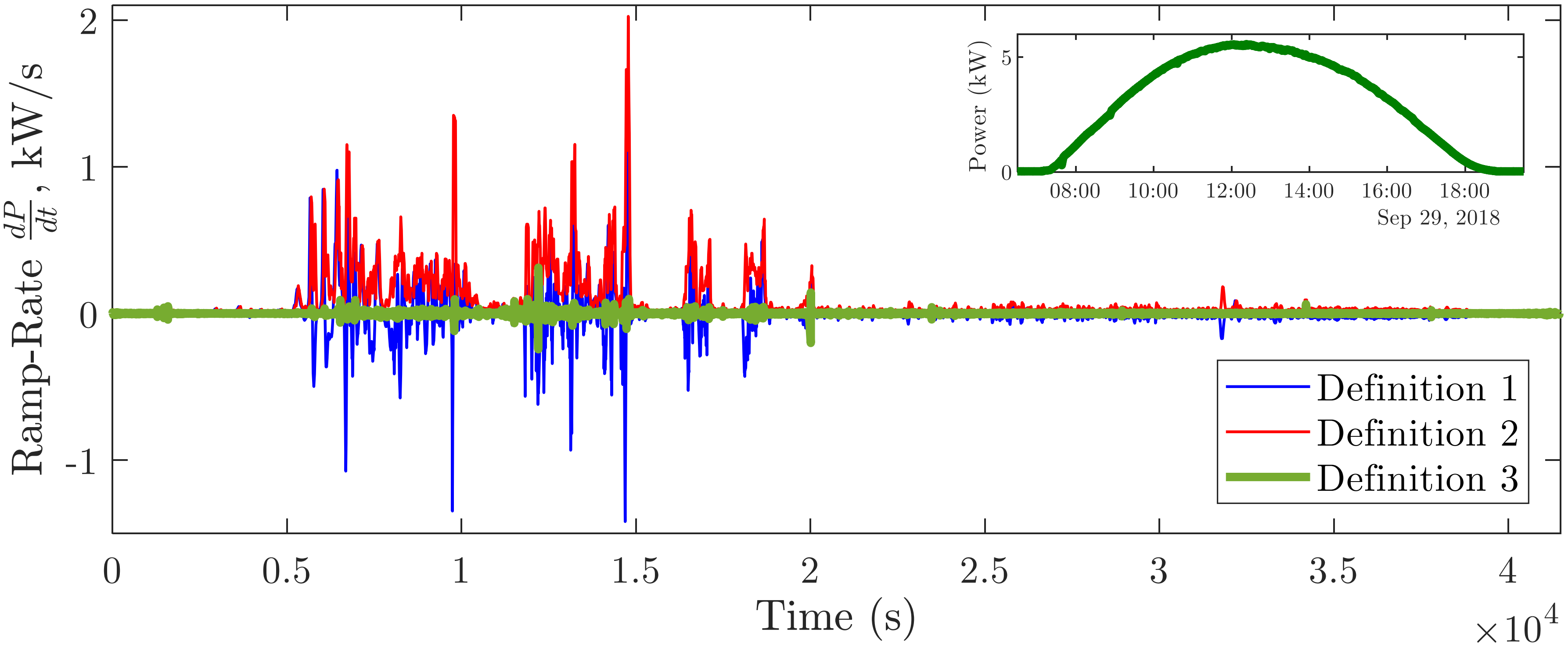


Figure: Daily PV Profiles of a 6.5kWp PVPP, **[8]**

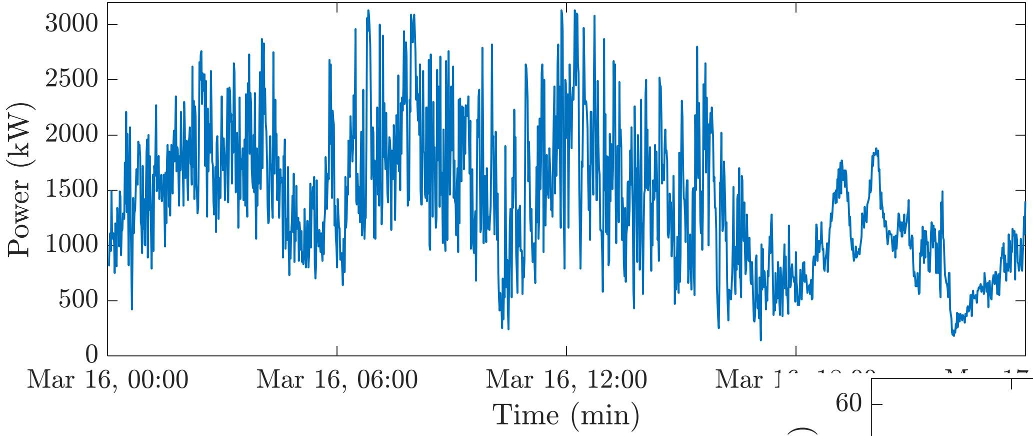
RRL Definitions 5 – Example Cloudy Day

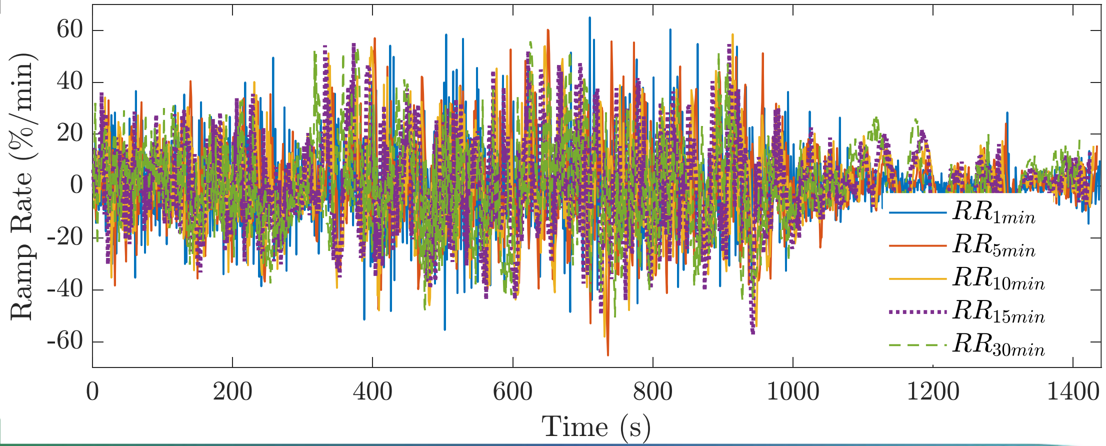


RRL Definitions 7 – Example Clear Day



RRL Definitions 8 – Example Wind Turbine





State-of-the-Art RRL Control Methods 1

RRL Control Categories:

RRL is performed considering that the DRES is connected to an Energy Storage System (ESS), **[7]-[10]**:

- Moving Average (MA) Methods
- Filter-Based (FB) Methods, e.g., Low-Pass Filter, Band-Pass Filter
- Direct RRL Methods

State-of-the-Art RRL Control Methods 2

RRL Control Categories:

RRL is performed considering that the DRES is connected to an Energy Storage System (ESS), **[7]-[10]**:

- Moving Average (MA) Methods
- Filter-Based (FB) Methods, e.g., Low-Pass Filter, Band-Pass Filter
- Direct RRL Methods

Disadvantages – MA &FB

- high computational complexity
- exhibition of ``memory effect'' and oversmoothing
  - the ESS is forced to operate even when the DRES RR is within specific limits
  - Increased ESS capacity
  - Decreased ESS operating life

State-of-the-Art RRL Control Methods 3

RRL Control Categories:

RRL is performed considering that the DRES is connected to an Energy Storage System (ESS) **[7]-[10]**:

- Moving Average (MA) Methods
- Filter-Based (FB) Methods, e.g., Low-Pass Filter, Band-Pass Filter
- Direct RRL Methods

Gaps in the RRL approaches

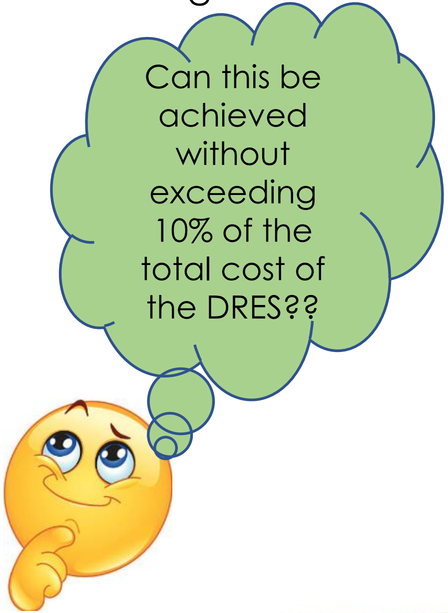
- BESS with slower dynamics → not suitable for high-frequency fluctuations at DRES level
- The State-of-Charge (SoC) is taken into account a-posteriori
  - do not guarantee that RR can be limited exactly to the prescribed level;
  - new RRL techniques should be developed to reduce the significant RRs at specific values

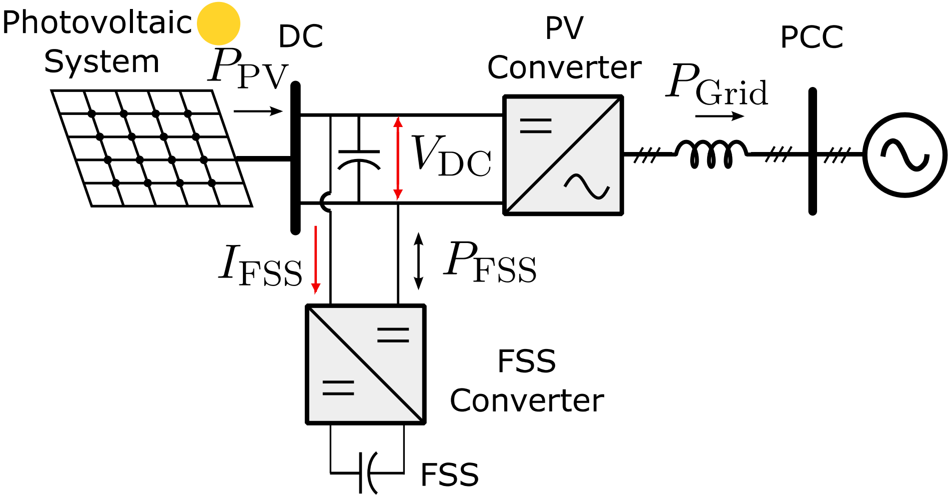
EASY-RES RRL Concept

RRL is defined at DRES and substation level

- At DRES level the UVSG limits the ramp rate of the DRES power using as a Fast-acting ESS (FSS) a Ultracapacitor. The FSS is placed at the DC-link of a DRES converter. The initial target RRL is

$$\frac{\Delta P}{\Delta t} = \frac{30\% P_{\text{DRES-nom}}}{\text{minute}}$$



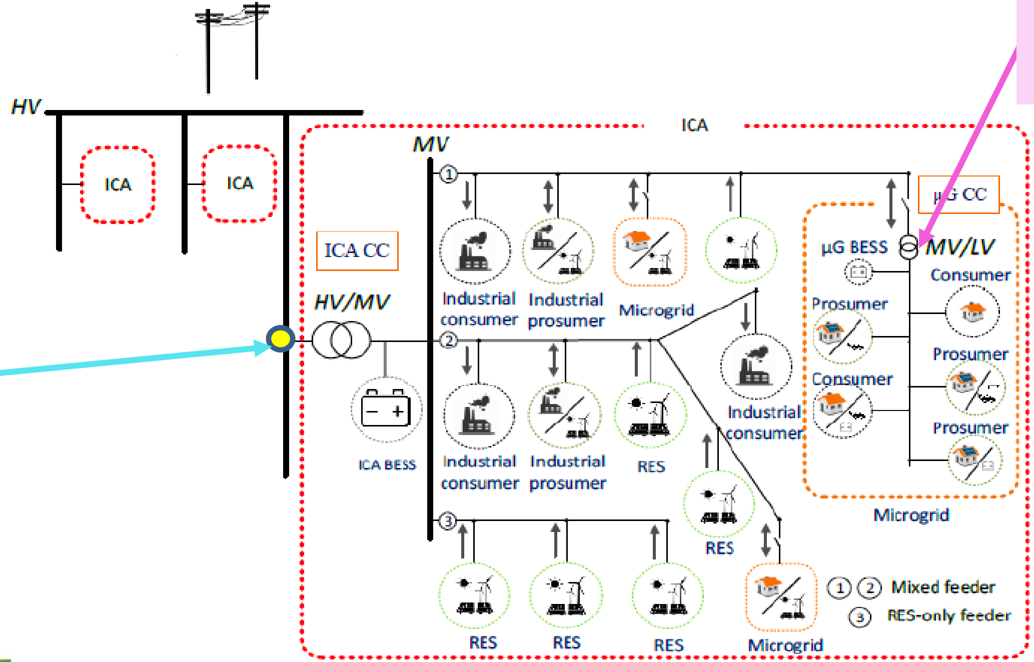


EASY-RES RRL Concept

RRL is defined at DRES and substation level

➢ A Battery ESS is assumed to be placed at MV/LV substation level and at HV/MV substation level.

$$\frac{\Delta P}{\Delta t} = \frac{10\% S^{\mathrm{MV/LV}}_{\mathrm{TR\text{-}nom}}}{\mathrm{minute}}$$

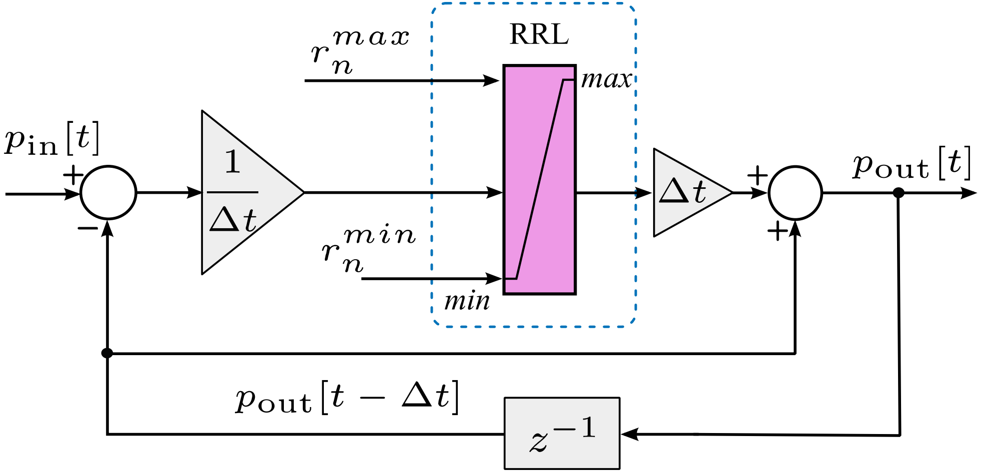


$$\frac{\Delta P}{\Delta t} = \frac{10\% S^{\mathrm{HV/MV}}_{\mathrm{TR\text{-}nom}}}{\mathrm{minute}}$$

EASY-RES Approach

EASY-RES RRL Control – General Structure

$$RR_{\text{2-point-calc}}[t] = \frac{p_{\text{out}}[t] - p_{\text{out}}[t-\Delta t]}{t[t] - t[t-\Delta t]}$$



Use of **Definition 3** for the RR calculation: Given the DSO/TSO RRL limit in % of nominal power per minute, RRL_{nom}, $r_n = RRL_{nom} \cdot P_{nom}/60$ [W/s]

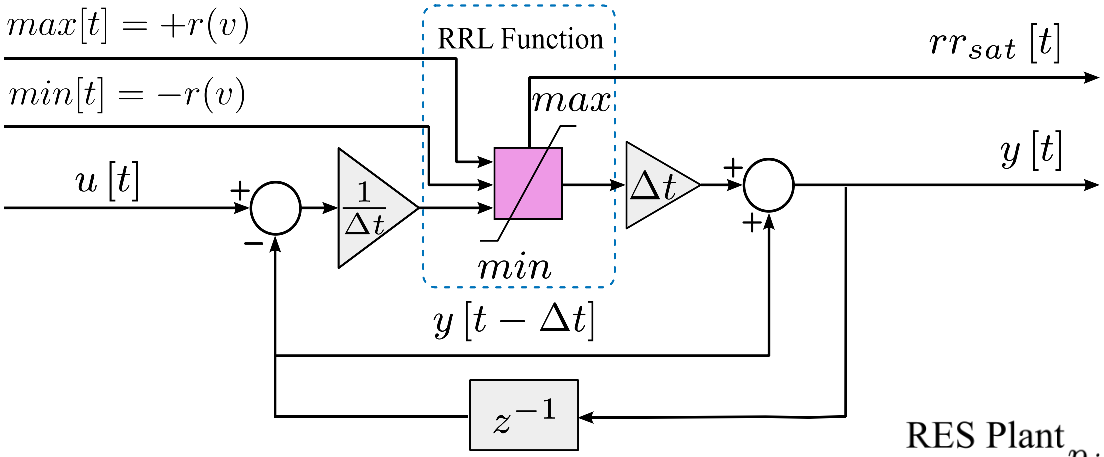
Example: for a PV with 10kWp, 10%/min is 1kW/min, hence, 16.66W/s

Algorithm 1 RRL Function

Require: act, $p_{\text{in}}[t]$, $p_{\text{out}}[t-\Delta t]$, r_n^{min}, r_n^{max}, Δt
Ensure: $p_{\text{out}}[t]$, $p_{\text{ESS, ref}}[t]$

$RR_{\text{2-point-calc}} \leftarrow \frac{p_{\text{in}}[t] - p_{\text{out}}[t-\Delta t]}{\Delta t}$
$p_{\text{ESS, calc}}[t] \leftarrow p_{\text{in}}[t] - p_{\text{out}}[t-\Delta t]$
if $act = 1$ **then**
  if $RR < r_n^{min}$ **then**
    $RR \leftarrow r_n^{min}$
  else if $RR > r_n^{max}$ **then**
    $RR \leftarrow r_n^{max}$
  else
    $RR \leftarrow RR_{\text{2-point-calc}}$
  end if
  $p_{\text{out}}[t] \leftarrow RR \cdot \Delta t + p_{\text{out}}[t-\Delta t]$
  $p_{\text{ESS, ref}}[t] \leftarrow p_{\text{in}}[t] - p_{\text{out}}[t]$
else
  $p_{\text{out}}[t] \leftarrow p_{\text{in}}[t]$
  $p_{\text{ESS, ref}}[t] \leftarrow 0$
end if

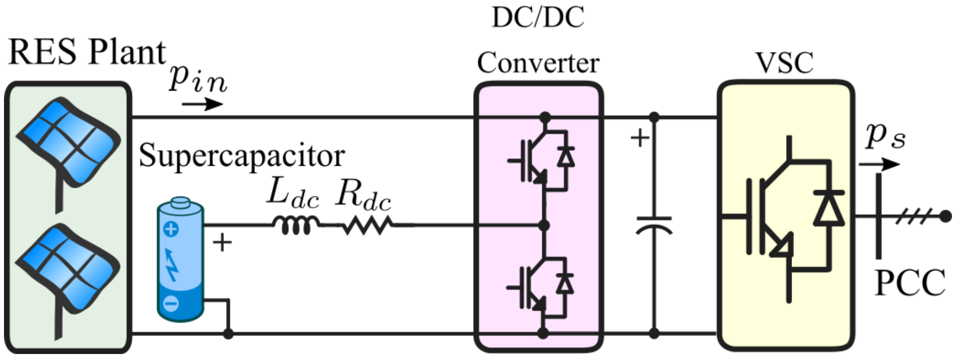
EASY-RES RRL Control: Ultracapacitor at DRES level



Ultracapacitor: performs 3 Ancillary Services - Simultaneously

- Inertial Response
- Fault-Ride-Through and Contribution to Fault-Clearing
- RRL

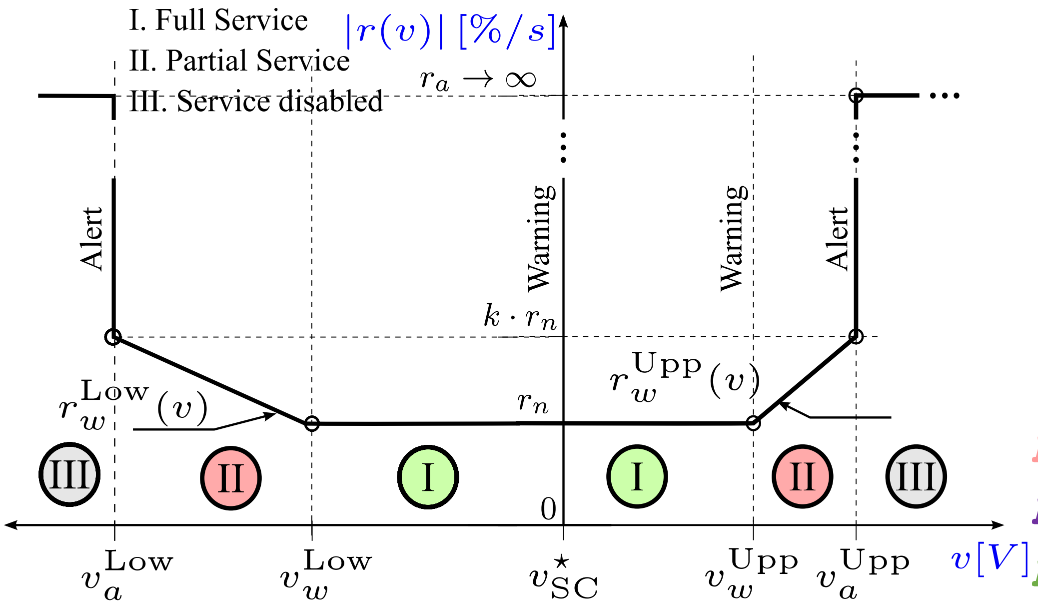
Ultracapacitor: Its energy recovery control should return its voltage to its reference value, **[11], [12]**



EASY-RES RRL Control: Ultracapacitor at DRES level **–[11]**

$$E_{\text{used}} = \frac{1}{2} \cdot C \cdot (v_{\max}^2 - v_{\min}^2)$$

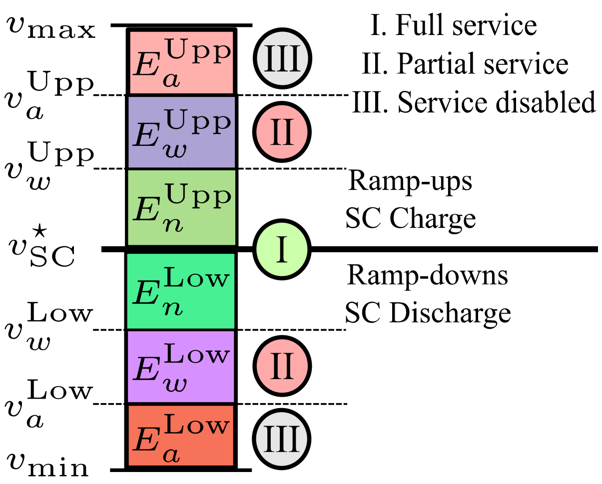
$$\text{SoC} = \frac{v_{SC}^2 - v_{\min}^2}{v_{\max}^2 - v_{\min}^2}$$



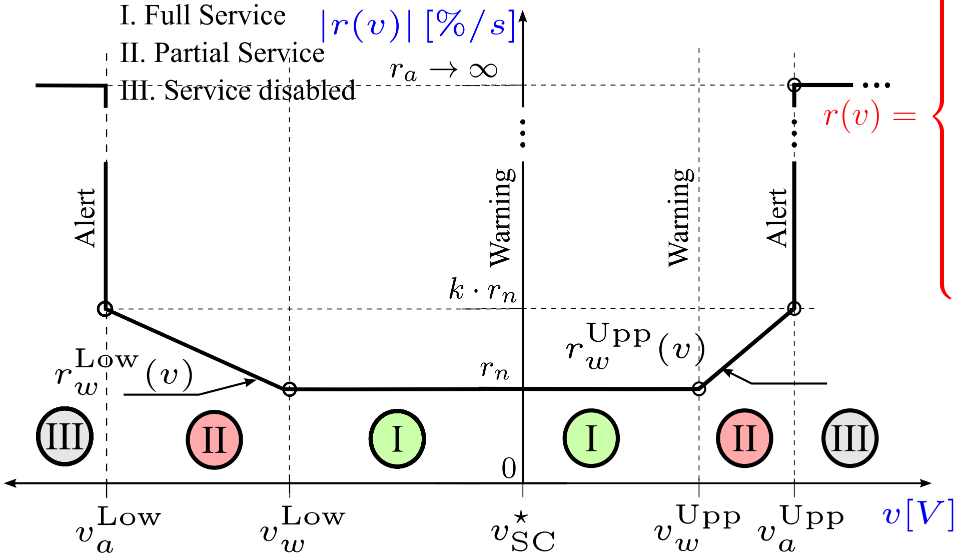
$E_a^{\text{Upp}} = E_a^{\text{Low}}$

$E_w^{\text{Upp}} = E_w^{\text{Low}}$

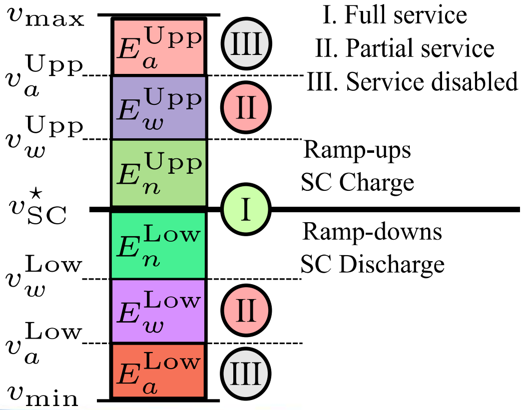
$E_n^{\text{Upp}} = E_n^{\text{Low}}$



EASY-RES RRL Control: Ultracapacitor at DRES level **–[11]**

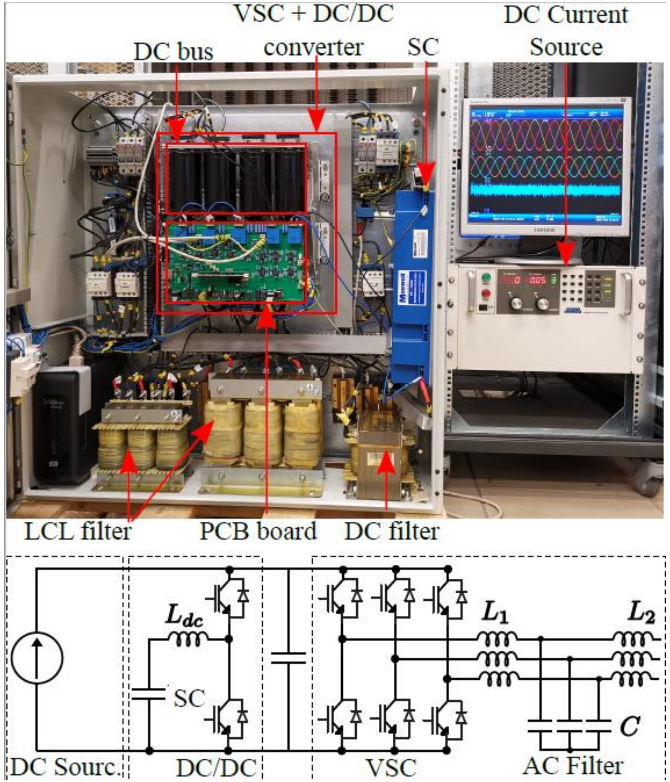


$$r(v) = \begin{cases} k \cdot r_n, & \text{if } \left(v_a^{\mathrm{Upp}} \leq v\right) \\ r_w^{\mathrm{Upp}}(v) = r_n + r_n \cdot (k-1) \cdot \dfrac{v - v_w^{\mathrm{Upp}}}{v_a^{\mathrm{Upp}} - v_w^{\mathrm{Upp}}}, & \text{if } \left(v_w^{\mathrm{Upp}} \leq v \leq v_a^{\mathrm{Upp}}\right) \\ r_n, & \text{if } \left(v_{\mathrm{SC}}^{\star} \leq v \leq v_w^{\mathrm{Upp}}\right) \\ -r_n, & \text{if } \left(v_w^{\mathrm{Low}} \leq v \leq v_{\mathrm{SC}}^{\star}\right) \\ r_w^{\mathrm{Low}}(v) = -r_n + r_n \cdot (k-1) \cdot \dfrac{v - v_w^{\mathrm{Low}}}{v_w^{\mathrm{Low}} - v_a^{\mathrm{Low}}}, & \text{if } \left(v_a^{\mathrm{Low}} \leq v \leq v_w^{\mathrm{Low}}\right) \\ -k \cdot r_n, & \text{if } \left(v_a^{\mathrm{Low}} \leq v\right) \end{cases}$$



EASY-RES Approach – Experimental Validation

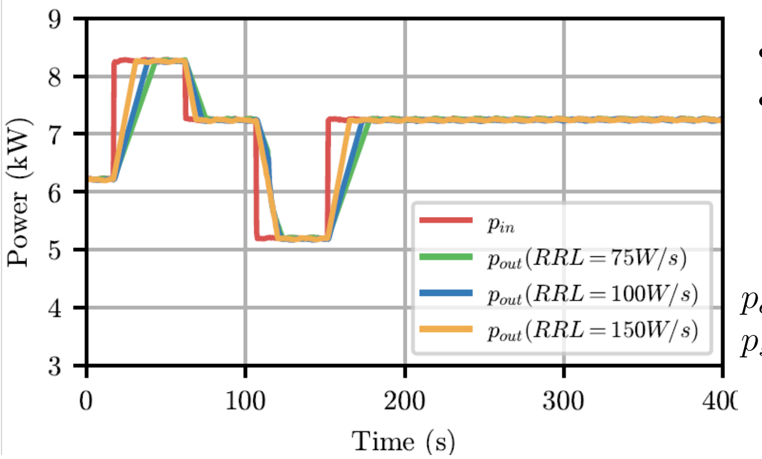
Ultracapacitor RRL: Experimental Results – Lab Set up



1. A 20 kVA three-phase three-wire VSC with $V_{DC}^{rated} = 750V$ and $V_{AC}^{rated} = 400V$
2. An SC of 6 F and 160 V, with maximum instantaneous power of 2kW and total SC energy is 21.33Wh (E_{used}= 9.33Wh for RRL control)
3. A controllable DC current source.
4. TMS320F28335 Delfino microcontroller with sampling frequency=20 kHz
5. Measuring Devices:
   i. SpeedGoat: sampling time 0.5 seconds
   ii. Oscilloscope: sampling time 50us

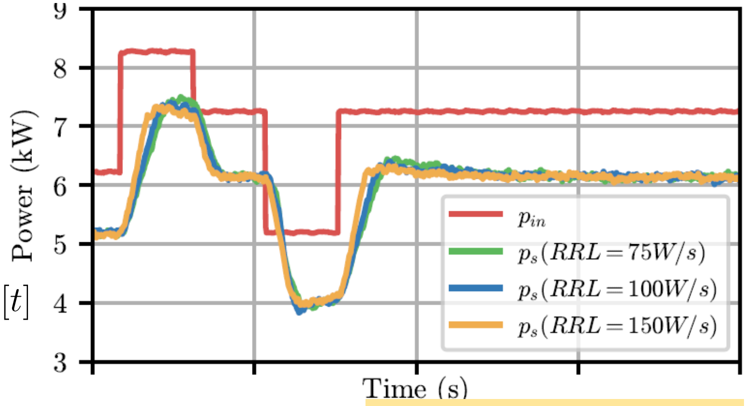
Further Description in **[12]**

Ultracapacitor RRL: Experimental Results – SpeedGoat



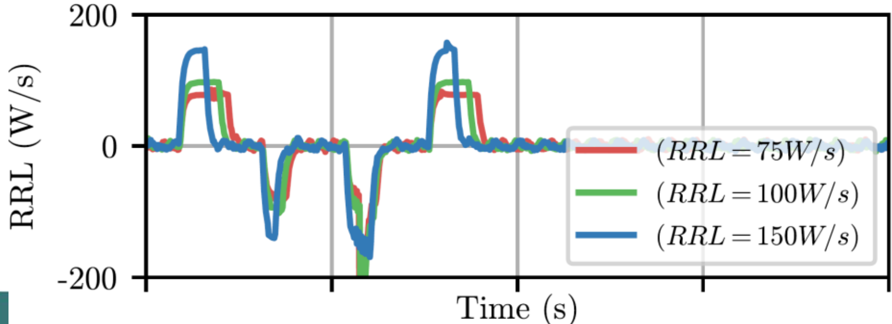
- $r_n = 75, 100, 150\ W/s$
- No Warning Area (k=1)

p_{in} : input power, $u[t]$
p_{out} : output RRL power, $y[t]$
p_s : grid-injected power



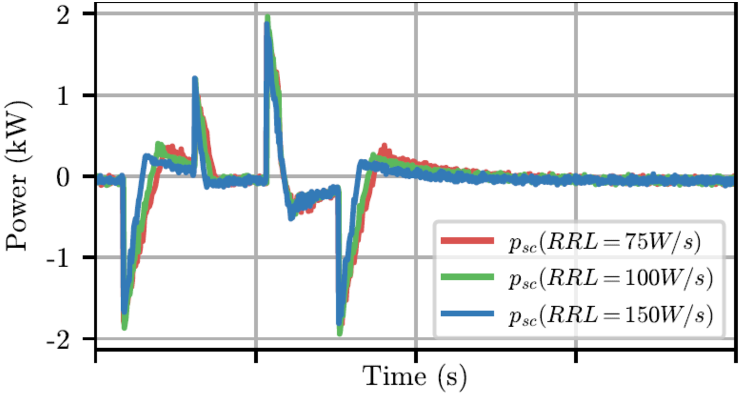
RRL Calculation with $\Delta t = 1s$

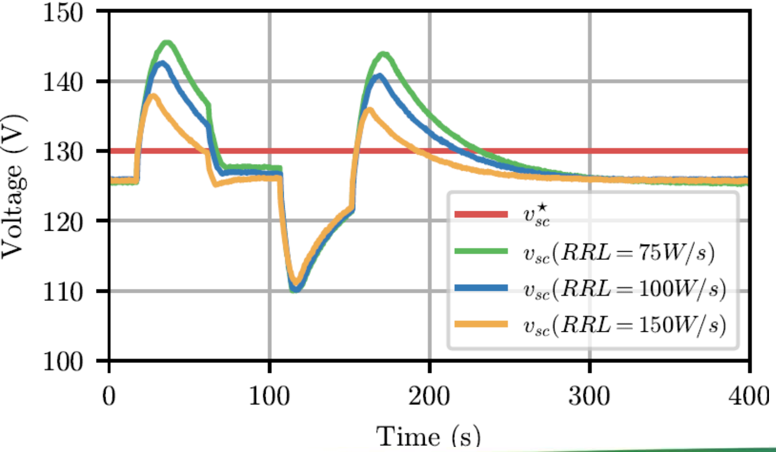
$$RR(t) = \frac{p(t) - p(t-1)}{t(t) - t(t-1)}$$

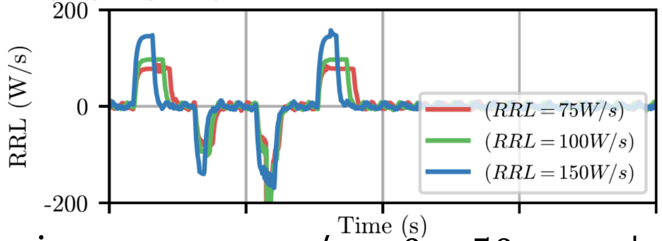


- ✓ the RRL control works perfectly and injects smoothed power to the grid.
- ✓ The lower the RRL r_n, the smoother is the p_s

EASY-RES Approach – Experimental Validation







Excellent operation during ramp-ups ($t = 0 - 50\,s$ and $t = 150 - 200\,s$) because the SC does not reach its power or voltage limits, i.e.:

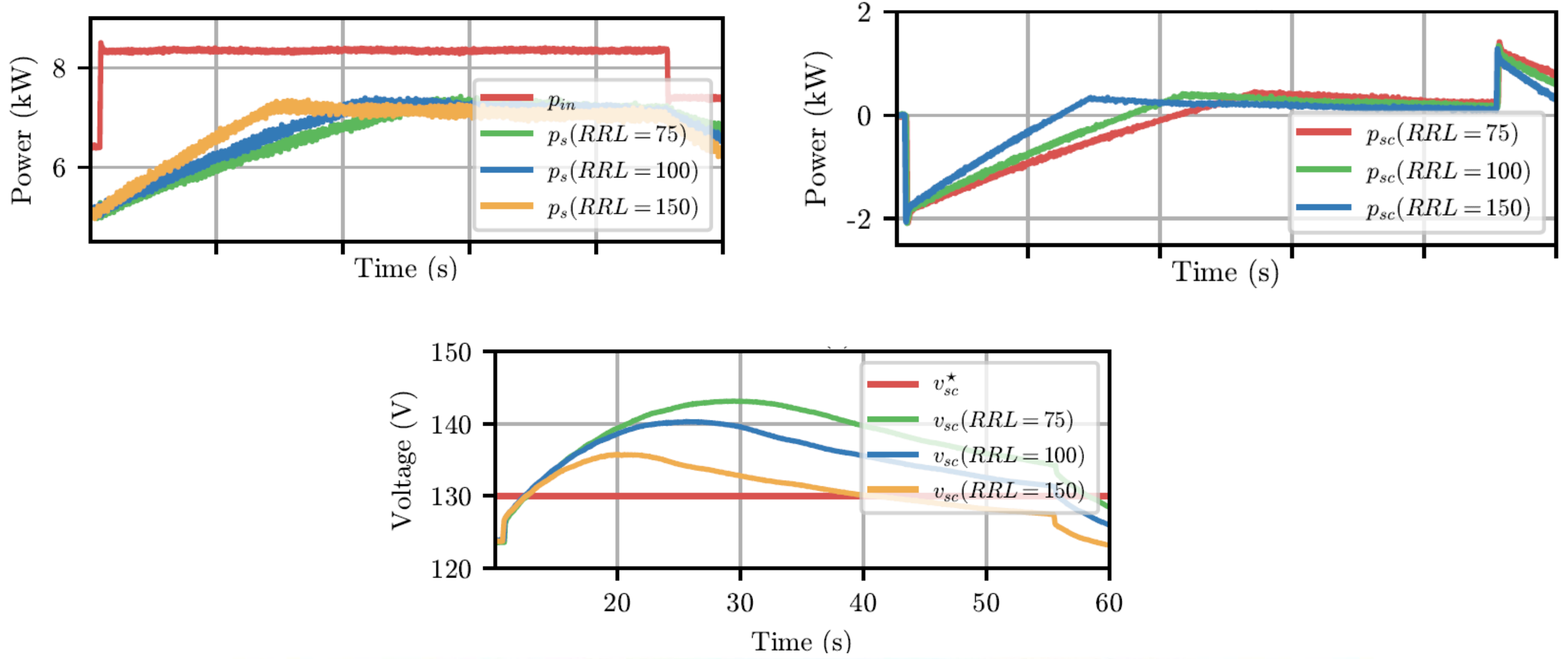
- the SC power reaches barely its maximum power limit -2kW (SC charging)
- the SC voltage does not reach 150V

During the successive ramp-downs (SC discharging) at $t = 50 - 150\,s$, the SC limits are reached:

- the SC power instantaneously exceeds its maximum power limit 2kW (discharge)
- the SC voltage reaches its lower limit 110V

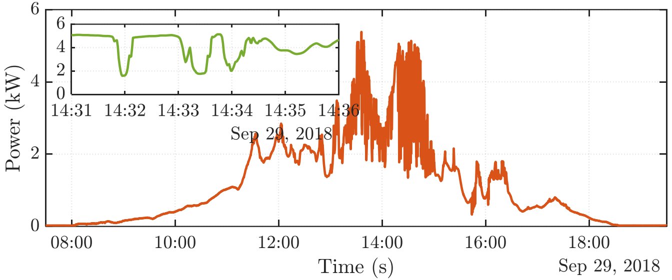
After $t = 300s$ the SC returns to v_{sc}^* avoiding in this way any oversmoothing and unnecessary operation.

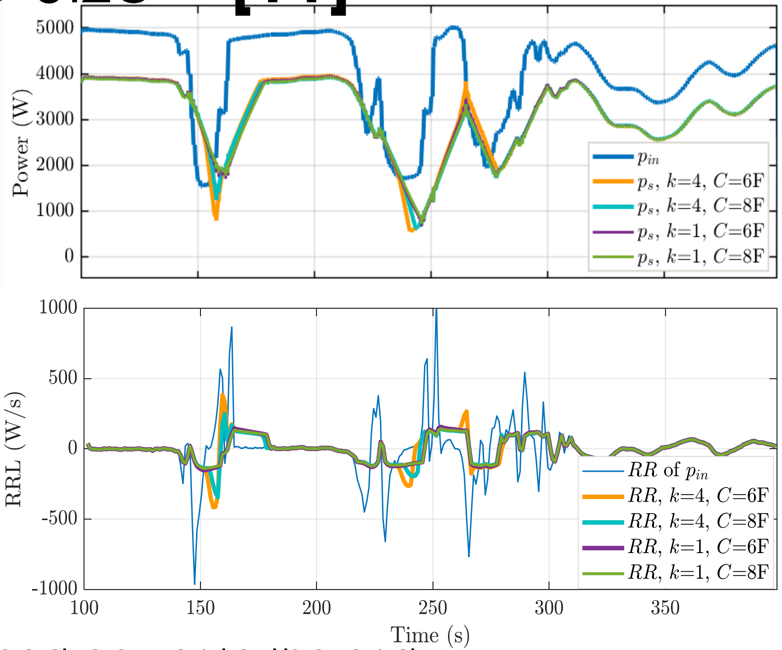
Ultracapacitor RRL: Experimental Results - Oscilloscope



EASY-RES Approach – Simulations

Ultracapacitor RRL: Simulation Results – Effect of Parameter k and SC Size – [11]



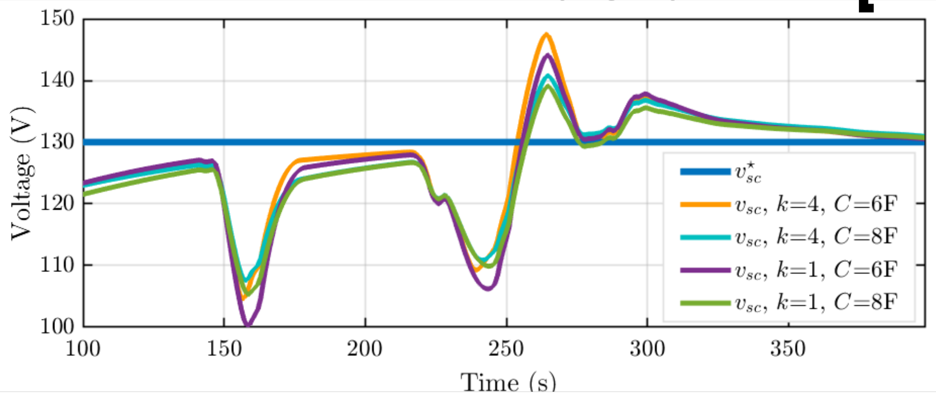


- Real 300s PV power Profile – PV system of 6.5kWp
- $r_n = 100\ W/s$
- No Warning Area *k*=1 & Warning Area with *k*=4
- SC Size 6F and 8F with the same voltage limits → Associated Energy increased by 33,33%

✓ the RRL control works perfectly and injects smoothed power to the grid.
✓ The lower the RRL r_n, the smoother is the active power, as expected.
✓ Avoid Oversmoothing after $t = 300s$

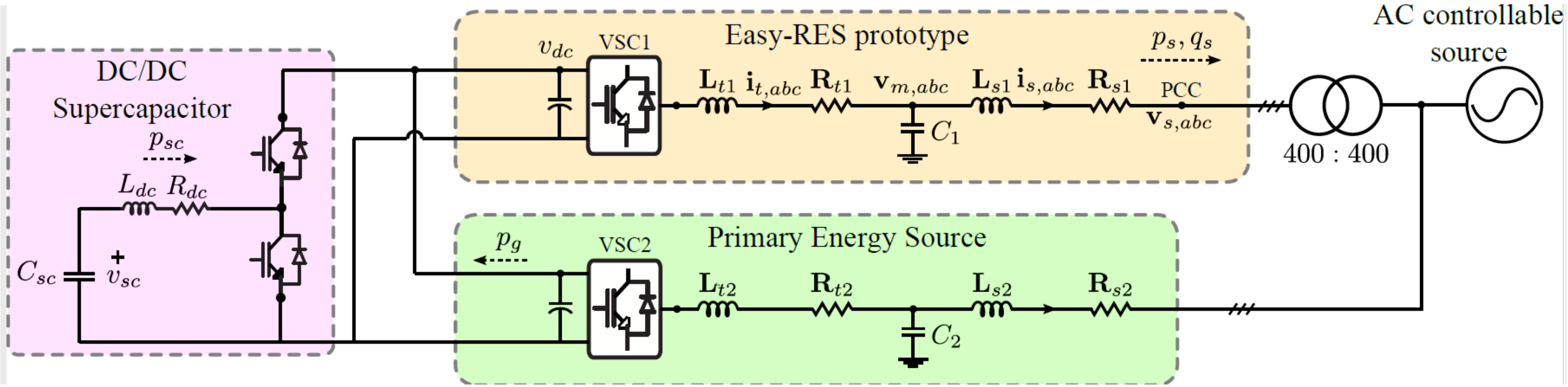
EASY-RES Approach – Simulations

Ultracapacitor RRL: Simulation Results – Effect of Parameter k and SC Size **– [11]**

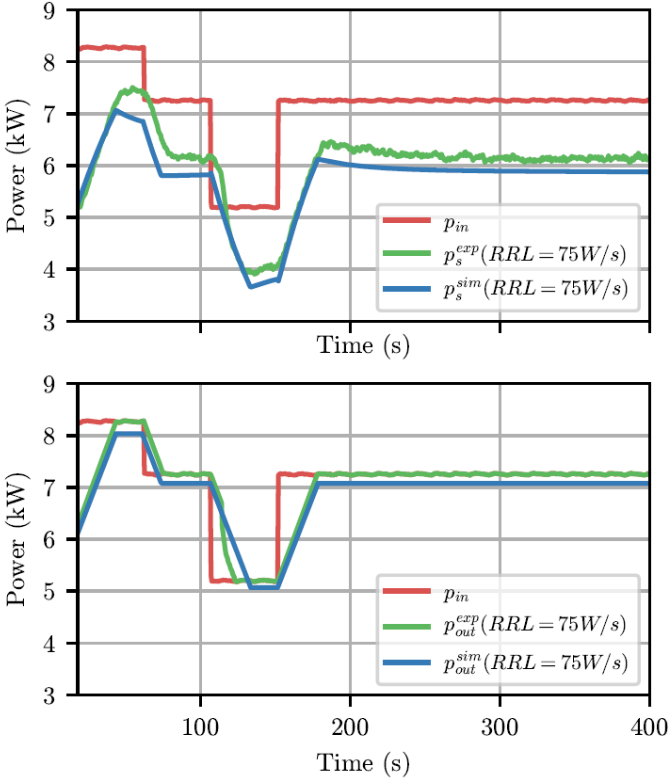


- ✓ At **C**=6F increasing ***k***=4 leads the SC to operate in higher voltage values, hence, into a safer area.
- ✓ Compared to **C**=6F/***k***=1, increasing **C** to 8F achieves the same smoothing (±100W/s) but this allows the SC to operate in a much safer region (around 110-140V).
- ✓ Increasing the SC size leads to better smoothing effect of the grid injected active power.
  - larger sizes may lead to excessive ESS costs.
  - Further issues on the appropriate sizing and costs are discussed within the paper.

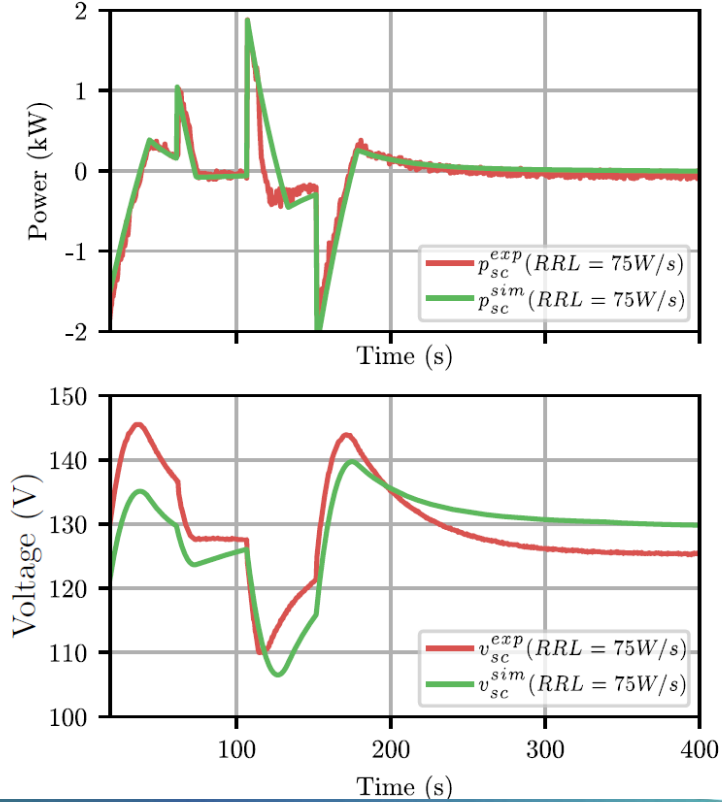
Simulation Model vs. Lab Set-Up 1



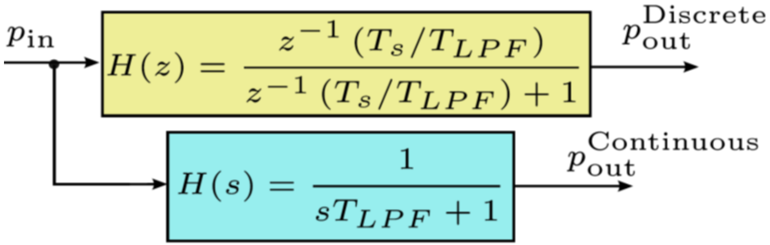
Simulation Model vs. Lab Set-Up 2



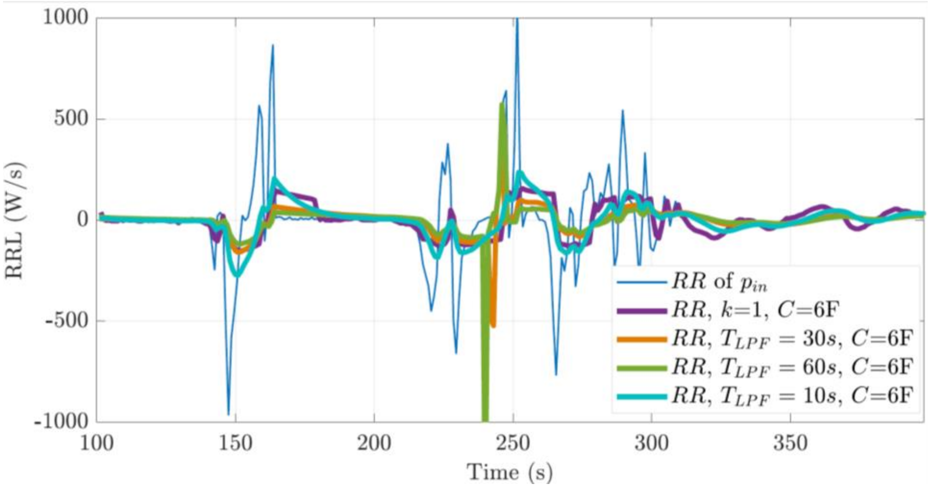
The data provided by the SC manufacturer are not sufficient to represent an accurate model, which is further aggravated in this case, since a SC bank is employed, consisting of individual SC cells and the data provided by the manufacturer for the bank are very limited.

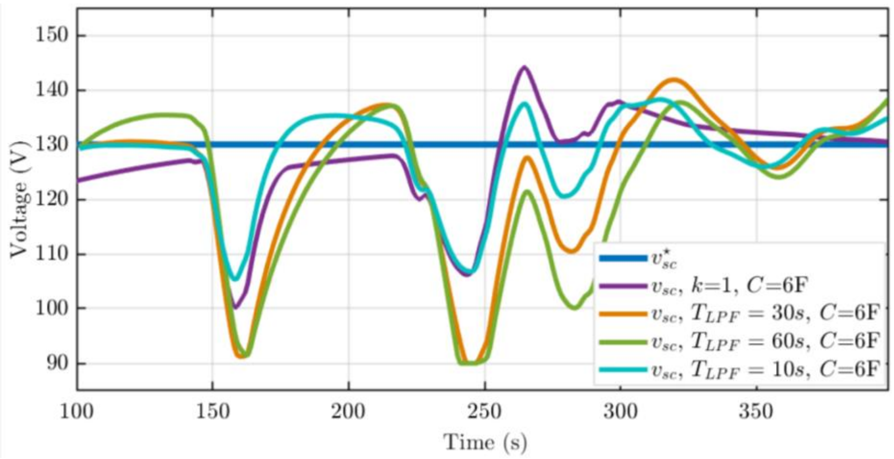


EASY-RES RRL vs. LPF 1

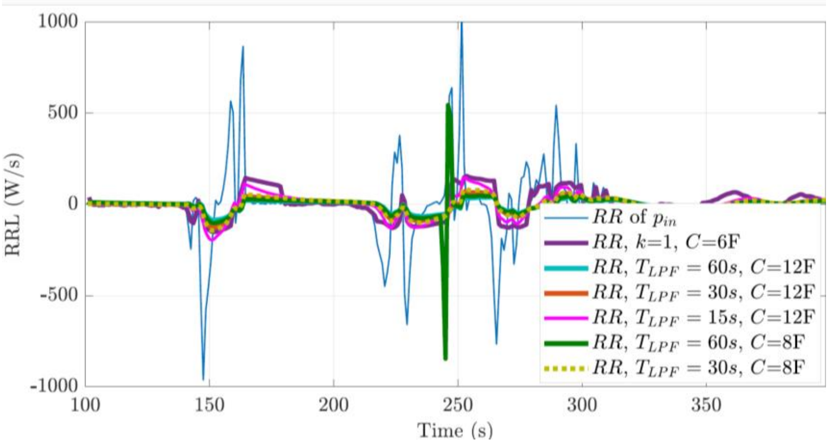


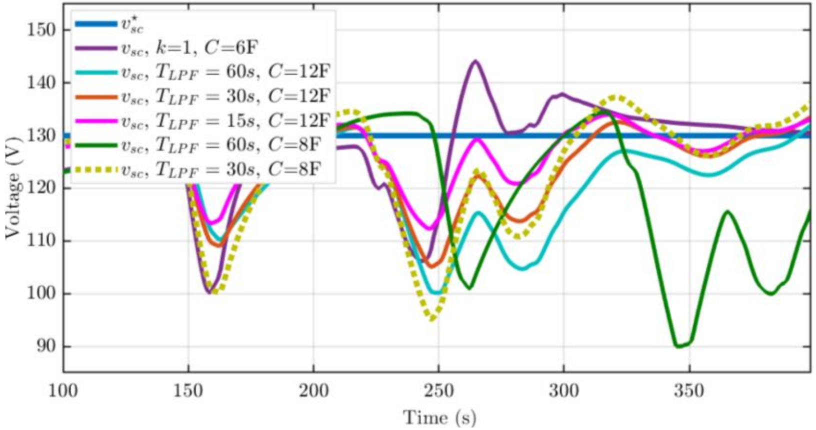
- ✓ In **[7]** BESS - T_{LPF}=70-370 seconds
- ✓ In **[10]** Ultracapacitor with T_{LPF} =600 seconds – 10 minutes





EASY-RES RRL vs. LPF 2

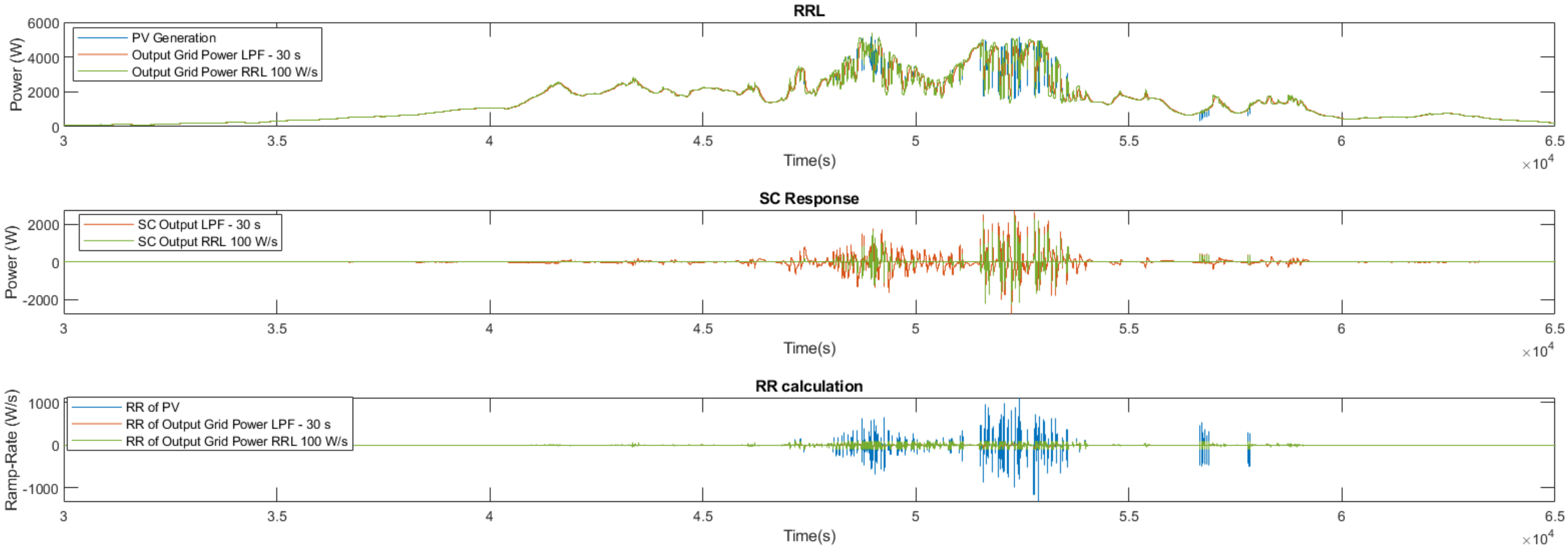




- ✓ the RRL-based control algorithm utilizes the less ESS capacity - hence, lower cost - than filter-based methods, due to the fact that the RRL algorithm limits the RRL to a pre-determined specific level and allows the ESS only to operate for significant fluctuations, avoiding in this way the oversmoothing.
- ✓ the RRL can be pre-defined by the DSOs or TSOs. On the contrary, with the filter-based approaches there can be NO correlation of the filter time constant with the achieved RRL

EASY-RES Approach

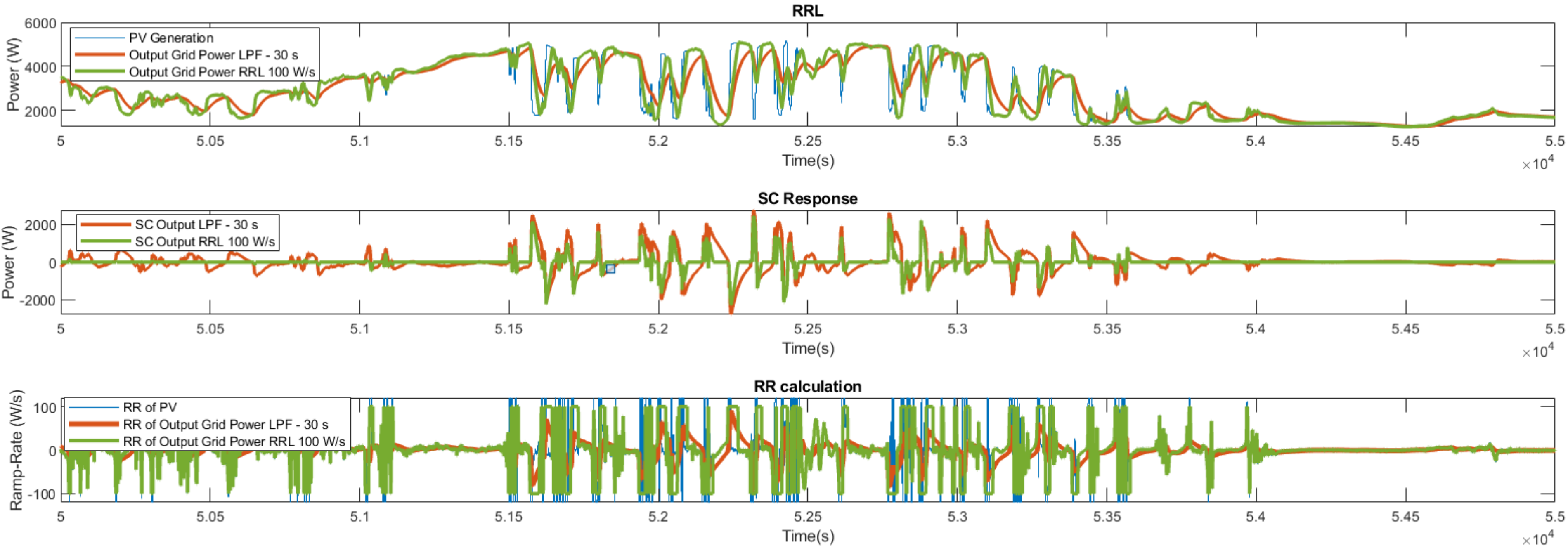
EASY-RES RRL vs. LPF 3



Maximum RR input = 1.117 kW/s

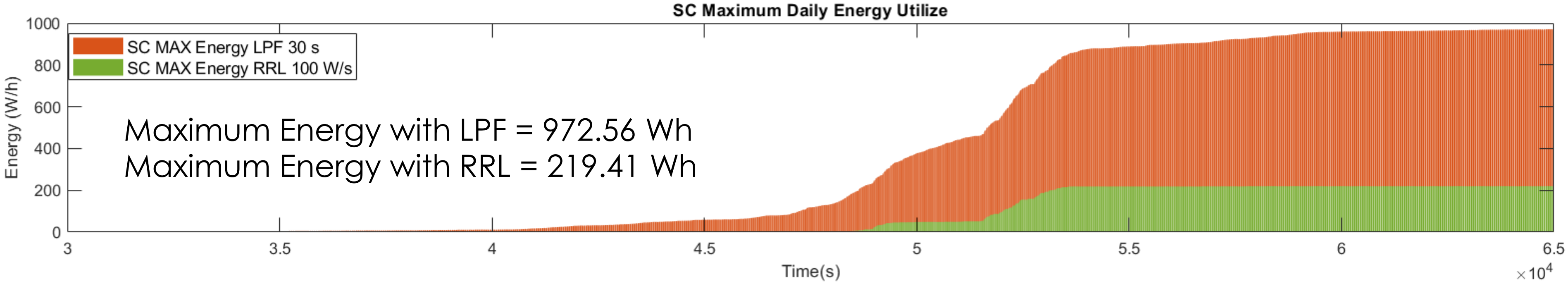
EASY-RES Approach

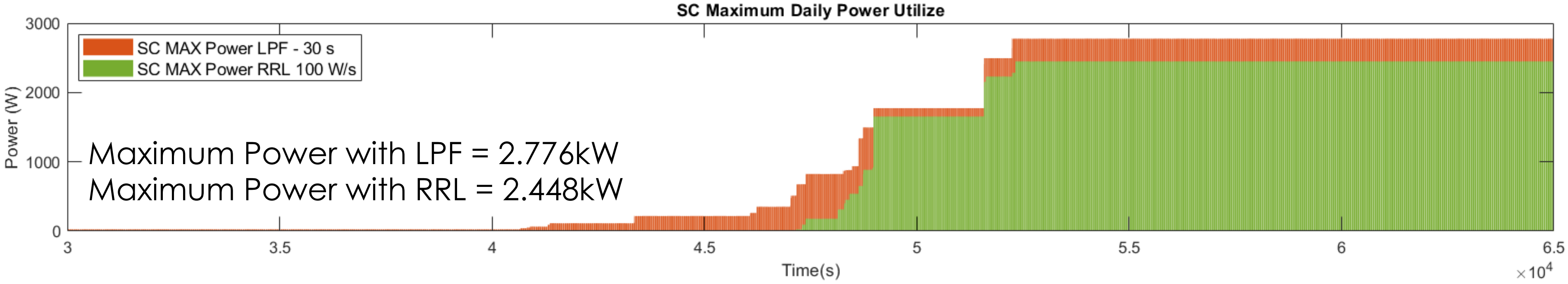
EASY-RES RRL vs. LPF 4



Maximum Achieved RRL with LPF = 91.68 W/s

EASY-RES RRL vs. LPF 5





EASY-RES RRL vs. LPF 6 – What about cost?

PV cost: 1000 euros per kWp installed
SC cost: 15000 per kWh

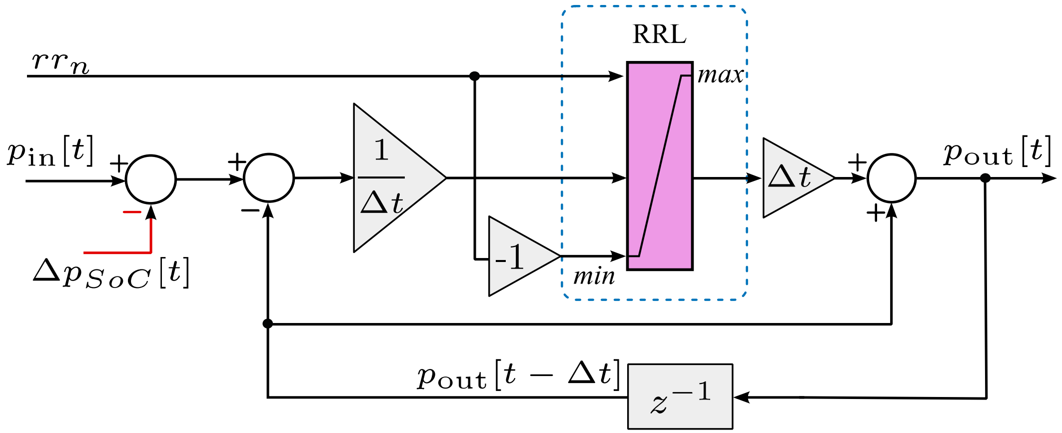
PV power: 7.32kWp

1. With LPF we need 1 kWh of SC → the SC costs twice (200%) the PV!!!
2. With the EASY-RES RRL we need 0.2kWh → the SC costs an additional 45% the PV cost

Need for proper techno-economic analysis!

Of course, fast acting ESS sizing can be performed using high-resolution data (in terms of seconds) to "catch" the effect of the cloud movement → Hence, it can be evaluated only in terms of a "worst-case" cloudy day profile

EASY-RES RRL Control: BESS at Substation Level

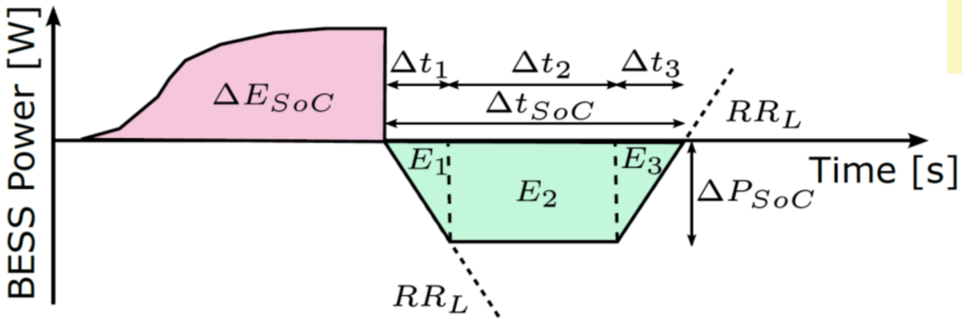


$$RR_{\text{2-point-calc}} = \frac{p_{\text{in}}[t] - \Delta p_{SoC}[t] - p_{\text{out}}[t-\Delta t]}{\Delta t}$$

$$p^{\star}_{\text{ESS}}[t] = p_{\text{in}}[t] - \Delta p_{SoC}[t] - p_{\text{out}}[t-\Delta t]$$

EASY-RES Approach

EASY-RES RRL Control: BESS at Substation Level



Algorithm 2 ESS SoC Function

Require: SoC, ΔSoC, SoC_{max}, SoC_{min}, ΔP_{SoC}
Ensure: Δp_{SoC}

1: **if** $SoC_{min} \leq SoC \leq 50 - \Delta SoC$ **then**
2: $\quad \Delta p_{SoC} \leftarrow -\Delta P_{SoC}$
3: **else if** $50 + \Delta SoC \leq SoC \leq SoC_{max}$ **then**
4: $\quad \Delta p_{SoC} \leftarrow \Delta P_{SoC}$
5: **else**
6: $\quad \Delta p_{SoC} \leftarrow 0$
7: **end if**

$$\Delta E_{SoC} = \frac{1}{2}\Delta t_1 \cdot \Delta P_{SoC} + \Delta P_{SoC} \cdot \Delta t_2 + \frac{1}{2}\Delta t_3 \cdot \Delta P_{SoC}$$

$$\Delta t_1 = \Delta t_3 = \frac{\Delta P_{SoC}}{RR_L}$$

$$\frac{\Delta P_{SoC}^2}{RR_L} - \Delta P_{SoC} \cdot \Delta t_{SoC} + \Delta E_{SoC} = 0$$

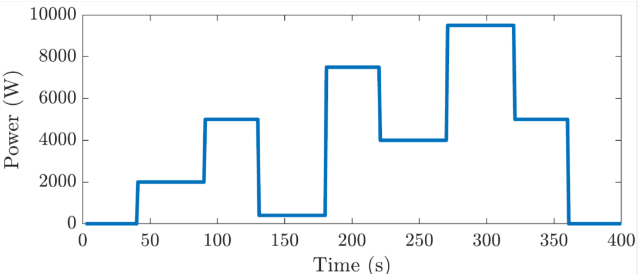
$$\Delta P_{SoC} = \frac{RR_L}{2} \cdot \left(-\Delta t_{SoC} + \sqrt{\Delta t_{SoC}^2 - \frac{4}{RR_L} \cdot \Delta E_{SoC}}\right)$$

$$\Delta E_{SoC} = \frac{1}{2} \cdot E_{BESS}$$

$$RR_L^{min} = \frac{4\Delta E_{SoC}}{\Delta t_{SoC}^2} = \frac{2E_{BESS}}{\Delta t_{SoC}^2}$$

$$\Delta t_{SoC}^{min} = \sqrt{\frac{2E_{BESS}}{RR_L}}$$

BESS Simulation Results 1

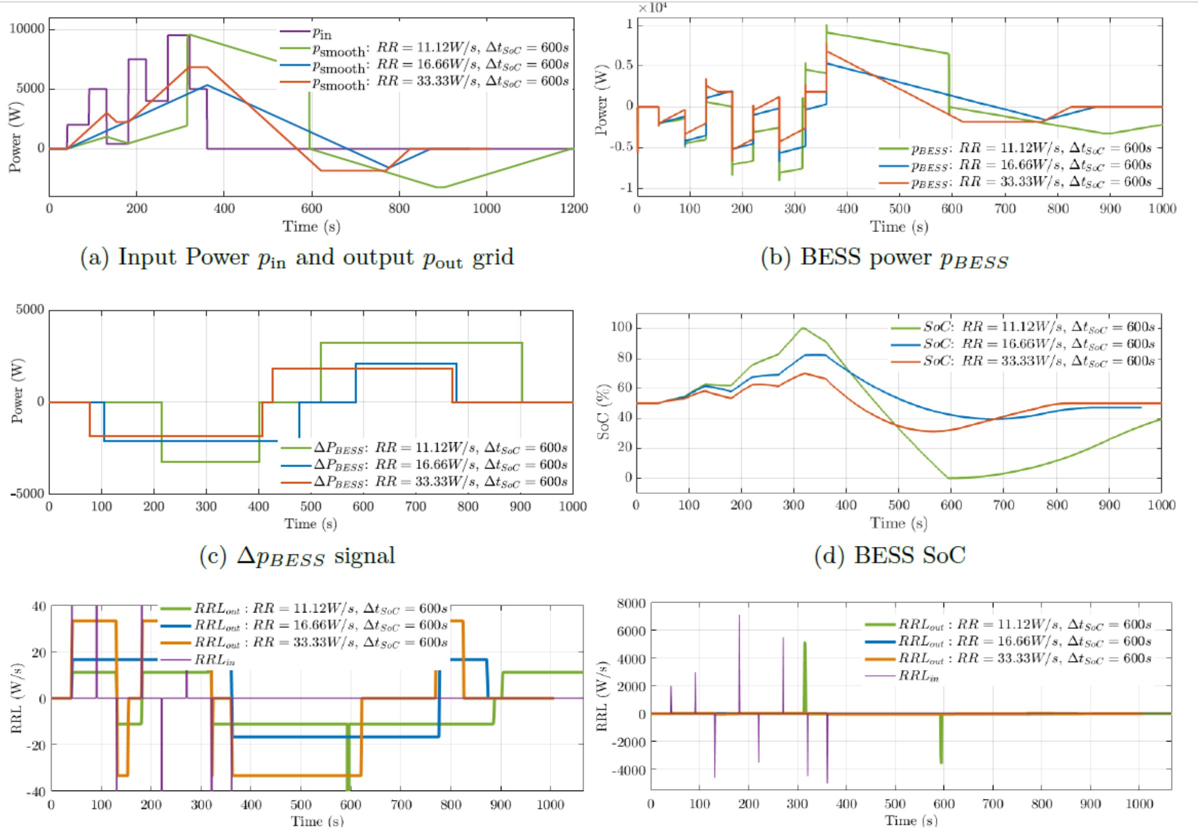


The Maximum power is 10kW, hence,

- 11.17 W/s is the equivalent of 7.5 %/min
- 16.66W/s is the equivalent of 10%/min
- 33.33 W/s is the equivalent of 20%/min

E_{BESS}=2MJ=0.556kWh

✓ **More details in the upcoming EASY-RES deliverable 1.7!**



(a) Input Power p_{in} and output p_{out} grid

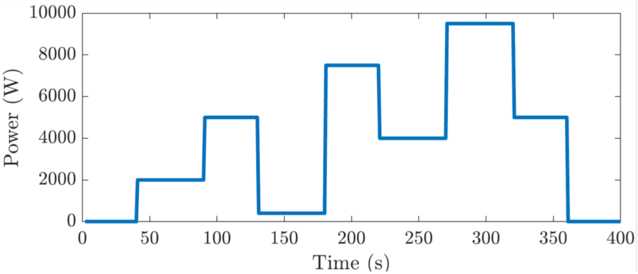
(b) BESS power p_{BESS}

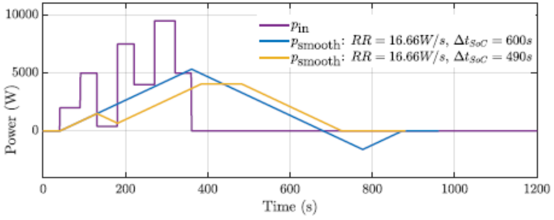
(c) Δp_{BESS} signal

(d) BESS SoC

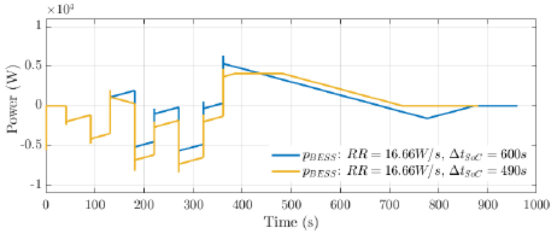
EASY-RES Approach

BESS Simulation Results 2

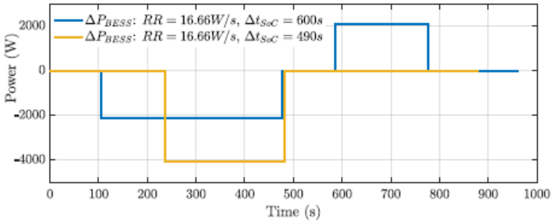




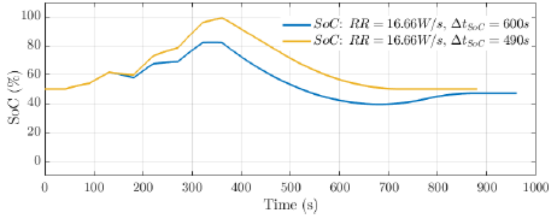
(a) Input Power p_{in} and output p_{out} grid



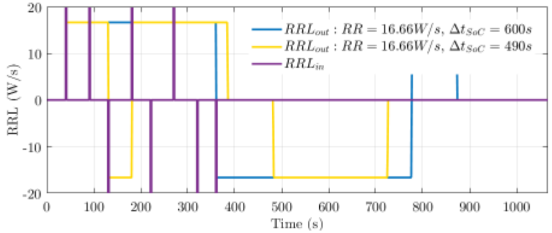
(b) BESS power p_{BESS}

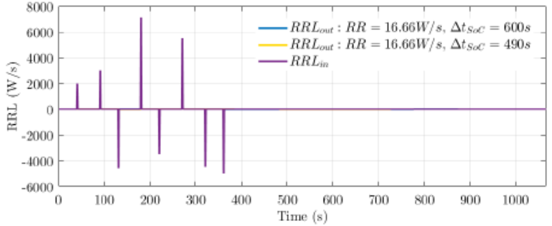


(c) Δp_{BESS} signal



(d) BESS SoC

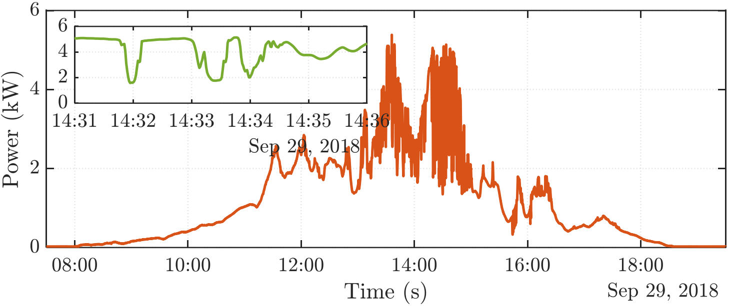


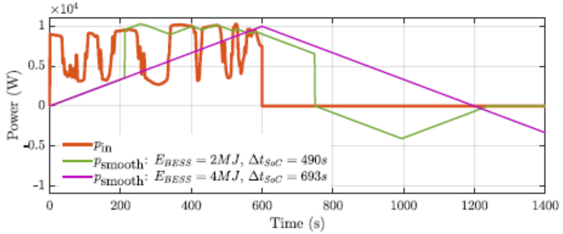


- ✓ **More details in the upcoming EASY-RES deliverable 1.7!**

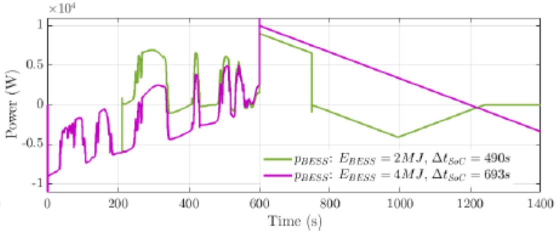
EASY-RES Approach

BESS Simulation Results 3

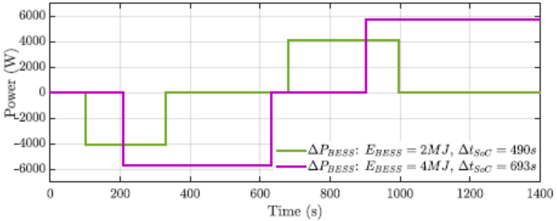




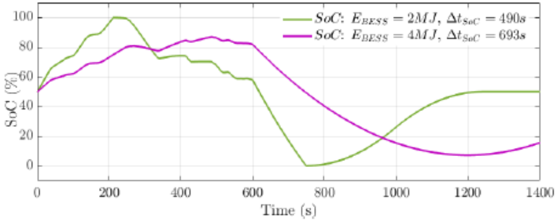
(a) Input Power p_{in} and output p_{out} grid



(b) BESS power p_{BESS}

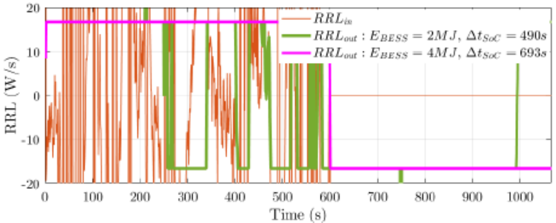


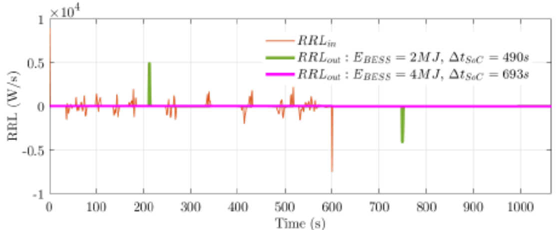
(c) Δp_{BESS} signal



(d) BESS SoC

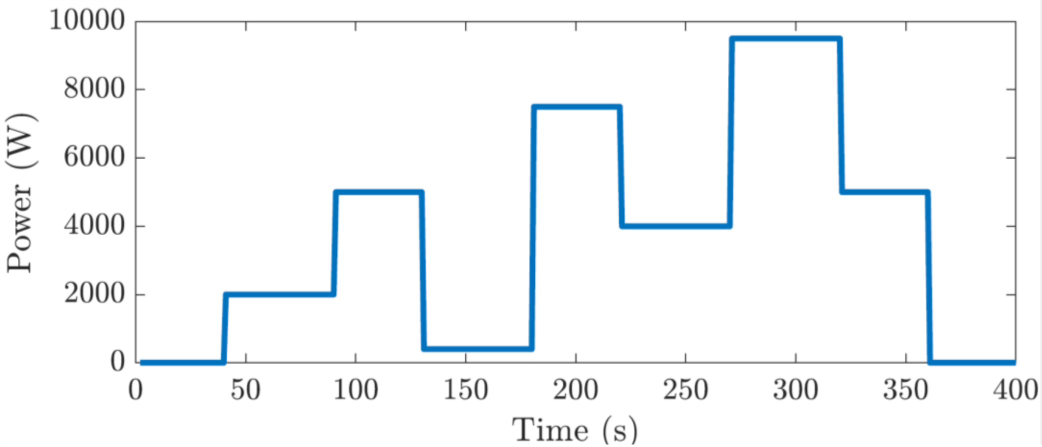
r_n=16.66W/s equivalent to 10%/min





✓ **More details in the upcoming EASY-RES deliverable 1.7!**

BESS Experimental Results 1



BESS Cap, kWh	11	
BESS Cap, J	39600000	
BESS Conv Power, W	5800	

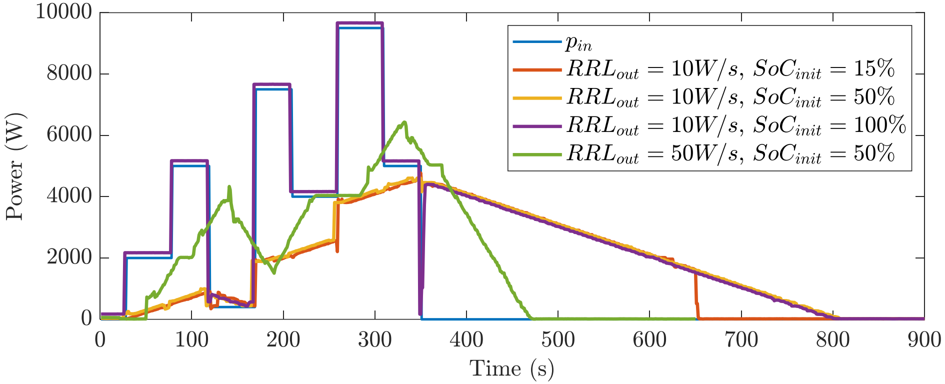
6%/min

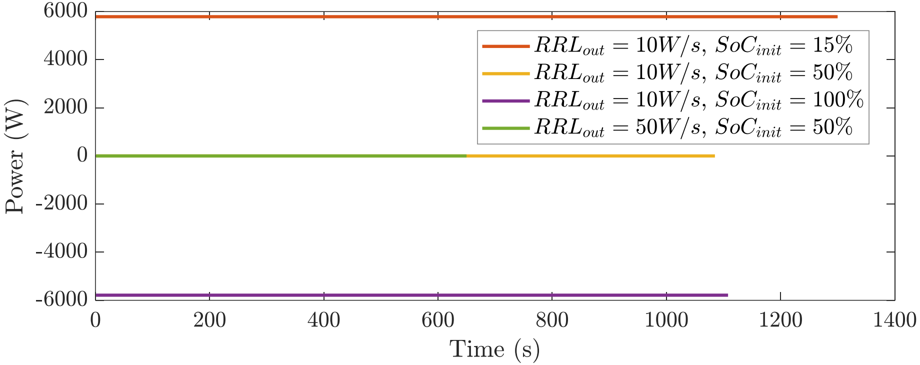
DESoc, J	19800000	
RRL	10	W/s
Dtsoc	4000	s
DP_SoC	-5787,3296	W
DE1_SoC,J	1674659,19	
DSoC, pu	0,04228937	
Dtsoc_min	2814,24946	s

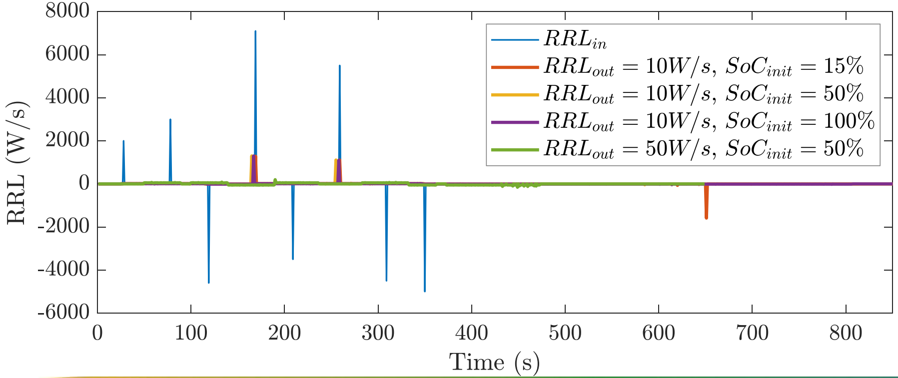
30%/min

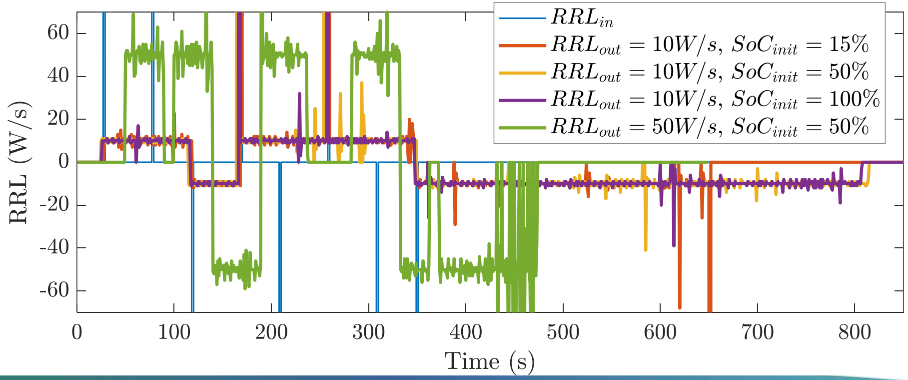
DESoc, J	19800000	
RRL	50	W/s
Dtsoc	4000	s
DP_SoC	-5078,9802	W
DE1_SoC,J	257960,399	
DSoC, pu	0,00651415	
Dtsoc_min	1258,57062	s

BESS Experimental Results 2



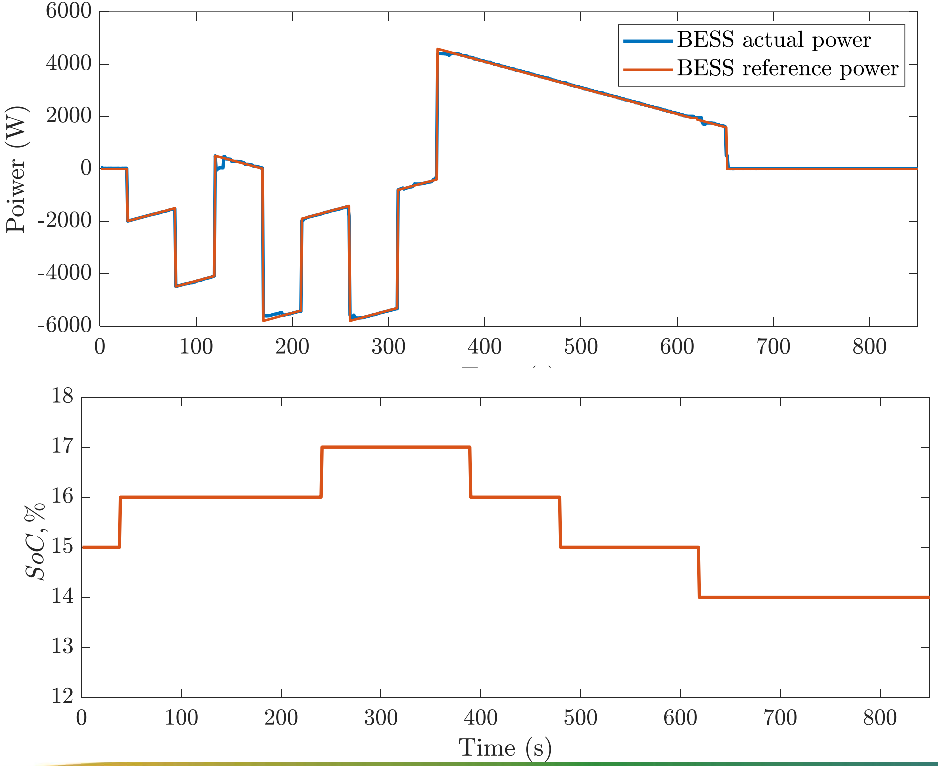




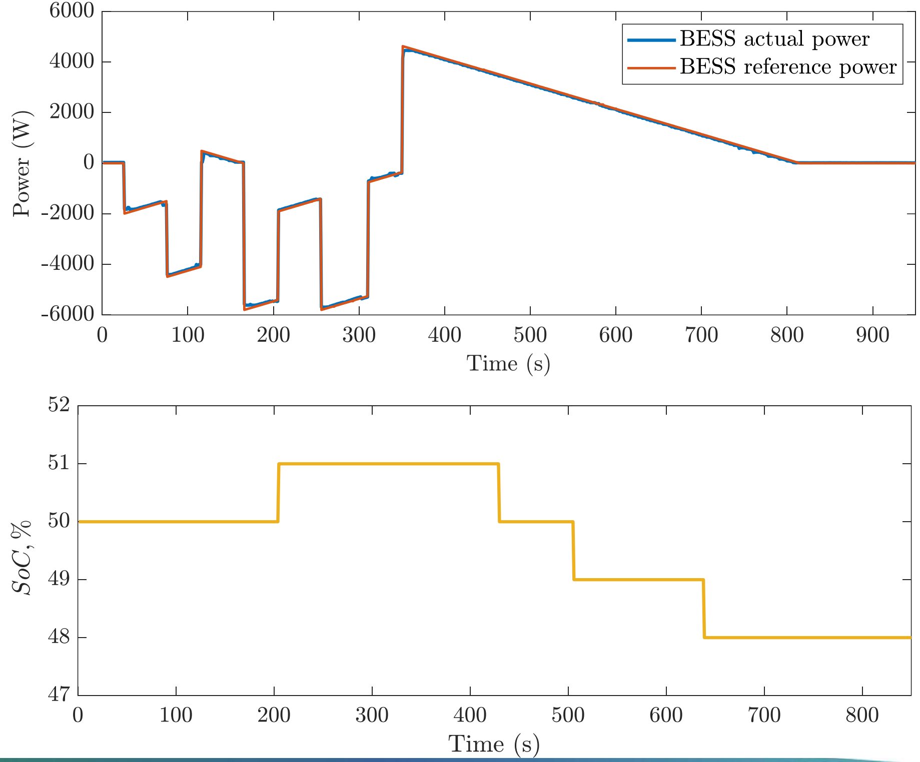


BESS Experimental Results 3

$RRL_{out} = 10W/s,\ SoC_{init} = 15\%$



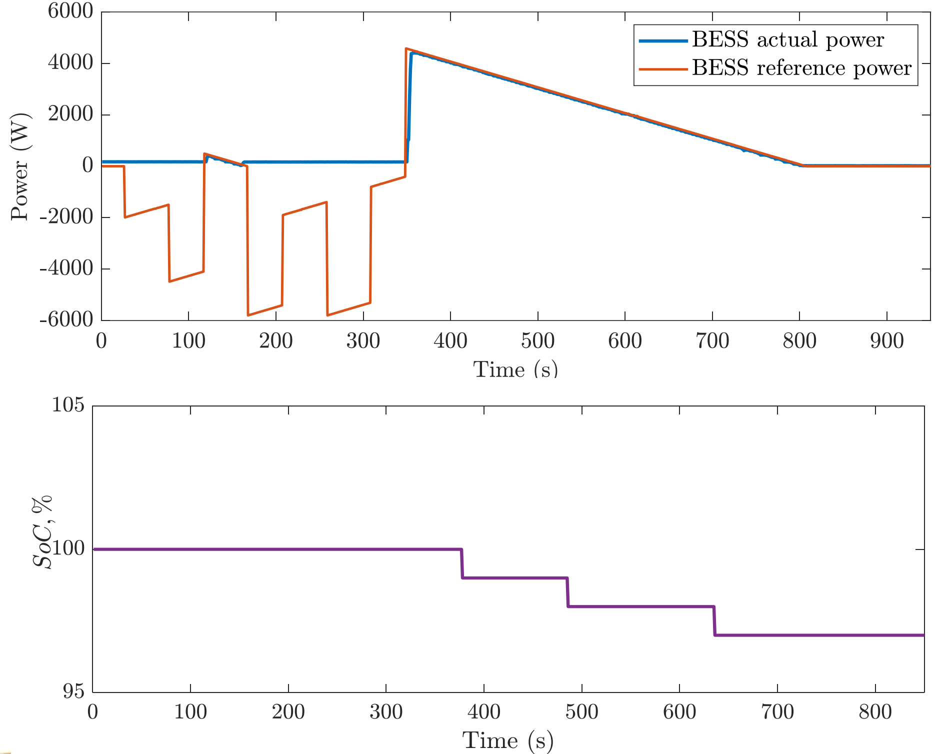
$RRL_{out} = 10W/s,\ SoC_{init} = 50\%$



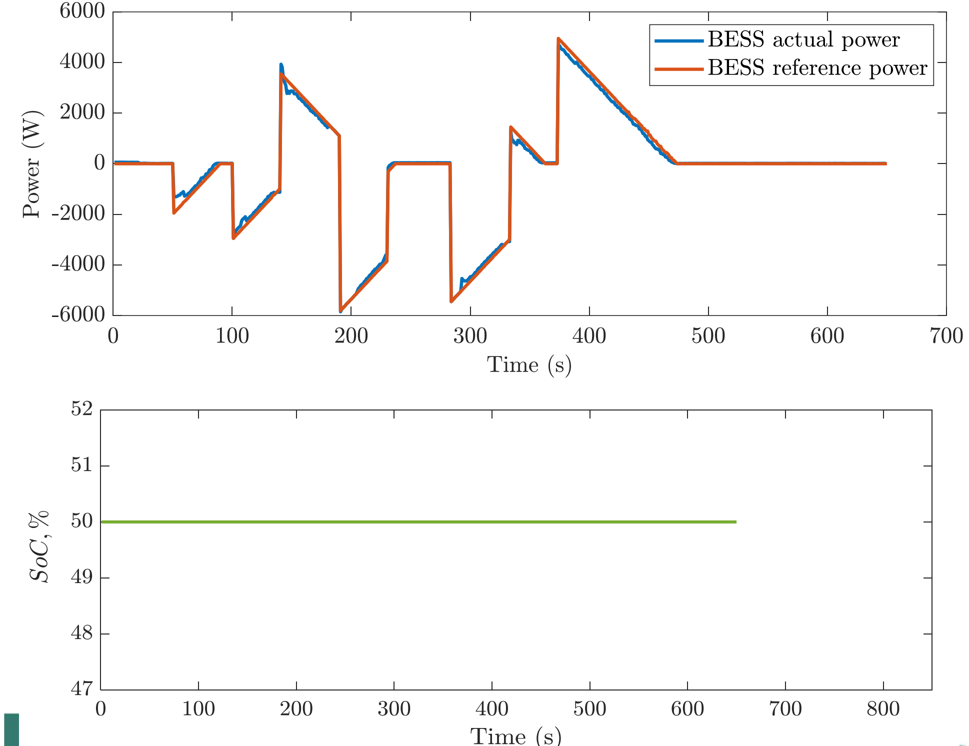
EASY-RES Approach

BESS Experimental Results 4

$RRL_{out} = 10W/s,\ SoC_{init} = 100\%$



$RRL_{out} = 50W/s,\ SoC_{init} = 50\%$



State-of-the-Art **[8]**

- ✓ Hybrid ESS sizing for Wind Parks – Frequency Domain Approaches
  - o Different ESS technologies have different response times
  - o Discrete Fourier Transformation (DFT) is usually used to decompose the balance error between the forecasted and actual wind power
  - o Higher frequencies are assigned to the faster ESS

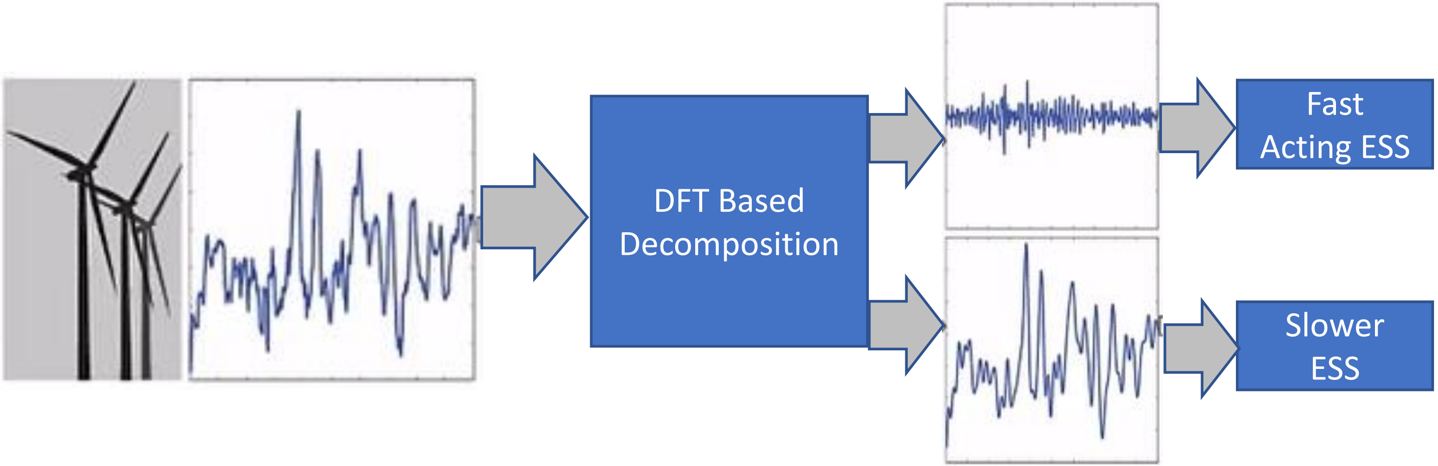
- ✓ ESS size in parallel with large-scale PVPPs (usually BESS) – Time domain Approaches
  - o Can be generally categorized as analytical, probabilistic or search-based
  - o **All** of them use *historical Data from the time-domain*
  - o **All** of them use the RRL of 10%/min
  - o Prevailing is the analytical method for the **worst-case** scenario, **[15]-[19]**

Frequency Domain Approaches **[13,14]**

Frequency domain Approaches Hybrid ESS sizing for Wind Parks

Objective to minimize the imbalance

$$P_{scheduled}(t) - P_{wind}(t) = P_{imbalance}(t)$$



Frequency Domain Approaches **[13,14]**

Algorithm

1. Find Imbalance power for 1-year
2. Find the DFT of imbalance power for the whole year
3. Use high pass and low pass filters (based on desired cut-off frequencies) to extract the respective high- and low-frequency components
4. Take Inverse DFT of the high- and low-frequency signals
5. Assign high-frequency components to fast acting ESS (intra-hour or some seconds or minutes) and low-frequency components to slower ESS (for frequencies > 1 minute)

$$P_{\text{fast ESS}} = max\left\{\left|P^{hf}_{imbalance}(t)\right|\right\}$$

$$P_{\text{slow ESS}} = max\left\{\left|P^{lf}_{imbalance}(t)\right|\right\}$$

number of data points per year is ***m*** (for example for 1 minute resolution data we have ***m***=84600)

$$E^{calc}_{\text{fast ESS}} = \sum_{m=0}^{t}\left[P^{hf}_{imbalance}(m)\cdot\frac{\text{resolution in minutes}}{\text{60 minutes}}\right]$$

$$E^{calc}_{\text{slow ESS}} = \sum_{m=0}^{t}\left[P^{lf}_{imbalance}(m)\cdot\frac{\text{resolution in minutes}}{\text{60 minutes}}\right]$$

Find the minimum ESS for each signal from the following expressions

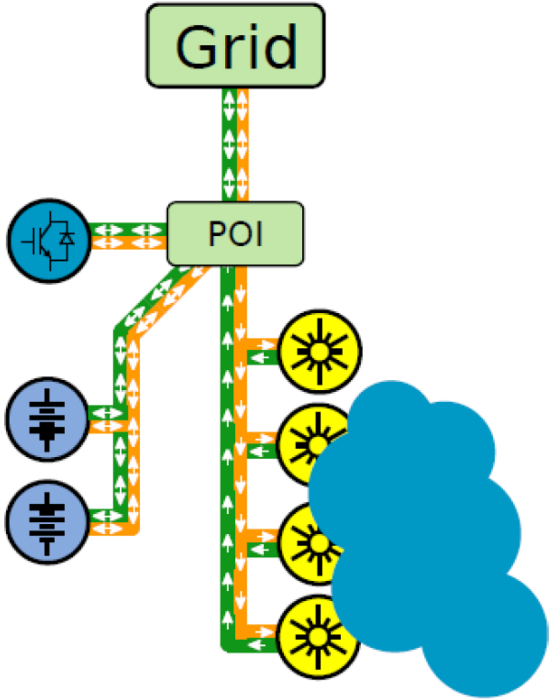
$$E^{\text{Rated}}_{\text{fast ESS}} = \frac{\max\left\{\left|E^{calc}_{\text{fast ESS}}\right|\right\} - \min\left\{\left|E^{calc}_{\text{fast ESS}}\right|\right\}}{SoC^{max}_{\text{fast ESS}} - SoC^{min}_{\text{fast ESS}}}$$

$$E^{\text{Rated}}_{\text{slow ESS}} = \frac{\max\left\{\left|E^{calc}_{\text{slow ESS}}\right|\right\} - \min\left\{\left|E^{calc}_{\text{slow ESS}}\right|\right\}}{SoC^{max}_{\text{slow ESS}} - SoC^{min}_{\text{slow ESS}}}$$

Time Domain Approaches **[15-19]**

Time domain Approaches for ESS together with PVPPs

- Capacity of the PVPP
- Field size of the PVPP (dimensions)
- Average and worst rate of fluctuations (average and high cloud speed based on historical data)
- Acceptable RRL by the DSO-TSO



Time Domain Approaches **[15-19]**

Time domain Approaches for ESS together with PVPPs

- ✓ The BESS is sized to support the worst fluctuation case → Drop in the PV power from 100% to 10% and vice versa
- ✓ The Power Drop is assumed to be an exponential function

$$P_{PV}(t) = 90e^{-t/\tau} + 10$$

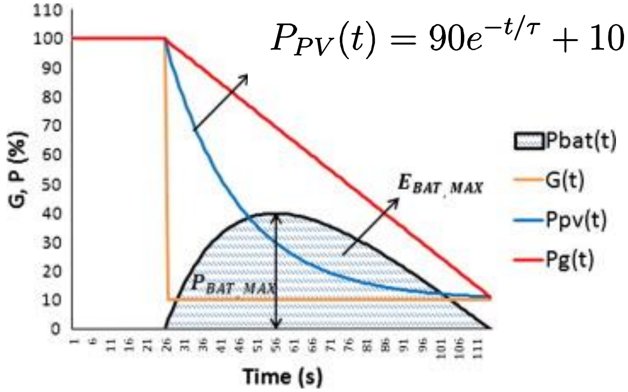


Figure: Worst Case Fluctuation of PV power Model, **[15] – [19]**

$$\tau = \frac{\sqrt{ab}}{v}$$

$$P_{BESS}(t) = 100 - rr_l.\text{t} - P_{PV}(t)$$

Time Domain Approaches **[15-19]**

BESS power
$$P_{BESS}(t) = \frac{P_{PV}^r}{\eta_{Inv}^{out}} \left(1 - r_l.\frac{t}{6000} - \left(0.9e^{-t/\tau} + 0.1\right)\right)$$

BESS derivative
$$\frac{dP_{BESS}(t)}{dt} = \frac{P_{PV}^r}{\eta_{Inv}^{out}} \left(rr_l 6000 + \frac{0.9}{\tau} e^{-t_{max}/\tau}\right)$$

$$t_{\max} = \tau \ln\left(\frac{5400}{\tau \cdot rr_l}\right)$$

BESS converter rated power

$P_{BESS}(t_{max})$
$$P_{rated} = \frac{P_{PV}^r}{100\eta_{Inv}^{out}} \left[90 - \frac{\tau.rr_l}{60}\left(1 + \ln\left(\frac{5400}{\tau.rr_l}\right)\right)\right]$$

$$\mathrm{T}_s = \frac{5400}{rr_l}$$

$$E_{rated} = 2\int_0^{\mathrm{T}_s} P_{BESS}(t)$$

$$E_{rated} = \frac{0.9P_{PV}^r}{1800\eta_{battery}^{out}} \left[\frac{2700}{r_l} - \tau - \tau.e^{-5400/\tau.r_l}\right]$$

Time Domain Approaches **[15-19]**

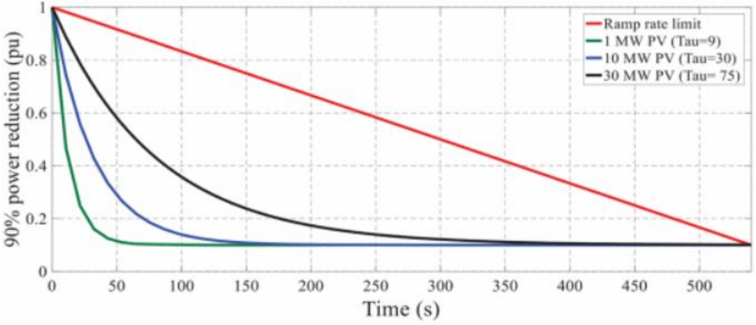


Figure: Effect of size of PVPP on sudden power drop, **[17]**

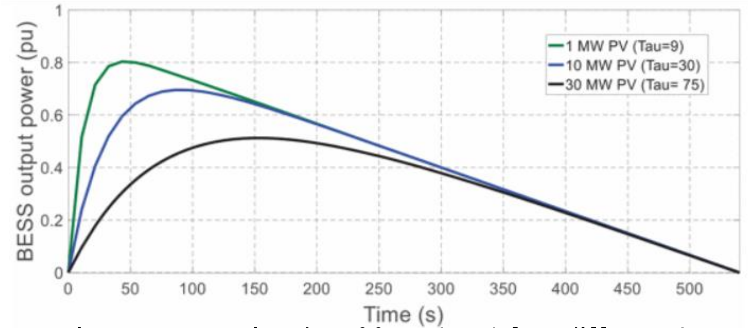


Figure: Required BESS output for different plants with different dimensions , **[17]**

- Wind Speed 40 miles per hour (17.88 m/s)
- A 1 MWp PVPP occupies an area of 10,500m^2
- A 9 MWp PVPP occupies an area of 94,500m^2
- Scale up for 30 MWp

9MWp PVPP

$$P_{rated} = 6500kW$$

$$E_{rated} = 1000kWh$$

- BESS Power and Energy ratings are relatively higher for smaller PVPPs
- Larger Size PVPP results in smoother output! Because the ramping takes longer →
- the cloud passes more quickly in a small PVPP rather than a large PVPP

Sizes may be reduced significantly in both Approaches if we consider to mitigate only a percentage of the ramp rate violations, e.g., 95%!

EASY-RES BESS Sizing 1

BESS size and the respective BESS converter power in respect to the following parameters:

- Distribution transformer rated power S_{tr}
- DRES penetration expressed through the coefficient k_p
- ramp rate limitation RR_L given by the DSO/Aggregator
- maximum ramp rate RR_M of the power at the POI with the upstream grid

The RR_L is always defined as:

$$RR_L = \frac{\Delta P}{\Delta t}$$

Hence, the time can be expressed by

$$\Delta t = \frac{\Delta P}{RR_L}$$

EASY-RES BESS Sizing 2

The involved BESS energy is always:

$$E_{BESS} = \Delta P \cdot \Delta t = \frac{(\Delta P)^2}{RR_L}$$

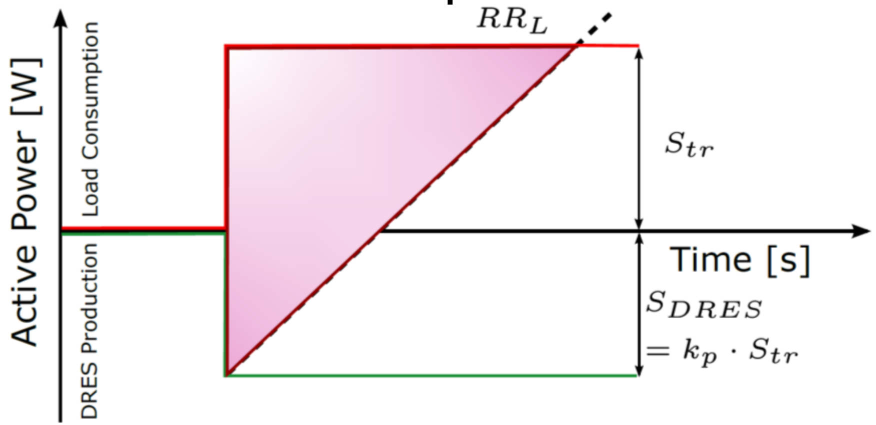
Two additional coefficients are introduced in order to avoid excessive BESS size:

- ✓ Minimum base load expressed through the coefficient k_{LD}
- ✓ Minimum base production expressed through the coefficient k_{DRES}

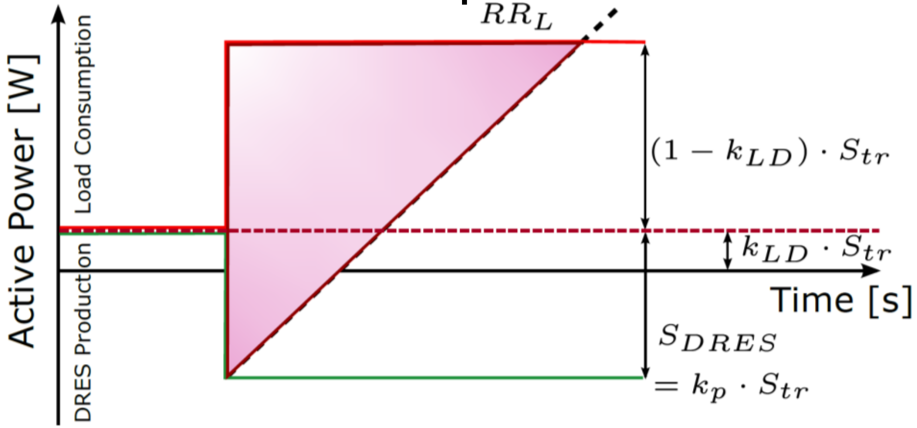
- ➢ **the time resolution/sampling of the data should be 1 minute at most (not 10 minutes or 15 minutes).**
- ➢ **In the literature, there are limited data with 1s to 1 min resolution.**
- ➢ **Yearly profiles should be used**

EASY-RES BESS Sizing 3

Step 1



Step 2



Worst-case scenario

$$E_{BESS}^{p} = \frac{1}{2} \cdot \frac{(S_{tr} + S_{DRES})^2}{RR_L} = \frac{1}{2} \cdot \frac{[S_{tr} \cdot (1 + k_p)]^2}{RR_L}$$

$$RR_L = \frac{\Delta P}{\Delta t} = \frac{(S_{tr} + S_{DRES})}{\Delta t}$$

$$k_p = \frac{S_{DRES}}{S_{tr}}$$ values within [0..1].

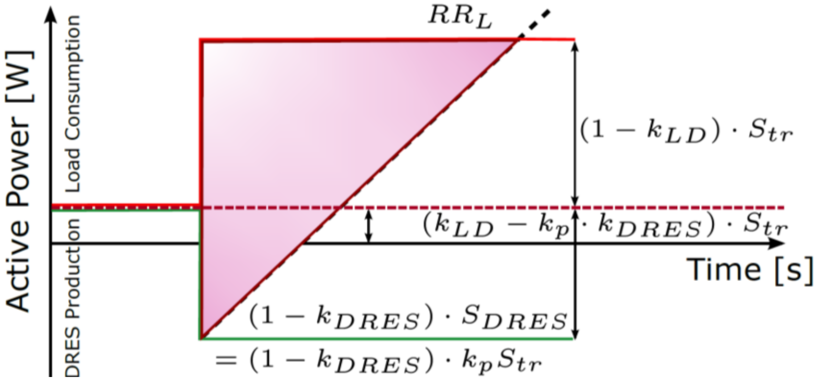
For PF=1, $S_{DRES} = P_{DRES}^{\text{Total}}$

$$\Delta P = S_{DRES} + (1 - k_{LD}) \cdot S_{tr}$$

$$E_{BESS}^{p} = \frac{1}{2} \cdot \frac{[(1 - k_{LD}) \cdot S_{tr} + S_{DRES}]^2}{RR_L} = \frac{1}{2} \cdot \frac{[S_{tr} \cdot (1 - k_{LD} + k_p)]^2}{RR_L}$$

EASY-RES BESS Sizing 4

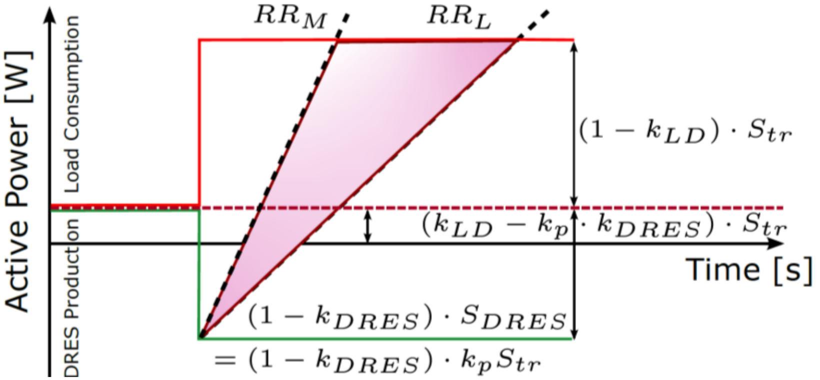
Step 3



$$\Delta P_{DRES} = S_{DRES}\,(1-k_{DRES})$$

$$E^p_{BESS} = \frac{1}{2}\cdot\frac{\left[(1-k_{LD})\cdot S_{tr} + (1-k_{DRES})\cdot S_{DRES}\right]^2}{RR_L} = $$
$$= \frac{1}{2}\cdot\frac{S_{tr}^2}{RR_L}\left[1-k_{LD}+(1-k_{DRES})\cdot k_p)\right]^2$$

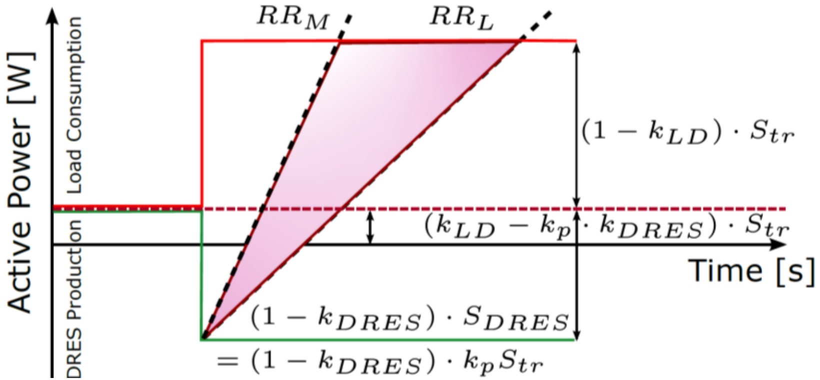
Step 4



$$\Delta P_{DRES} = S_{DRES}\,(1-k_{DRES})$$

$$E^p_{BESS} = \frac{1}{2}\cdot\left(\frac{1}{RR_L}-\frac{1}{RR_M}\right)\cdot S_{tr}^2\cdot$$
$$\cdot\left[1-k_{LD}+(1-k_{DRES})\cdot k_p\right]^2$$

EASY-RES BESS Sizing 5



Step 5

$$E_{BESS} = E^p_{BESS} + E^n_{BESS} =$$
$$= S_{tr}^2 \cdot [1 - k_{LD} + (1 - k_{DRES}) \cdot k_p]^2 \cdot \left(\frac{1}{RR_L} - \frac{1}{RR_M}\right)$$

Step 6

$$P_{BESS} = S_{tr} \cdot \left(1 - \frac{RR_M}{RR_L}\right) \cdot [1 - k_{LD} + (1 - k_{DRES}) \cdot k_p)]$$

- ✓ **Each Distribution Grid is unique → All the coefficients should be carefully evaluated based on DRES and Load penetration, mixture and base case**
- ✓ **More details in the upcoming EASY-RES deliverable 1.7!**

EASY-RES BESS Sizing Numerical Example 1

BESS Sizing

Distribution transformer rated power S_{tr}	100.000,00 W	
DRES penetration coefficient k_p	0,70 pu	10 %/min
The ramp rate limitation RR_L	166,67 W/s	10000 W/min
The maximum ramp rate RR_M	0,00 W/s	0 W/min
Minimum base load coefficient k_{LD}	0,00 pu	
Minimum base production coefficient k_{DRES}	0,00 pu	

BESS Energy	173.400.000,00 Ws	173400 kJ
	2.890.000,00 Wmin	
	48.166,67 Whour	48,167 kWh

BESS Power	170.000,00 W	170 kW

$$E_{BESS} = E_{BESS}^{p} + E_{BESS}^{n} = S_{tr}^{2} \cdot \left[\frac{[(1+k_p)]^2}{RR_L} \right]$$

$$P_{BESS} = S_{tr} \cdot (1+k_p))$$

Assuming a BESS cost of 600$/1kWh → 28.900,00 $

EASY-RES BESS Sizing Numerical Example 2

BESS Sizing

Input Data	Distribution transformer rated power S_{tr}	100.000,00 W	
	DRES penetration coefficient k_p	0,70 pu	10 %/min
	The ramp rate limitation RR_L	166,67 W/s	10000 W/min
	The maximum ramp rate RR_M	0,00 W/s	0 W/min
	Minimum base load coefficient k_{LD}	0,20 pu	
	Minimum base production coefficient k_{DRES}	0,00 pu	
Output	BESS Energy	135.000.000,00 Ws	135000 kJ
		2.250.000,00 Wmin	
		37.500,00 Whour	37,5 kWh
	BESS Power	150.000,00 W	150 kW

$$E_{BESS} = E^{p}_{BESS} + E^{n}_{BESS} = S^2_{tr} \cdot \left[\frac{[(1 - k_{LD} + k_p)]^2}{RR_L} \right]$$

$$P_{BESS} = S_{tr} \cdot (1 - k_{LD} + k_p)$$

Assuming a BESS cost of 600$/1kWh → 22.500,00 $

EASY-RES BESS Sizing Numerical Example 3

BESS Sizing

Input Data	Distribution transformer rated power S_{tr}	100.000,00 W	
	DRES penetration coefficient k_p	0,70 pu	10 %/min
	The ramp rate limitation RR_L	166,67 W/s	10000 W/min
	The maximum ramp rate RR_M	0,00 W/s	0 W/min
	Minimum base load coefficient k_{LD}	0,20 pu	
	Minimum base production coefficient k_{DRES}	0,10 pu	
Output	BESS Energy	122.694.000,00 Ws	122694 kJ
		2.044.900,00 Wmin	
		34.081,67 Whour	34,082 kWh
	BESS Power	143.000,00 W	143 kW

$$E_{BESS} = E_{BESS}^{p} + E_{BESS}^{n} = S_{tr}^{2} \cdot \left[\frac{\left[(1 - k_{LD} + (1 - k_{DRES}) \cdot k_p)\right]^2}{RR_L} \right]$$

$$P_{BESS} = S_{tr} \cdot \left(1 - k_{LD} + (1 - k_{DRES}) \cdot k_p\right)$$

Assuming a BESS cost of 600$/1kWh → 20.449,00 $

EASY-RES Approach

EASY-RES BESS Sizing Numerical Example 4

BESS Sizing

Input Data

Distribution transformer rated power S_{tr}	100.000,00 W	
DRES penetration coefficient k_p	0,70 pu	10 %/min
The ramp rate limitation RR_L	166,67 W/s	10000 W/min
The maximum ramp rate RR_M	1.333,33 W/s	80000 W/min
Minimum base load coefficient k_{LD}	0,20 pu	
Minimum base production coefficient k_{DRES}	0,10 pu	

Output

BESS Energy	107.357.250,00 Ws	107357 kJ
	1.789.287,50 Wmin	
	29.821,46 Whour	29,821 kWh
BESS Power	125.125,00 W	125,13 kW

$$E_{BESS} = E^p_{BESS} + E^n_{BESS} = S^2_{tr} \cdot \left[\frac{[(1-k_{LD}+(1-k_{DRES})\cdot k_p)]^2}{RR_L} - \frac{[(1-k_{LD}+(1-k_{DRES})\cdot k_p)]^2}{RR_M} \right]$$

$$P_{BESS} = S_{tr} \cdot \left(1 - \frac{RR_L}{RR_M}\right) \cdot (1 - k_{LD} + (1-k_{DRES}) \cdot k_p))$$

Assuming a BESS cost of 600$/1kWh → 17.893,00 $

EASY-RES BESS Sizing Numerical Example 5

BESS Sizing

Input Data

Distribution transformer rated power S_{tr}	100.000,00 W	
DRES penetration coefficient k_p	0,70 pu	10 %/min
The ramp rate limitation RR_L	166,67 W/s	10000 W/min
The maximum ramp rate RR_M	333,33 W/s	20000 W/min
Minimum base load coefficient k_{LD}	0,20 pu	
Minimum base production coefficient k_{DRES}	0,10 pu	

Output

BESS Energy	61.347.000,00 Ws	
	1.022.450,00 Wmin	
	17.040,83 Whour	17,041 kWh
BESS Power	71.500,00 W	71,5 kW

With the proposed Analysis → 3 times lower cost!

$$E_{BESS} = E_{BESS}^{p} + E_{BESS}^{n} = S_{tr}^{2} \cdot \left[\frac{[(1 - k_{LD} + (1 - k_{DRES}) \cdot k_p)]^2}{RR_L} - \frac{[(1 - k_{LD} + (1 - k_{DRES}) \cdot k_p)]^2}{RR_M} \right]$$

$$P_{BESS} = S_{tr} \cdot \left(1 - \frac{RR_L}{RR_M}\right) \cdot (1 - k_{LD} + (1 - k_{DRES}) \cdot k_p))$$

Assuming a BESS cost of 600$/1kWh → 10.225,00 $

Ramp Rate Limit Revision – Puerto Rico 1 **[3]**

- In previous studies, PREPA proposed a limit of 10%/min for the RRL → to protect the system from significant changes in power from wind and PV power plants.
- This rule will be re-assessed due to
  - ✓ high costs (large ESS or even diesel generators)
  - ✓ the fact that the aggregate wind and solar ramp distribution as a percentage of combined capacity is much smaller than for individual plants

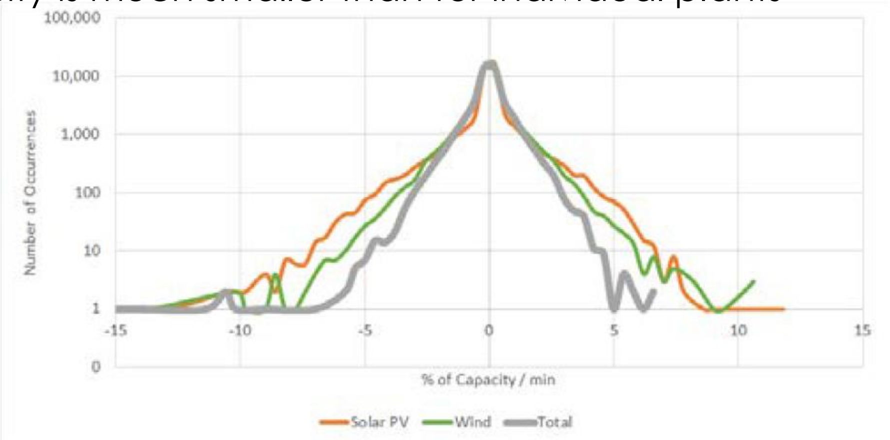


Figure: Aggregate wind and solar 1-min ramps **[3]**

Ramp Rate Limit Revision – Puerto Rico 2 **[3]**

- PV vs. PV+BESS→the BESS provides only marginal improvements (the size of the BESS is not mentioned in this paragraph)
- **Conclusion**: Even if PVs are equipped with ESS, the ESS can be controlled to provide the most benefits on an aggregate system level rather than responding to resource variability within only the plant footprint.
- Probably a faster ESS could provide better smoothing at DRES level → BESS is too slow to follow cloud movement

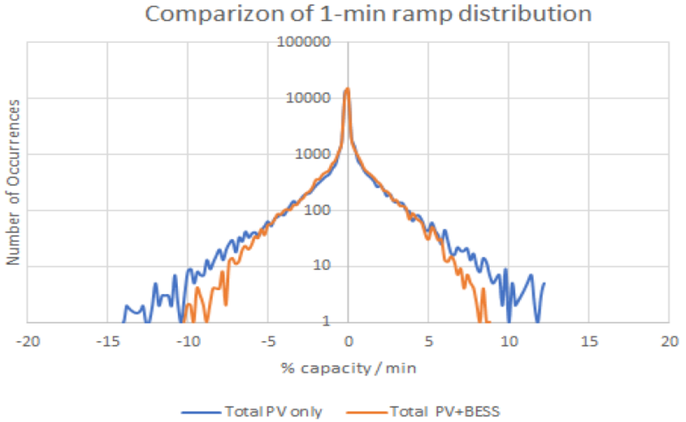
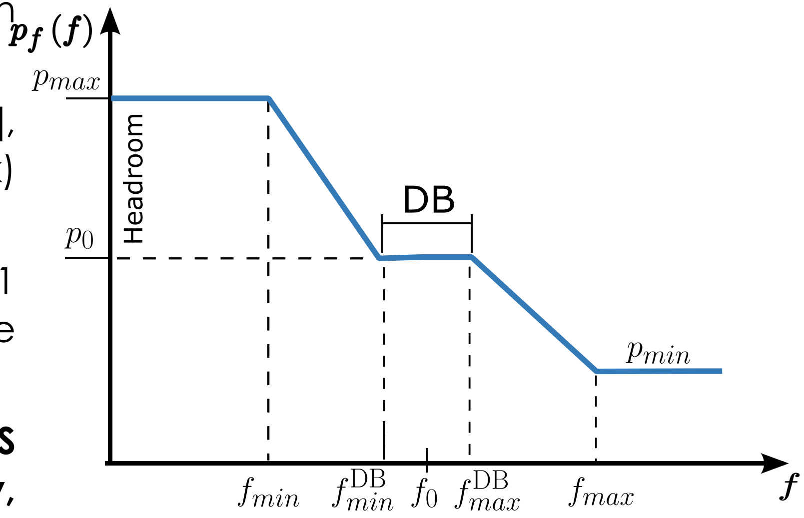


Figure: Comparison of total PV and PV+BESS ramps for a typical summer month **[3]**

When should RRL be activated?

- EASY-RES considers DRES located within distribution networks (DNs)
- Within DNs, already existing Standards like **[20]** and **[21]**, as well as individual grid codes (e.g., Germany, Denmark) prescribe the operation of DRES with *P-f* droops
- Droops with Deadband around 200mHz (range 49.9-50.1 Hz) → Hence they are in the Limited Frequency Sensitive mode
- **When an under-frequency event happens, the DRES+ESS system should not curtail any power → on the contrary, inject as much power as possible!**



✓ **In the upcoming EASY-RES deliverable 2.5, we propose that the RRL is activated when the frequency is within a deadband**

✓ **In the upcoming EASY-RES deliverable 6.5 the RRL control use as preventive action will be demonstrated under a large frequency disturbance**

When should RRL be activated?

- In **[22]** the operation of a 20MW PVPP is analyzed, and measurements are presented when the PVPP provides grid-friendly Ancillary Services, e.g., PFR and ramp-rate control.
- The maximum rate of change of power is 10% of nameplate capacity per minute while for the tests also the RRL of (20% operating capacity/minute is considered.
- The plant output was set to follow a target droop characteristic with 5% slope.
- Most of the time this was achieved except during periods of large solar ramps.

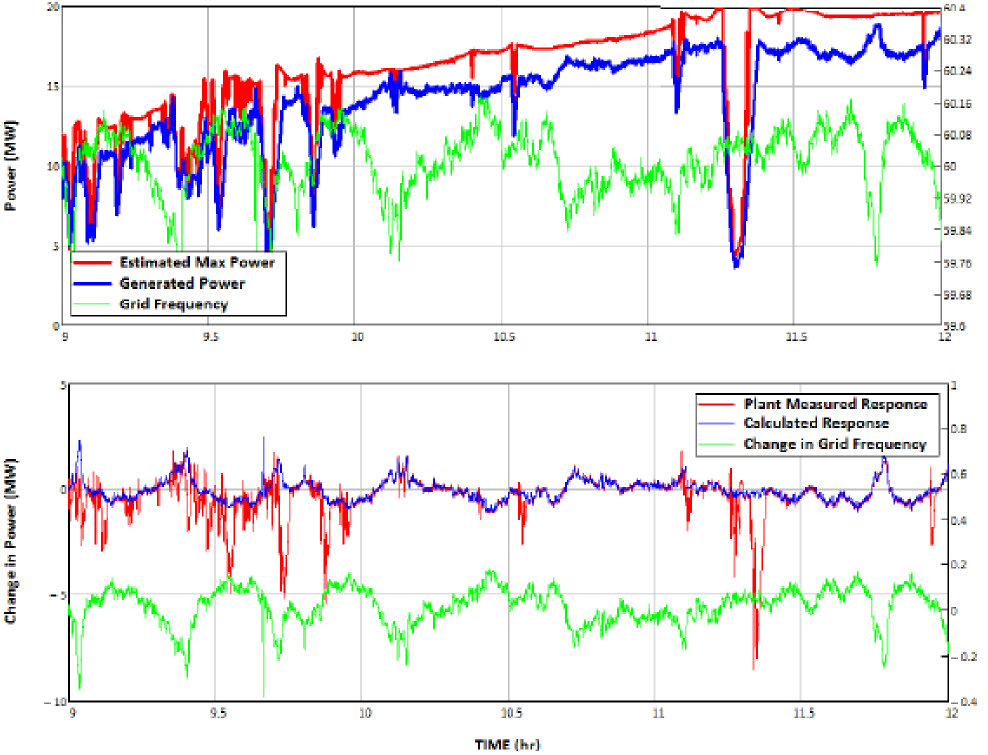


Figure: Power data for 5% droop test, August 18, 2015, **[22]**

When should RRL be activated?

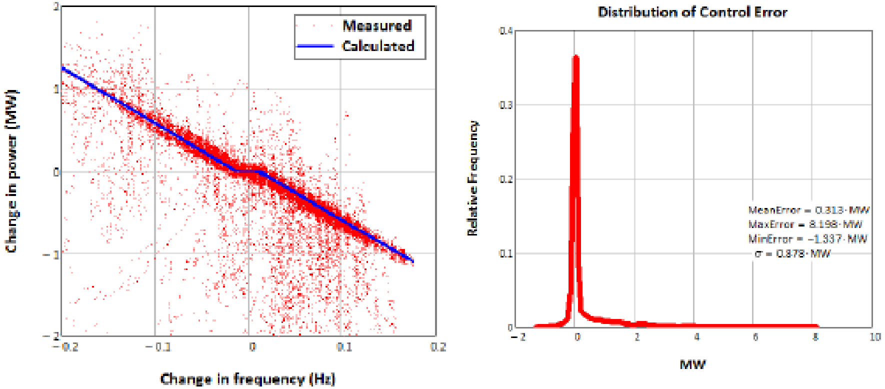


Figure: Measured droop characteristic and Statistical error, **[22]**

The measured droop performance was unsatisfactory and did not meet the expectation for a converter-coupled generator to provide fast and precise droop response.

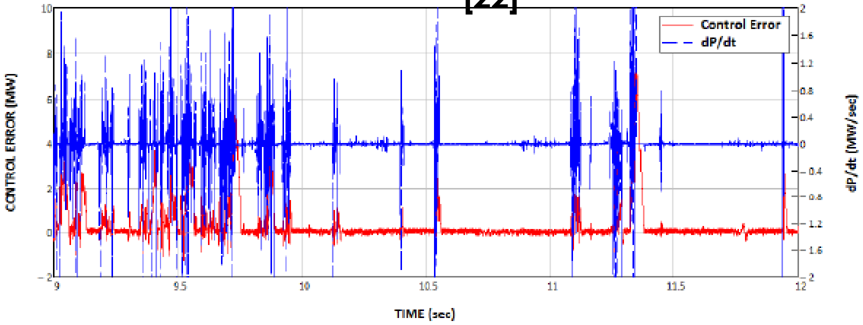


Figure: Control error during 5% droop test, **[22]**

The controller error was at a zero level during periods of smooth production, and it increased significantly during solar ramping events → Why?

Droop and RRL control simultaneously performed!

When should RRL be activated?

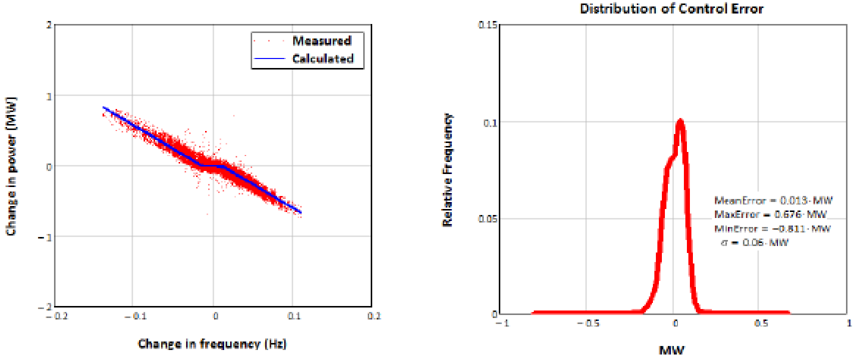


Figure: Measured droop characteristic – Slope 5%- and Statistical error, **[22]**

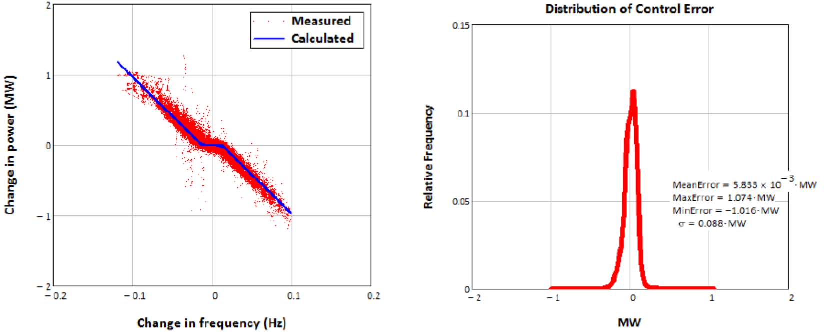


Figure: Measured droop characteristic – Slope 3%- and Statistical error, **[22]**

More droop tests were conducted with the modified control. Without any active ramp-rate limiting, the plant demonstrated much better droop performance with far less scatter.

When should RRL be activated?

For this reason, in **[23]** where the reliability services provided by a 300-MW Solar PVPP →

All active power ramp rates in the PPC were bypassed when the plant is in frequency regulation mode

- ✓ All ramp-rate settings in the PV power plant's PPC were set at very high level of 600 MW/min (10 MW/sec) during the AGC tests
- ✓ The active power ramp-rate limit in the PPC was set at 600 MW/min (10 MW/sec) during the droop control tests

References

[1] Paul Denholm, Erik Ela, Brendan Kirby, and Michael Milligan, "The Role of Energy Storage with Renewable Electricity Generation", Technical Report, NREL/TP-6A2-47187, January 2010, Available [Online]: https://www.nrel.gov/docs/fy10osti/47187.pdf

[2] Elia Group Public Consultation "Methodology for the dimensioning of the aFRR needs", 2 June 2020, Available [Online]: https://tinyurl.com/52xy36h2

[3] ADMIE Technical Report "ΜΕΘΟΔΟΛΟΓΙΑ – Καθορισμός Ζωνικών/Συστημικών αναγκών Ισχύος Εξισορρόπησης", August 2020, Available [Online]: https://tinyurl.com/d3h9saza

[4] Vahan Gevorgian, Murali Baggu, and Dan Ton, "Interconnection Requirements for Renewable Generation and Energy Storage in Island Systems: Puerto Rico Example", *4th International Hybrid Power Systems Workshop*, Crete, Greece, May 22–23, 2019, Available [Online]: https://www.nrel.gov/docs/fy19osti/73848.pdf

[5] Eirgrid and SONI Technical Report: "LFC Block Operational Agreement (LBCBOA) Ireland and Northern Ireland (also incorporating LFC operational agreement)", 23 August 2019, Available [Online]: https://tinyurl.com/9am99brr

[6] Malamaki, K.-N.et al, "D1.1 description of the metrics developed for the quasi-steady-state operation and report on the review of the respective current grid codes," *H2020 EASY-RES Project Deliverable*, Aug. 2018. Available [Online]: https://cordis.europa.eu/project/id/764090/results

[7] J. Martins, S. Spataru, D. Sera, D.-I. Stroe, and A. Lashab, "Comparative study of ramp-rate control algorithms for pv with energy storage systems," *Energies*, vol. 12, no. 7, 2019.

References

[8] K.-N. Malamaki, A. Marano, U. Mushtaq, and M. Cvetkovic, "D1.3 1streport on the reactive power control algorithm for converter-interfaced DRES/BESS and analytical tool for parametric BESS sizing for low-frequency power smoothing," *H2020 EASY-RES Project Deliverable*, Jul. 2019, Available [Online]: https://cordis.europa.eu/project/id/764090/results

[9] S. Sukumar, M. Marsadek, K. Agileswari, and H. Mokhlis, "Ramp-rate control smoothing methods to control output power fluctuations from solar photovoltaic (pv) sources—a review, "*Journal of Energy Storage*, vol. 20, pp. 218 – 229, 2018.

[10] G. Gonzalez, R. Chacon, B. Delgado, D. Benavides, and J. Espinoza, "Study of energy compensation techniques in photovoltaic solar systems with the use of supercapacitors in low-voltage networks," *Energies*, vol. 13, no. 15, 2020.

[11] Kyriaki-Nefeli D. Malamaki, Francisco Casado-Machado, Manuel Barragan-Villarejo, Andrei Mihai Gross, Georgios C. Kryonidis, Jose L. Martinez-Ramos, Charis S. Demoulias, "Ramp-rate control of DRES employing supercapacitors in distribution systems," presented in *4th International Conference on Smart Energy Systems and Technologies (SEST 2021)*, pp. 1–6, 2021

[12] Andrei Mihai Gross, Kyriaki-Nefeli D. Malamaki, Manuel Barragan-Villarejo, Georgios C. Kryonidis, Jose L. Martinez-Ramos, Charis S. Demoulias, "Energy Management in Converter-Interfaced Renewable Energy Sources Through Ultracapacitors for Provision of Ancillary Services," presented in *4th International Conference on Smart Energy Systems and Technologies (SEST 2021)*, pp. 1–6, 2021

References

[13] Y. Yuan, C. Sun, M. Li, S. S. Choi, and Q. Li, “Determination of optimal supercapacitor-lead-acid battery energy storage capacity for smoothing wind power using empirical mode decomposition and neural network,” *Electr. Power Syst. Res.*, vol. 127, pp. 323–331, 2015

[14] H. Jia, Y. Mu, Y. Qi, "A statistical model to determine the capacity of battery–supercapacitor hybrid energy storage system in autonomous microgrid", Int. J. Electr. Power Energy Syst., vol. 54, pp. 516-524, Jan. 2014.

[15] J. Marcos, I. de la Parra, M. García, L. Marroyo, "Control strategies to smooth short-term power fluctuations in large photovoltaic plants using battery storage systems", *Energies*, vol. 7, no. 10, pp. 6593-6619, Oct. 2014.

[16] I. de la Parra, J. Marcos, M. García, L. Marroyo, "Control strategies to use the minimum energy storage requirement for PV power ramp-rate control", *Solar Energy*, vol. 111, pp. 332-343, Nov. 2014

[17] J. Marcos, O. Storkel, L. Marroyo, M. Garcia, E. Lorenzo, "Storage requirements for PV power ramp-rate control", *Solar Energy*, vol. 99, pp. 28-35, Nov. 2013.

[18] I. de la Parra, J. Marcos, M. Garcia, L. Marroyo, "Storage requirements for PV power ramp-rate control in a PV fleet", *Solar Energy*, vol. 118, pp. 426-440, June 2015.

[19] I. N. Moghaddam and B. Chowdhury, "Battery energy storage sizing With Respect to PV-induced power ramping concerns in distribution networks," *2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, 2017, pp. 1-5.

References

[20] *EN50549-1:2019 Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV distribution network- Generating plants up to and including Type B*, European Committee for Electrotechnical Standardization (CENELEC), 2019.

[21] *EN50549-2:2019 Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating Plants up to and including Type B*, European Committee for Electrotechnical Standardization (CENELEC), 2019.

[22] Vahan Gevorgian and Barbara O'Neill, "Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants", *Technical Report NREL/TP-5D00-65368*, January 2016, Available [Online]: https://www.nrel.gov/docs/fy16osti/65368.pdf

[23] Clyde Loutan, Peter Klauer, Sirajul Chowdhury, Stephen Hall, Mahesh Morjaria, Vladimir Chadliev, Nick Milam, Christopher Milan, Vahan Gevorgian, "Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant", *Technical Report NREL/TP-5D00-67799*, March 2017, Available [Online]: https://www.nrel.gov/docs/fy17osti/67799.pdf

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Thank you!

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