Integration of High Penetration of Solar and Wind Power in Power Systems: Experiences and Challenges

Lecture 3-4 + Tutorial 2

Lennart Söder
Professor in Electric Power Systems
KTH, Royal Institute of Technology, Stockholm, Sweden

Set-up of Lectures L3-L4 + T2

Lecture L3: Solar power, examples and general challenges

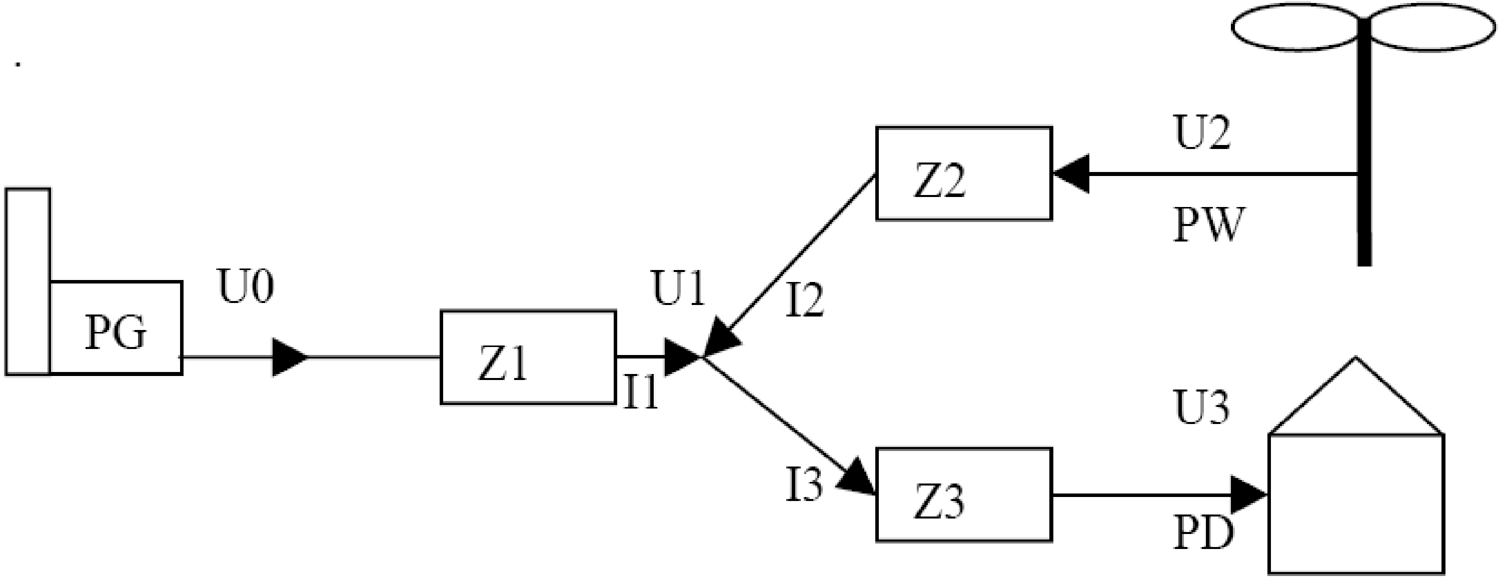
Lecture L4: Voltage control in low voltage grids with solar power

Tutorial T2: Application of voltage control in radial and meshed grids with solar and wind power

Aim of a power system

1. The consumers should get the required power (e.g. a 60 W bulb), when the push the on-button. This should work no matter there is an outage in a plant, wind is changing etc. = keep a **balance between total production and total consumption**.
2. The consumers must have a **realistic voltage**, e.g. around 230 V, in the outlet.
3. Point 1-2 should be obtained at a **realistic reliability.** This is **never** 100,000... percent,
4. Point 1-3 should be obtained in an **economic and sustainable** way.

Wind power integration challenge



Solar PV at Ekerö - Stockholm

28 August 2017

Lennart Söder
Professor Electric Power Systems, KTH

”Renewable private house”

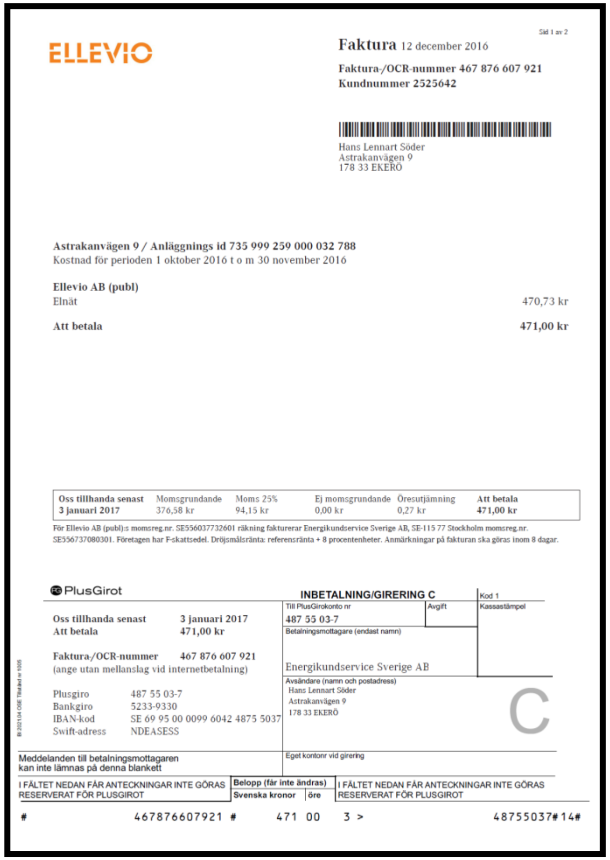
5-6 tons/year
min 4,9 kWh/kg

Wood burning for heating and solar power for electricity

Measurements at Lennart Söder: (ca 4300 kWh/year)

(Nordpools price/hour for SE3 + certifikats + 3.5 öre/kWh + 390 SEK/year)

+ El.tax + VAT



Sid 1 av 2

ELLEVIO

Faktura 12 december 2016

Faktura-/OCR-nummer 467 876 607 921
Kundnummer 2525642

Hans Lennart Söder
Astrakanvägen 9
178 33 EKERÖ

Astrakanvägen 9 / Anläggnings id 735 999 259 000 032 788
Kostnad för perioden 1 oktober 2016 t o m 30 november 2016

Ellevio AB (publ)	
Elnät	470,73 kr
Att betala	**471,00 kr**

Oss tillhanda senast	Momsgrundande	Moms 25%	Ej momsgrundande	Öresutjämning	Att betala
3 januari 2017	376,58 kr	94,15 kr	0,00 kr	0,27 kr	**471,00 kr**

För Ellevio AB (publ):s momsreg.nr. SE556037732601 räkning fakturerar Energikundservice Sverige AB, SE-115 77 Stockholm momsreg.nr. SE556737080301. Företagen har F-skattsedel. Dröjsmålsränta: referensränta + 8 procentenheter. Anmärkningar på fakturan ska göras inom 8 dagar.

PlusGirot

INBETALNING/GIRERING C

Kod 1

Oss tillhanda senast	**3 januari 2017**
Att betala	**471,00 kr**
Faktura-/OCR-nummer	**467 876 607 921**

(ange utan mellanslag vid internetbetalning)

Plusgiro	487 55 03-7
Bankgiro	5233-9330
IBAN-kod	SE 69 95 00 0099 6042 4875 5037
Swift-adress	NDEASESS

Bl 2021.04 OSE Tillstånd nr 1005

Till PlusGirokonto nr
487 55 03-7

Avgift

Kassastämpel

Betalningsmottagare (endast namn)
Energikundservice Sverige AB

Avsändare (namn och postadress)
Hans Lennart Söder
Astrakanvägen 9
178 33 EKERÖ

C

Meddelanden till betalningsmottagaren
kan inte lämnas på denna blankett

Eget kontonr vid girering

I FÄLTET NEDAN FÅR ANTECKNINGAR INTE GÖRAS
RESERVERAT FÖR PLUSGIROT

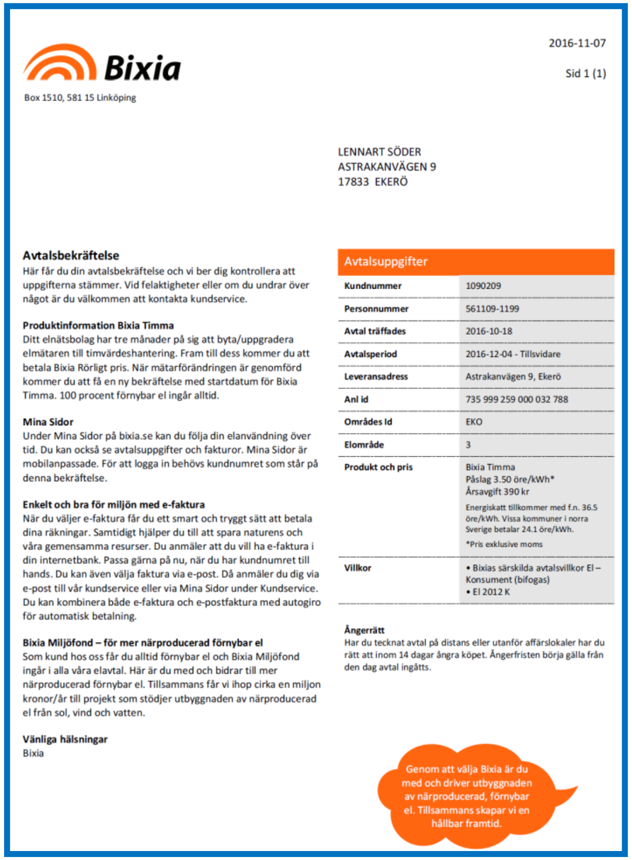
Belopp (får inte ändras)
Svenska kronor | **öre**

I FÄLTET NEDAN FÅR ANTECKNINGAR INTE GÖRAS
RESERVERAT FÖR PLUSGIROT

467876607921 # 471 00 3 > 48755037#14#

Grid invoice

(monopoly)



Bixia

Box 1510, 581 15 Linköping

2016-11-07

Sid 1 (1)

LENNART SÖDER
ASTRAKANVÄGEN 9
17833 EKERÖ

Avtalsbekräftelse

Här får du din avtalsbekräftelse och vi ber dig kontrollera att uppgifterna stämmer. Vid felaktigheter eller om du undrar över något är du välkommen att kontakta kundservice.

Produktinformation Bixia Timma

Ditt elnätsbolag har tre månader på sig att byta/uppgradera elmätaren till timvärdeshantering. Fram till dess kommer du att betala Bixia Rörligt pris. När mätarförändringen är genomförd kommer du att få en ny bekräftelse med startdatum för Bixia Timma. 100 procent förnybar el ingår alltid.

Mina Sidor

Under Mina Sidor på bixia.se kan du följa din elanvändning över tid. Du kan också se avtalsuppgifter och fakturor. Mina Sidor är mobilanpassade. För att logga in behövs kundnumret som står på denna bekräftelse.

Enkelt och bra för miljön med e-faktura

När du väljer e-faktura får du ett smart och tryggt sätt att betala dina räkningar. Samtidigt hjälper du till att spara naturens och våra gemensamma resurser. Du anmäler att du vill ha e-faktura i din internetbank. Passa gärna på nu, när du har kundnumret till hands. Du kan även välja faktura via e-post. Då anmäler du dig via e-post till vår kundservice eller via Mina Sidor under Kundservice. Du kan kombinera både e-faktura och e-postfaktura med autogiro för automatisk betalning.

Bixia Miljöfond – för mer närproducerad förnybar el

Som kund hos oss får du alltid förnybar el och Bixia Miljöfond ingår i alla våra elavtal. Här är du med och bidrar till mer närproducerad förnybar el. Tillsammans får vi ihop cirka en miljon kronor/år till projekt som stödjer utbyggnaden av närproducerad el från sol, vind och vatten.

Vänliga hälsningar
Bixia

Avtalsuppgifter	
Kundnummer	1090209
Personnummer	561109-1199
Avtal träffades	2016-10-18
Avtalsperiod	2016-12-04 - Tillsvidare
Leveransadress	Astrakanvägen 9, Ekerö
Anl id	735 999 259 000 032 788
Områdes Id	EKO
Elområde	3
Produkt och pris	Bixia Timma Påslag 3.50 öre/kWh* Årsavgift 390 kr Energiskatt tillkommer med f.n. 36.5 öre/kWh. Vissa kommuner i norra Sverige betalar 24.1 öre/kWh. *Pris exklusive moms
Villkor	• Bixias särskilda avtalsvillkor El – Konsument (bifogas) • El 2012 K

Ångerrätt

Har du tecknat avtal på distans eller utanför affärslokaler har du rätt att inom 14 dagar ångra köpet. Ångerfristen börja gälla från den dag avtal ingåtts.

Genom att välja Bixia är du med och driver utbyggnaden av närproducerad, förnybar el. Tillsammans skapar vi en hållbar framtid.

Energy invoice

(competition): ≈140 actors

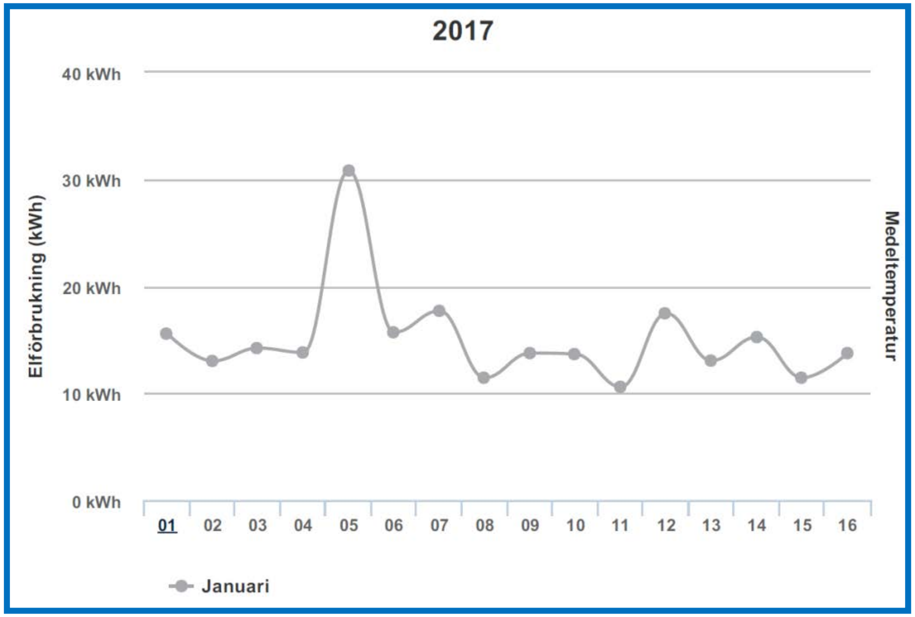
- Sends data one time per day
- Sends hourly data
- Uses GSM (GPRS)

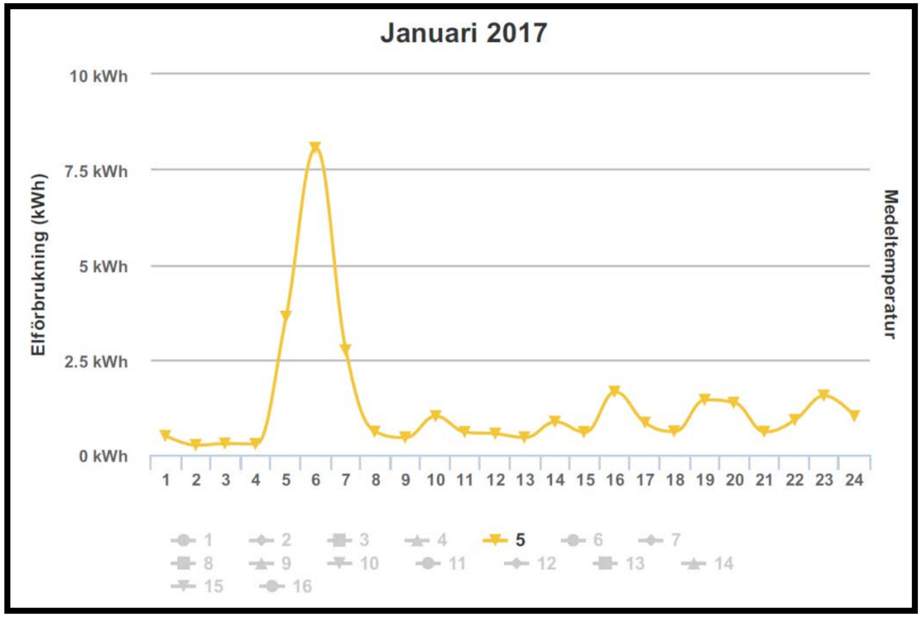
- Surplus caused by PV
- Sold for Nordpool price per hour
- Additional 60 öre/kWh in tax reduction

Measurements at Lennart Söder: (ca 4300 kWh/year)

(Nordpools price/hour for SE3 + certifikats + 3.5 öre/kWh + 390 SEK/year)

+ tax + VAT





1 - 16 January

5 januari

Meter in January:

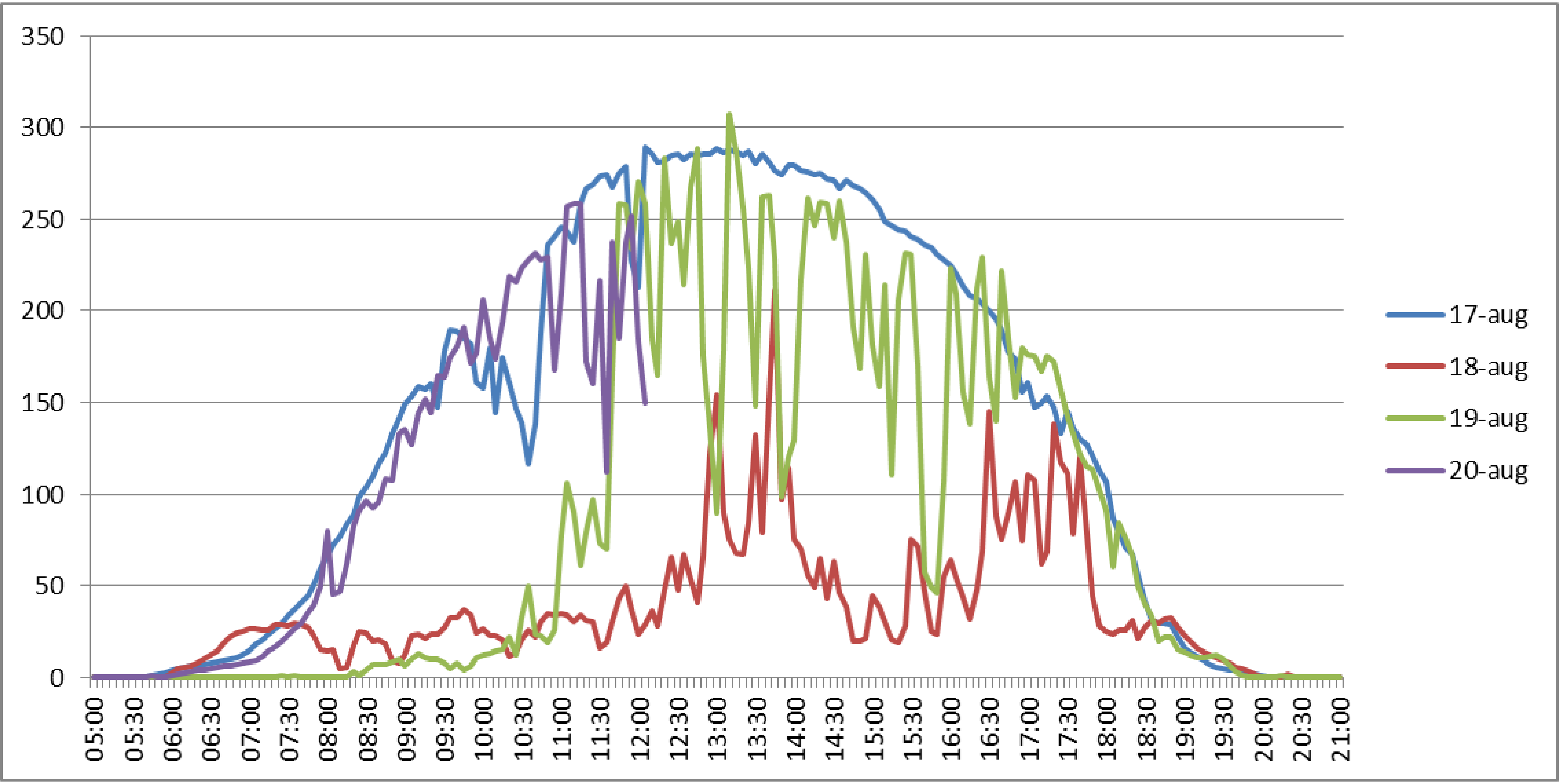
New meter:

Lennart Söders solar PV: Ekerö / Ellevio

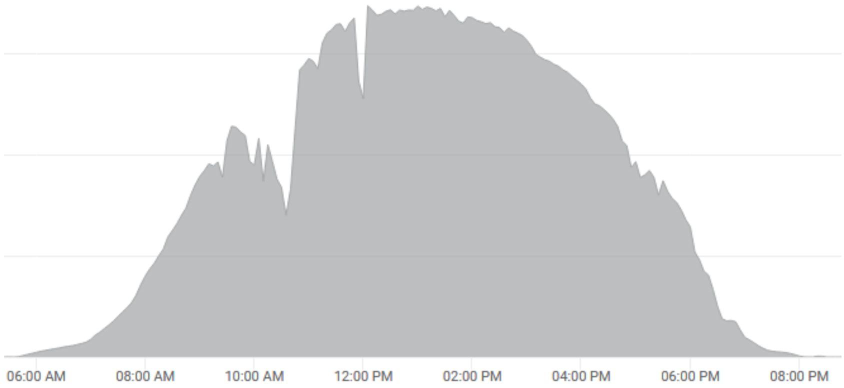
← **Converter from PV (DC) to grid (AC)**

- **4,5 kW (PV-max and converter)**
- **Installed 17-19 July 2017**
- **Ca 4300 kWh/year ≈ yearly consumption**
- **25 m^2**

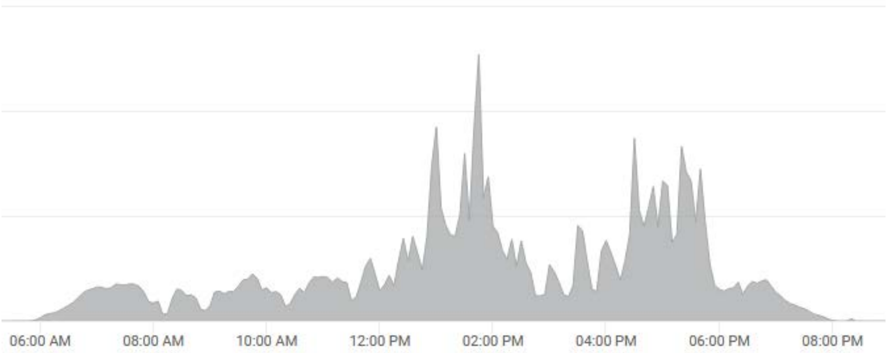
Production: 17-20 August, 2017
[Wh/5-minutes]: 300 ➔ 3,6 kW



Production: 17-20 August, 2017



08/17/2017 Premium

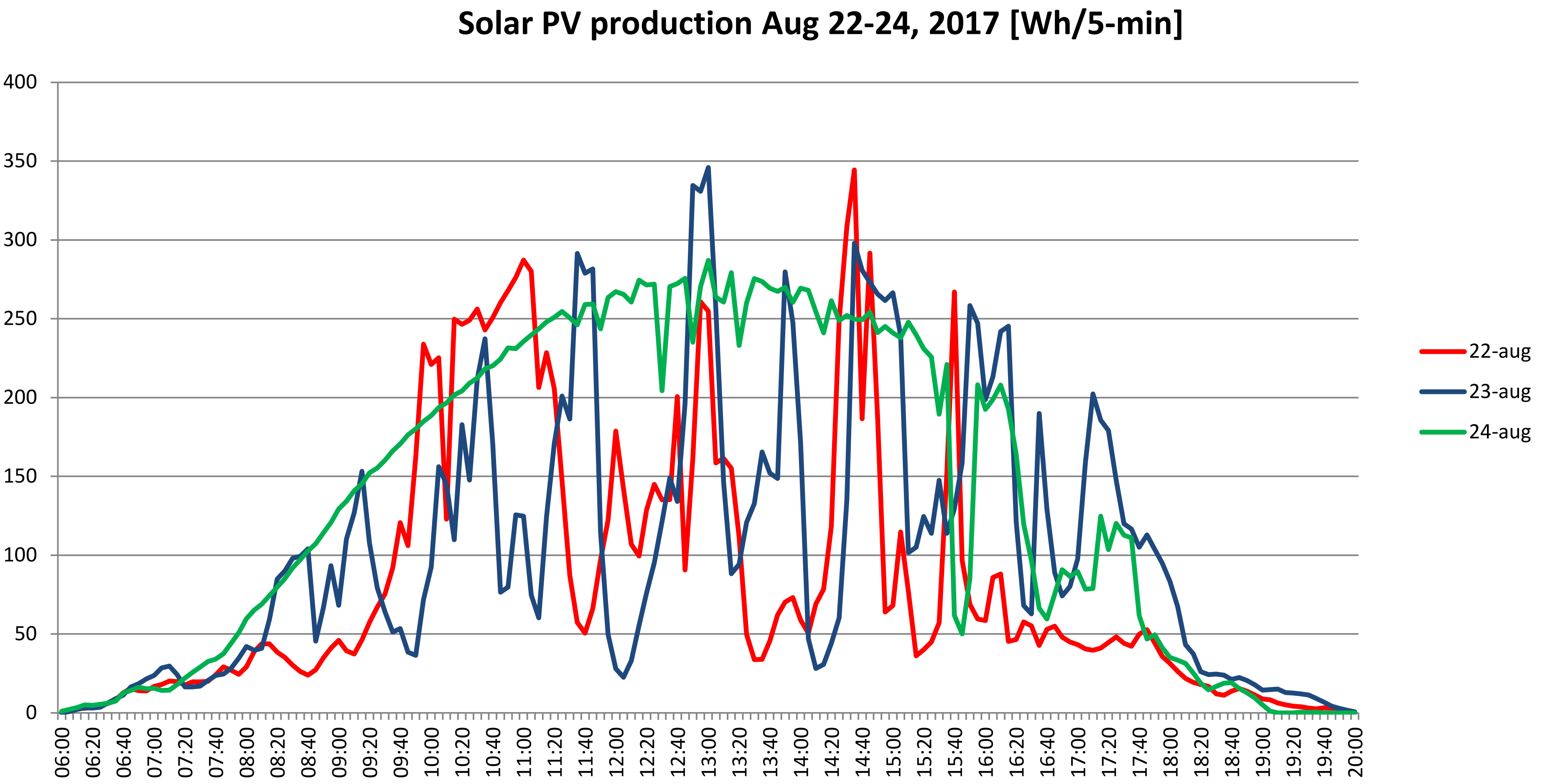


08/18/2017

08/19/2017

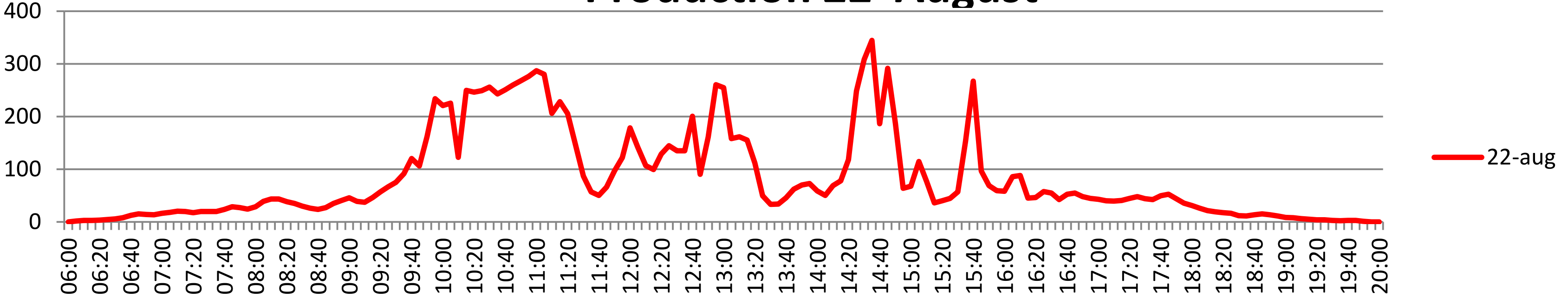
08/20/2017

Production: 22-24 August, 2017

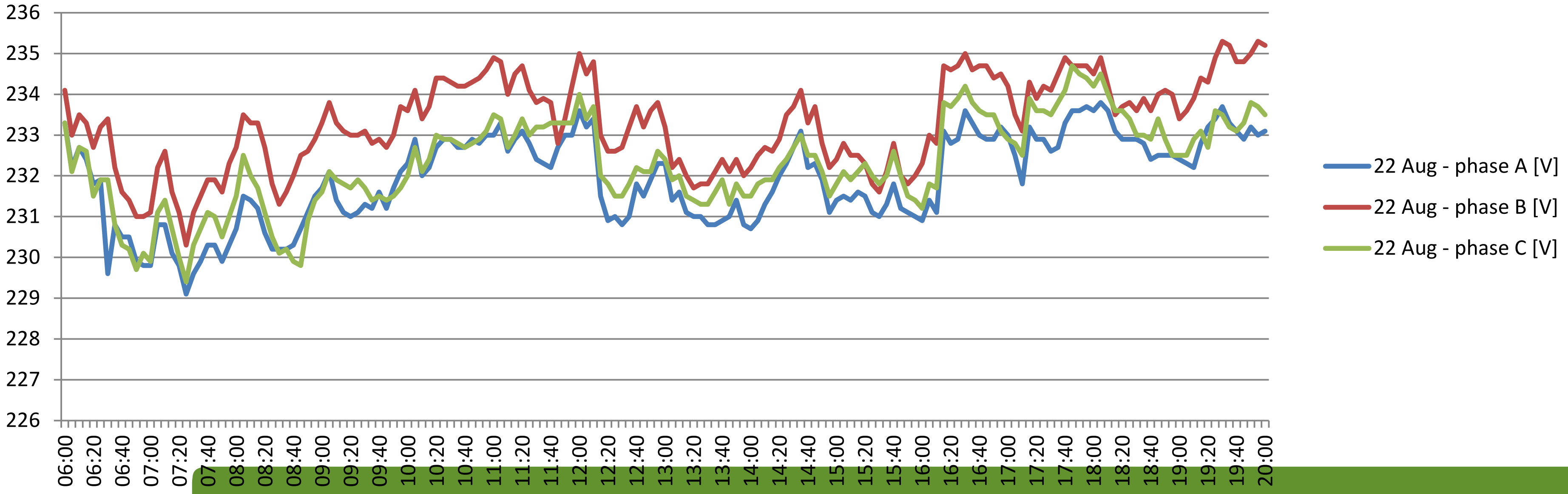


Three phase voltages: 22 August, 2017

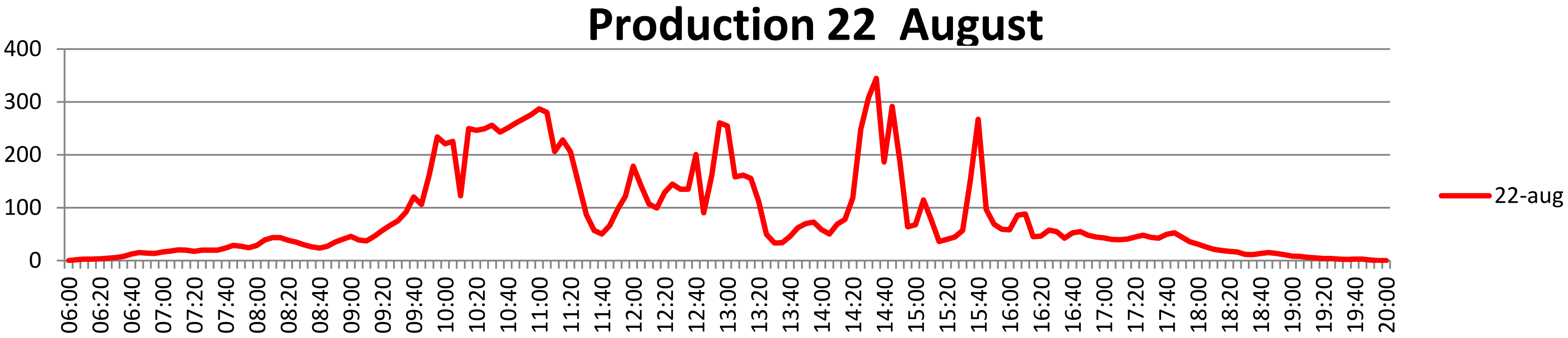
Production 22 August

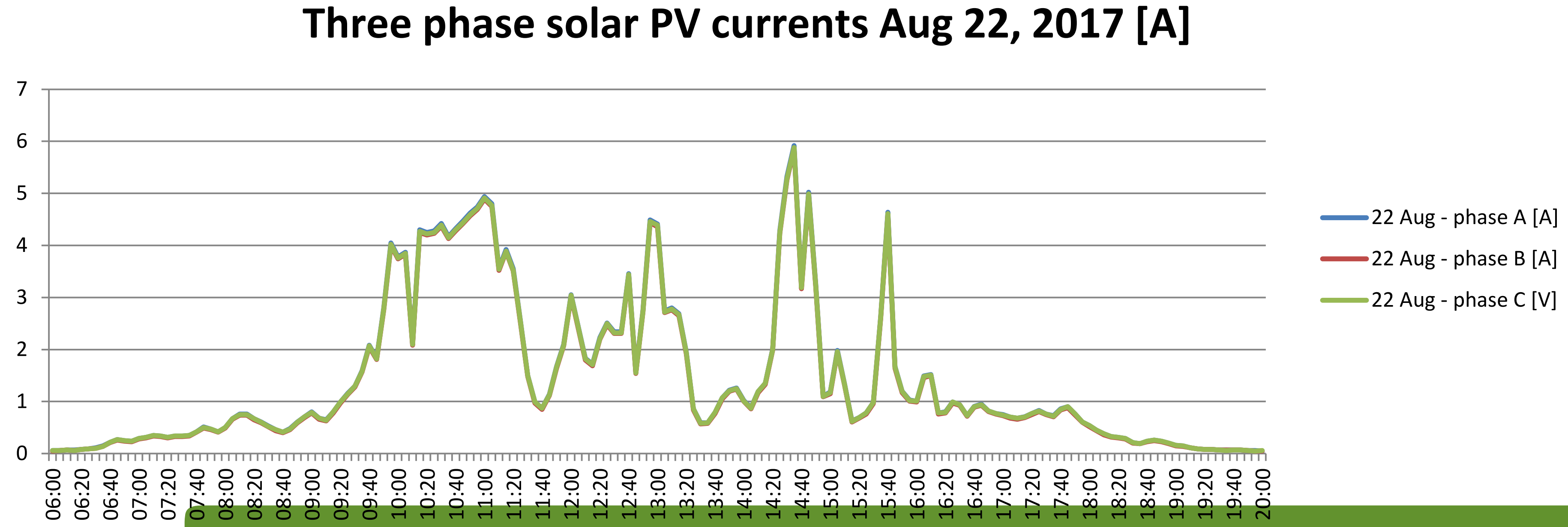


Three phase voltages Aug 22, 2017 [V]



Three phase currents: 22 August, 2017


Production 22 August


Three phase solar PV currents Aug 22, 2017 [A]

Solar power (preliminary) economics

Costs:

- **Investment cost: Panels, construction, converter, grid connection.** Borrow funding from bank and/or do not use available money for other issues: ➔ Interest rate essential!
- **Installation cost**: Do it yourself or hire persons to do it
- **Possible subsidy**: Can reduce investment cost
- **Possible grid connection fee**: Who pays for grid? Consumers and/or producers?

Income:

1. **Reduced purchase**: Some of the solar power reduces purchase. Purchase can include energy cost, grid tariff, taxes etc
2. **Surplus**: When production is higher than local demand this is fed to the system. **Net-metering** ➔ Same value as for reduced purchase. At **specific measurement** ➔ Power price of some kind, sometimes feed-in tariff
3. **Subsidies**: Different types: Certificates, Guaranties of Origin, etc

Ekerö solar power (preliminary) economics

Investment cost: 89500 SEK (PV-panels: 41720 (47%), other inv.: 17880 (20%), installation: 29900 (33%), ROT-decrease (-8055 SEK). Probably later **INSTEAD** a subsidy of 20% (-18350 SEK) ➔ Total cost of 0,8*90700 = 72560 SEK. (maybe -30% ?)

Income:

1. **Reduced purchase**: 1,26 SEK/kWh
2. **Surplus**: Nordpool price (25 öre/kWh) + Certificates (5 öre/kWh) + Guarantees of Origin (0 öre/kWh) + Tax reduction (60 öre/kWh) = 0,90 SEK/kWh
3. Assume 70% replaces consumption ➔ mean value = 0,70*1,26 + 0,30*0,90 = 1,15 SEK/kWh. 4300 kWh/year ➔ 4954 SEK/year.

Result:

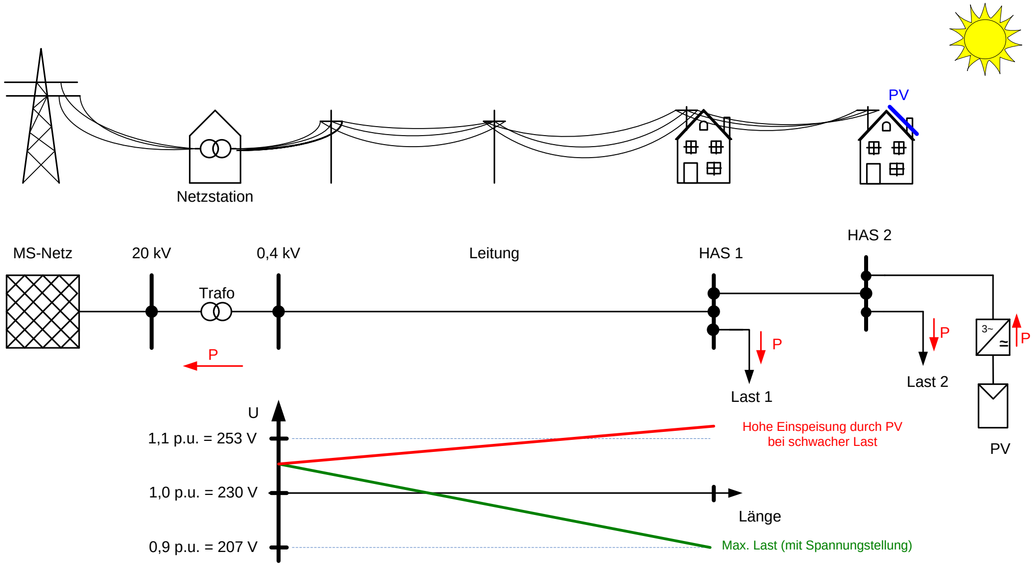
- 72560/4954 = 14,6 years
- Or: ”Yearly interest rate of 5018/72560 = 6,8% which is much higher than putting money in the bank,

Solar power in distribution grids

Steady state voltage limits

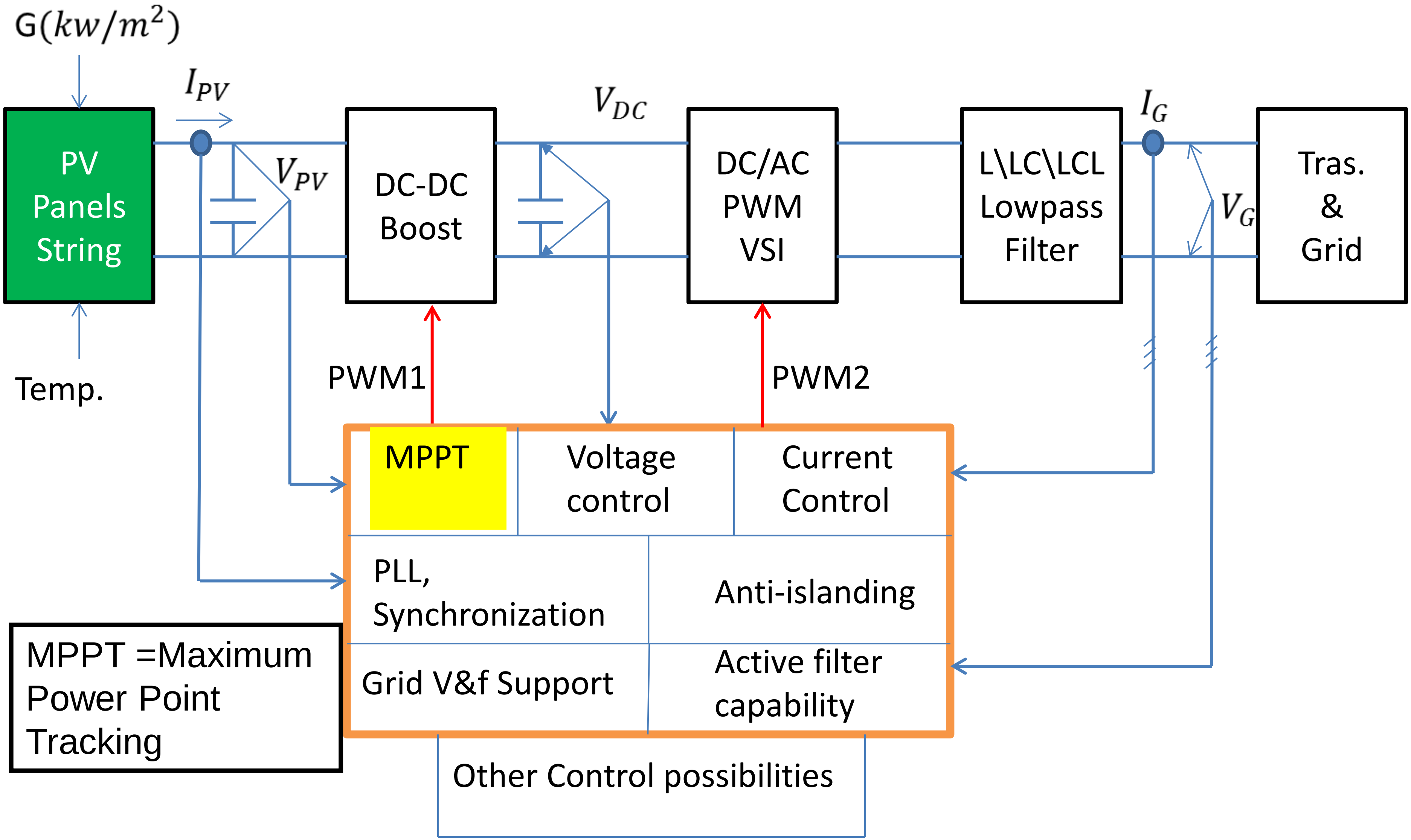
- Nearly all PV plants < 100 kWp in DE (total > 10 GWp) are connected to LV networks.
- Thermal limits of network assets (transformers, lines etc) are in many cases not the limiting factor!
- Violation of the voltage change (rise) is the main limiting factor!

  The steady state voltage change dU due to **all** generators connected to an distribution network may not changed by more than
  3% (LV) resp. 2% (MV) compared to the situation without generation



Source: B. Engel, „Lastflussumkehr in Verteilnetzen durch dezentrale Einspeisung erneuerbaren Energien - Paradigmenwechsel und technische Lösungen, 22.4.2009

An Overview from Control Structure of Double Stage PV Generator



G(kw/m^2)

I_{PV}

V_{PV}

V_{DC}

I_G

V_G

PV Panels String

Temp.

DC-DC Boost

PWM1

DC/AC PWM VSI

PWM2

L\LC\LCL Lowpass Filter

Tras. & Grid

MPPT

Voltage control

Current Control

PLL, Synchronization

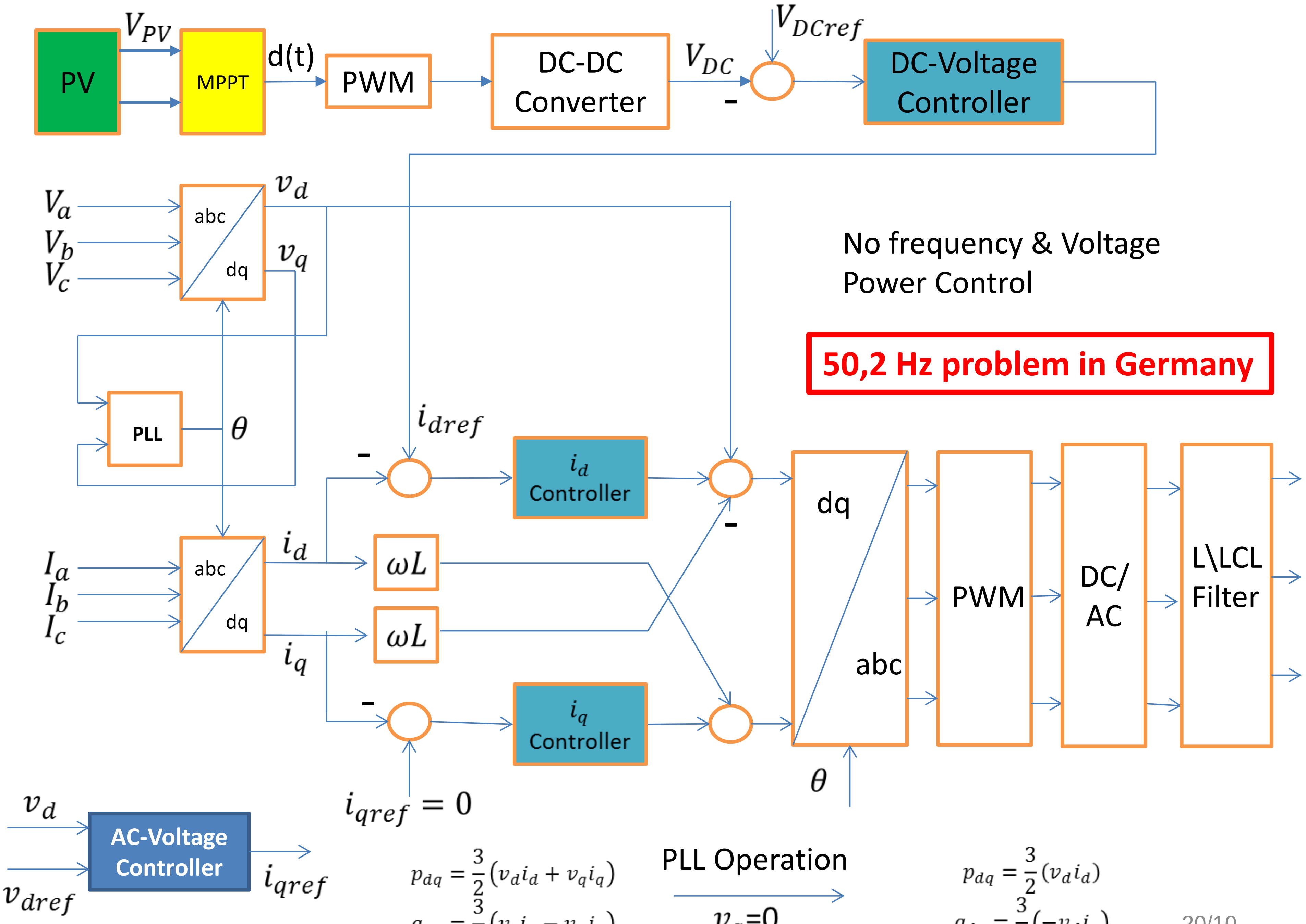
Anti-islanding

Grid V&f Support

Active filter capability

Other Control possibilities

MPPT =Maximum Power Point Tracking



No frequency & Voltage Power Control

50,2 Hz problem in Germany

$$p_{dq} = \frac{3}{2}(v_d i_d + v_q i_q)$$
$$q_{dq} = \frac{3}{2}(v_q i_d - v_d i_q)$$

PLL Operation $\xrightarrow{\hspace{2em}}$ v_q=0

$$p_{dq} = \frac{3}{2}(v_d i_d)$$
$$q_{dq} = \frac{3}{2}(-v_d i_q)$$

Large Solar Power Integration in Local and Regional Grids (KTH PhD thesis: Afshin Samadi)

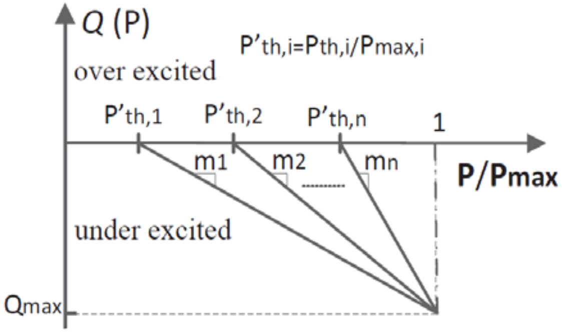
Research contribution:

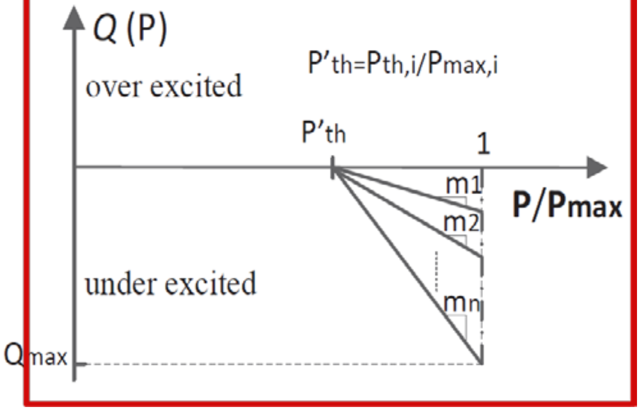
- Voltage control of distribution grids via reactive power support of PVs
- A static equivalent of distribution grids with high PV penetration level

Results:

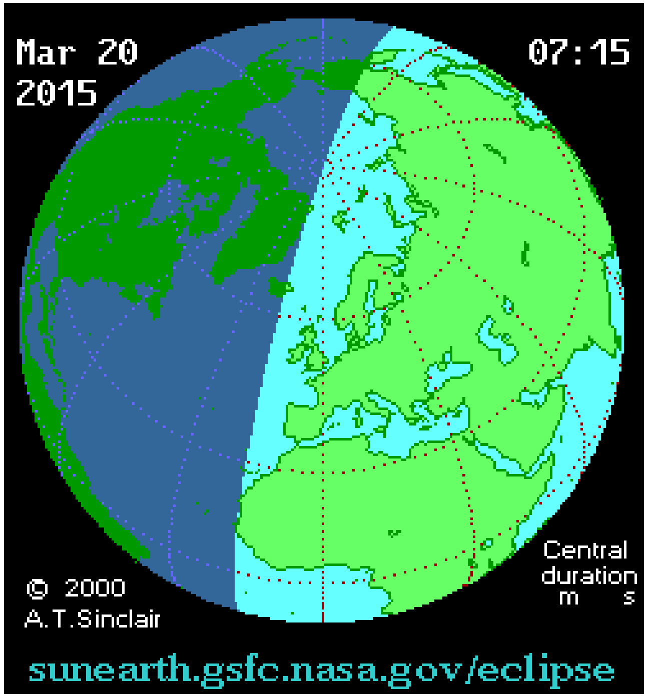
- Developing coordinated active power dependent (APD) voltage regulation, Q(P)
- Developing coordinated droop-based voltage (DBV) regulation, Q(V)
- Developing a static equivalent model of distribution grids with high penetration of PV systems embedded with a voltage support scheme

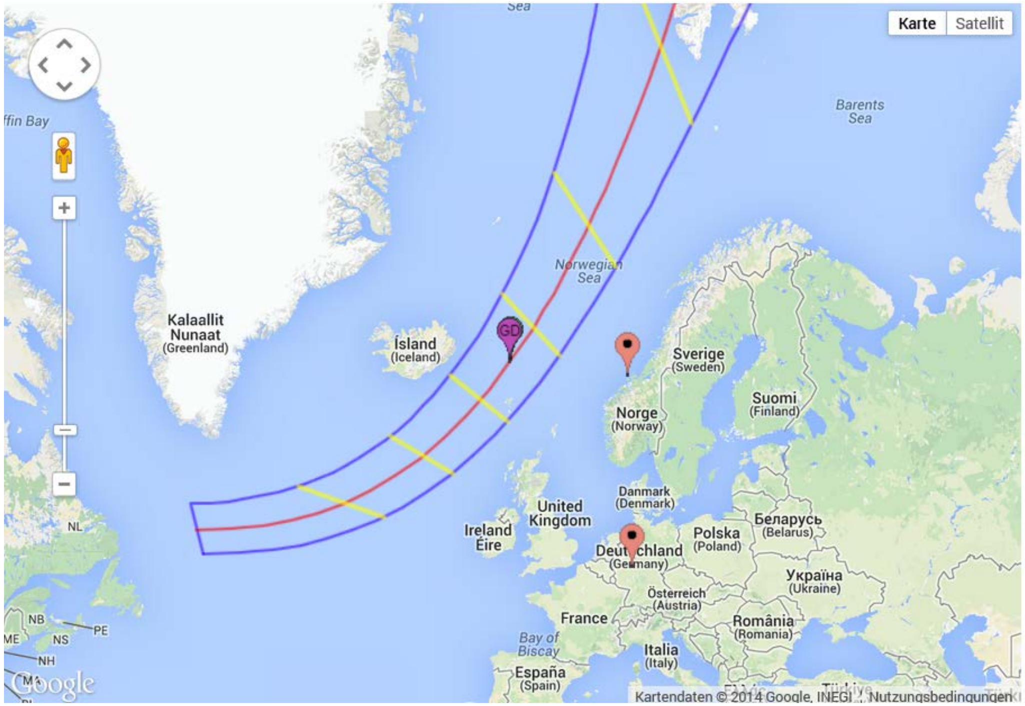
German Grid Code for PV





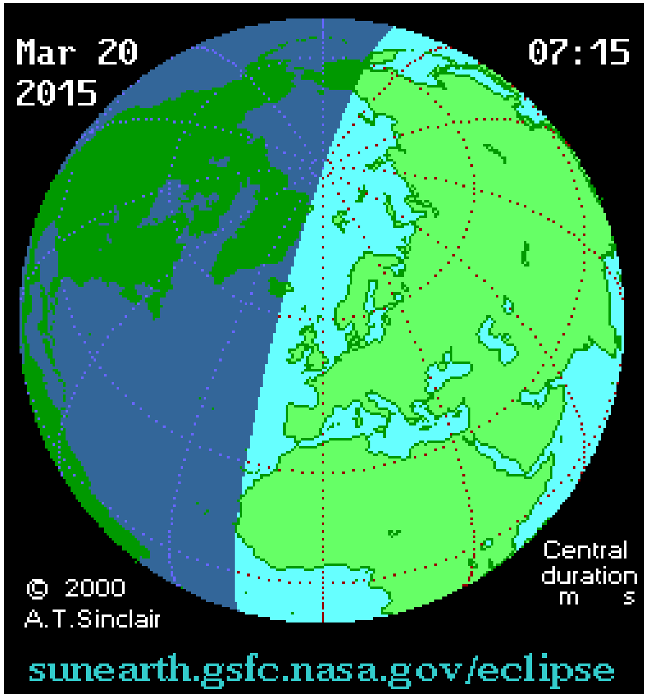
Solar eclipse over Europe on 20 March 2015

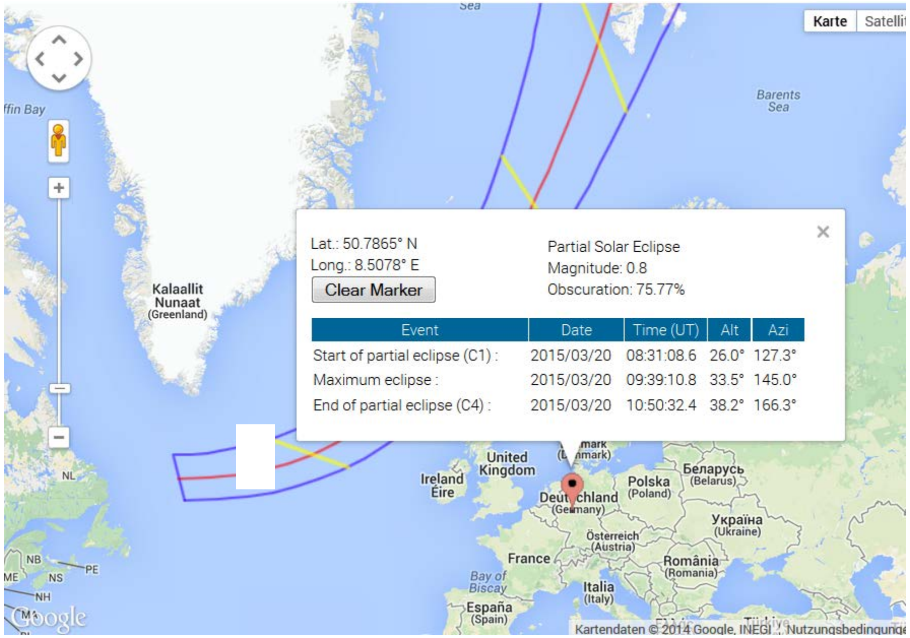




http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2015Mar20Tgoogle.html

Solar eclipse over Germany on 20 March 2015





Lat.: 50.7865° N
Long.: 8.5078° E

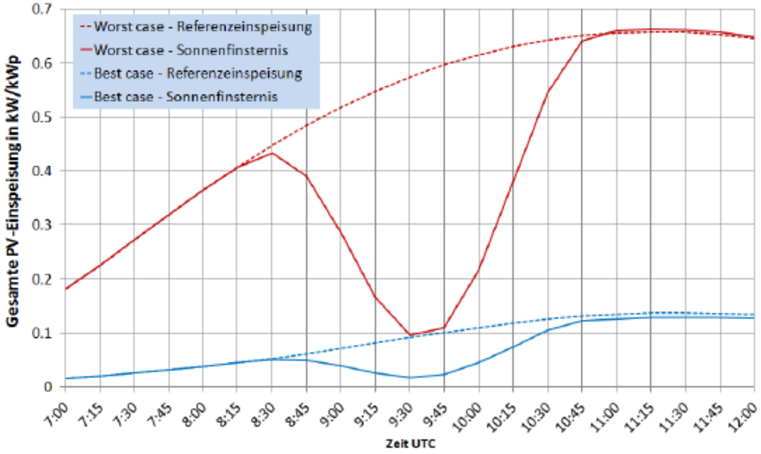
Partial Solar Eclipse
Magnitude: 0.8
Obscuration: 75.77%

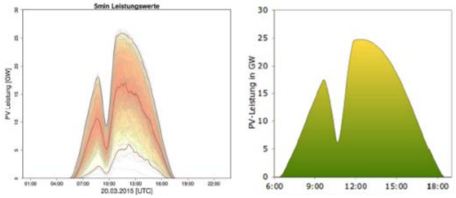
Event	Date	Time (UT)	Alt	Azi
Start of partial eclipse (C1) :	2015/03/20	08:31:08.6	26.0°	127.3°
Maximum eclipse :	2015/03/20	09:39:10.8	33.5°	145.0°
End of partial eclipse (C4) :	2015/03/20	10:50:32.4	38.2°	166.3°

http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2015Mar20Tgoogle.html

[source: HTW Berlin]

Some Results





[source: HTW Berlin und Fraunhofer ISE]

<u>Estimated</u> average <u>maximum</u> values of three studies

1. Worst Case:
    - Decrease 11 GW, -11 GW/h, 250MW/min
    - Increase 19 GW, +15GW/h, 350MW/min
2. Best Case
    - Decrease 1.3 GW, 1.3 GW/h, 25MW/min
    - Increase 4 GW, 3.2GW/h, 65MW/min

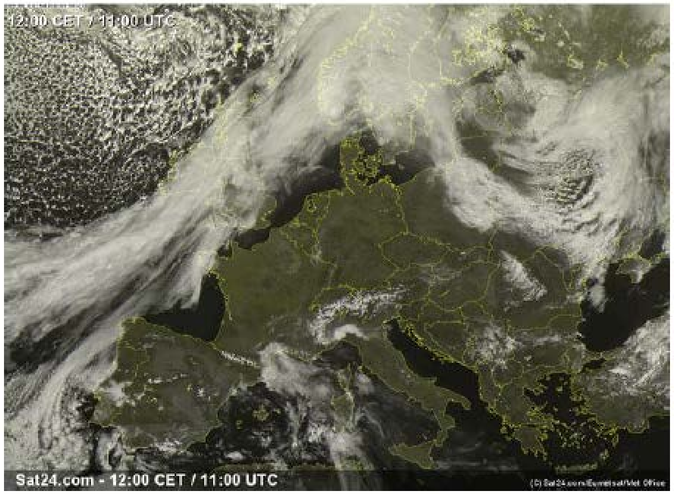


Abbildung 2-1: Satellitenbild vom 20.03.2014 um 11:00 Uhr UTC – der Tag der für das Worst Case Szenario ausgewählt wurde (Quelle: www.Sat24.com).

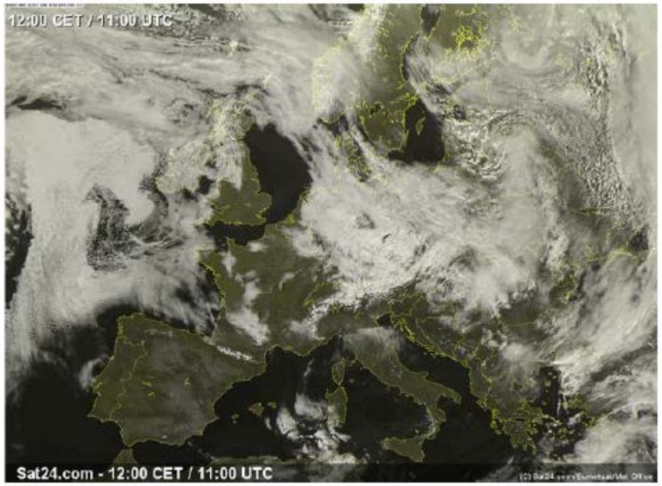
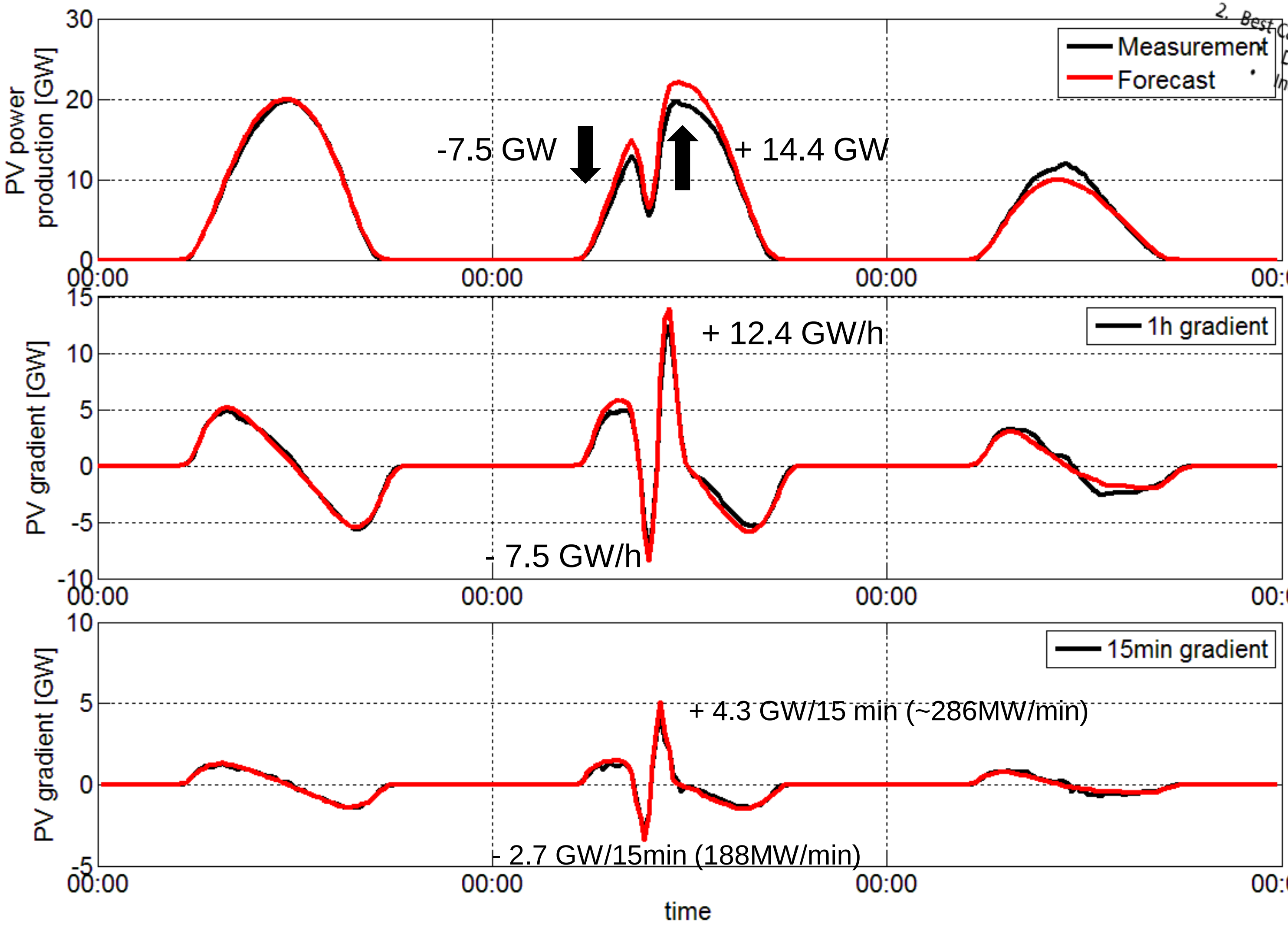
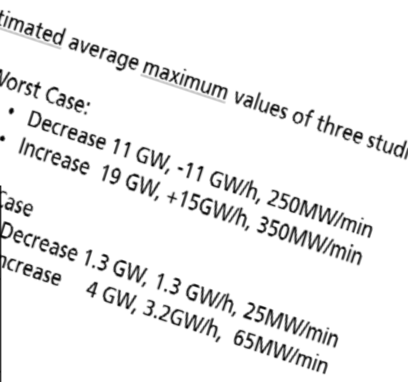


Abbildung 2-2: Satellitenbild vom 16.03.2014 um 11:00 Uhr UTC – der Tag der für das Best Case Szenario ausgewählt wurde (Quelle: www.Sat24.com).

PV Measurement & Forecast





Estimated average maximum values of three studi

1. Worst Case:
   - Decrease 11 GW, -11 GW/h, 250MW/min
   - Increase 19 GW, +15GW/h, 350MW/min
2. Best Case
   - Decrease 1.3 GW, 1.3 GW/h, 25MW/min
   - Increase 4 GW, 3.2GW/h, 65MW/min

Some comments/challenges

1. Depending on load at maximal local PV production, there can be a “need” of more grid.
2. Voltage can be controlled in PV converters. Today “German Grid Code” is used, but flexible parameters can be settled.
3. There is a balance between how much the “grid capacity” can be handled by PV-converts and/or if grid has to be expanded or use of other voltage control equipment
4. A question is if it is acceptable to “spill” solar power. Probably economical at some level, but depends on regulation
5. In Germany it is said that there are 100000 batteries, since there are requirements of “local balancing” ➔ reduced need of grid.

Active / Reactive Power Control in EWR Grids
High Penetration of Rooftop PV and Wind

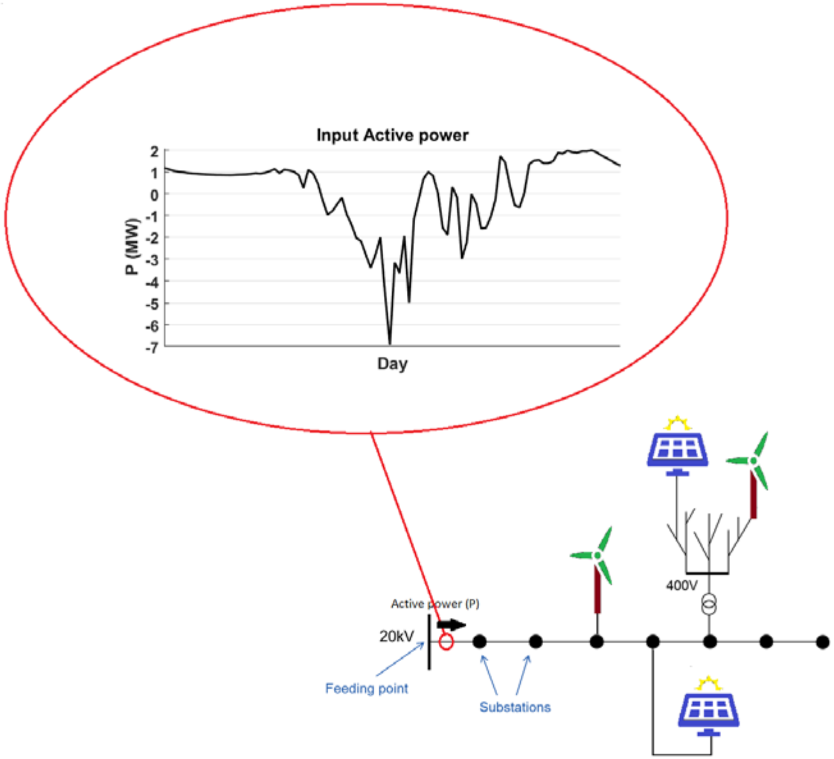
Poria Hasanpor Divshali
poriahd@kth.se

Problem Definition

Inverse active power

Problem Definition

High integration of RESs leads to reverse active power

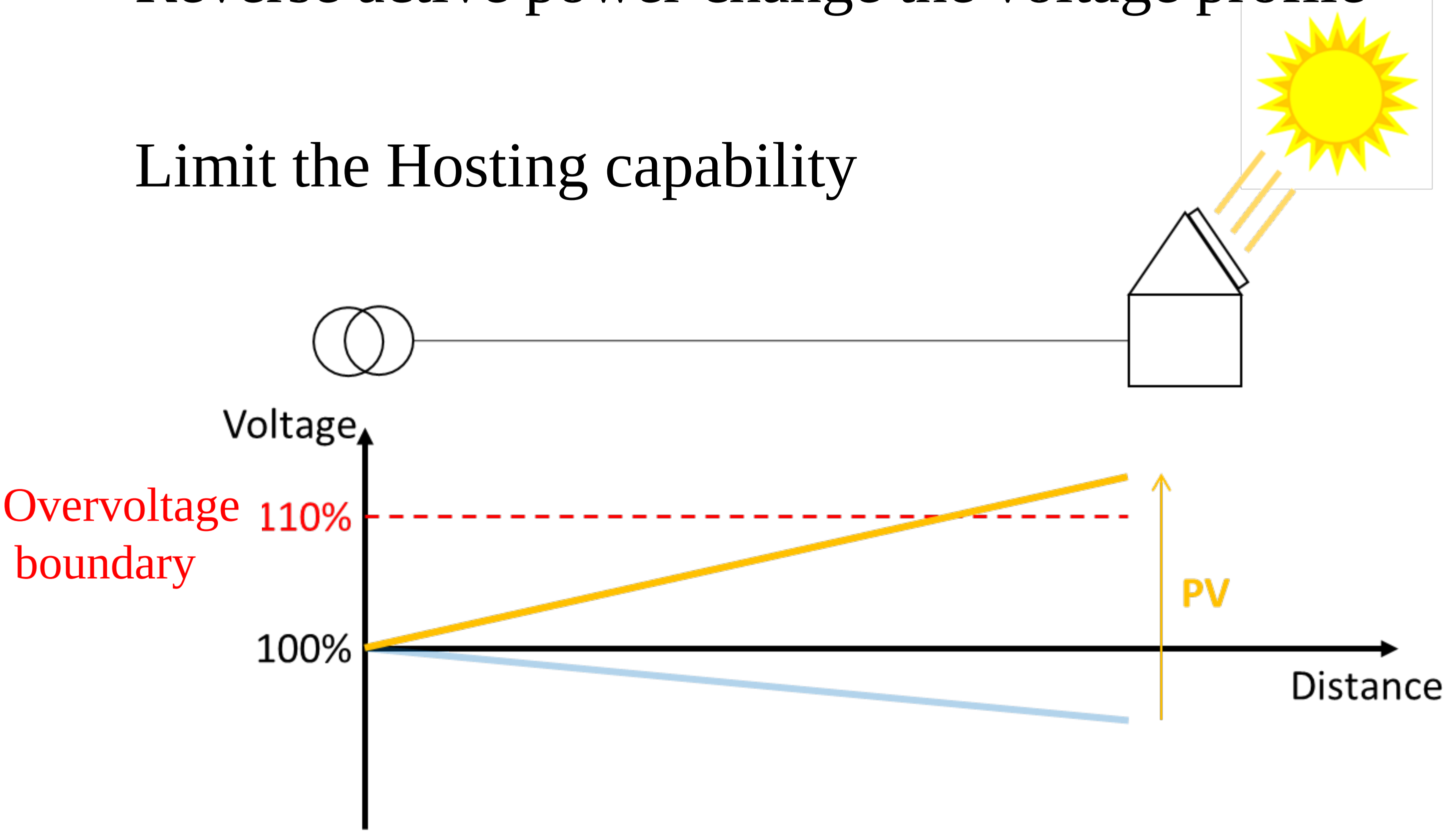


Voltage profile

Problem Definition

Reverse active power change the voltage profile

Limit the Hosting capability



Standard EN 50160

Problem Definition

Voltage Characteristics of Public Distribution Systems

- Static Characteristics
  - @ LV and MV grids
  - mean 10-minutes voltage rms ±10% ; for 95% of week

- Dynamic Characteristics
  - @ LV grid
  - Rapid Voltage change < 5%

Hosting Capacity (HC)

Problem Definition

The amount of power could be produced by PVs installed in LV and MV grids without causing any technical problem, is limited.

$$HC = \mathrm{Max}\left(\sum_{i} P_{PV,i} \right) \quad \forall \mathrm{t},$$

Maximizing the HC

$$s.t.$$

$$I_k(t) < \mathrm{I}_{k,\max},$$

Current limit

$$V_{\min} < V_i(t) < V_{\max},$$

Voltage limit

$$F_i(P_{\mathrm{L},i}(t) - k_i\, P_{PV,i}(t) - \mathrm{P}_{\mathrm{BSS,i}}(t),\; Q_{\mathrm{L},i}(t) - k_i\, Q_{PV,i}(t) - Q_{\mathrm{BSS},i}(t)) = 0.$$

Power flow equations

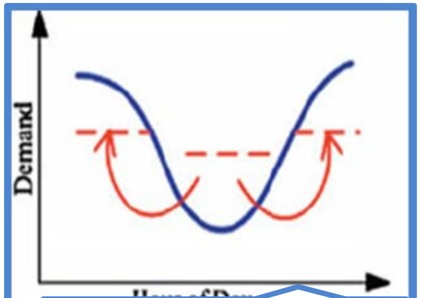
Solutions

Problem Definition

Grid reinforcement

On-load tap changers for MV/LV

Active power curtailment



Demand side management

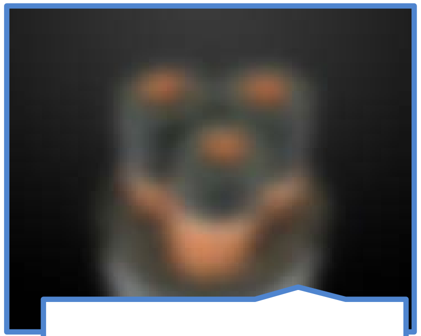
Storage system & Electrical vehicles

Reactive power control of RES

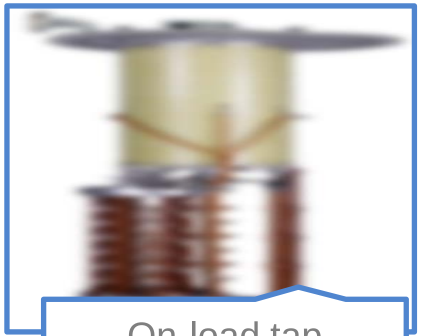
Solutions

✓ More Economical

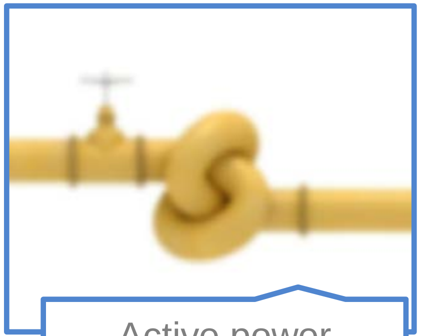
Problem Definition



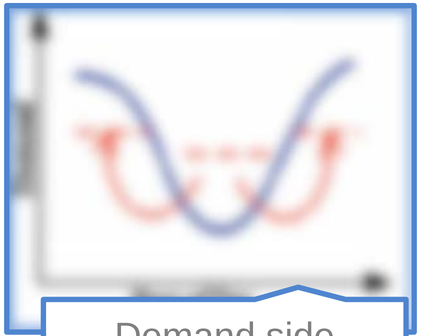
Grid reinforcement



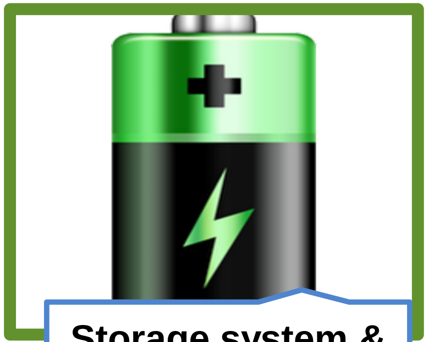
On-load tap changers for MV/LV



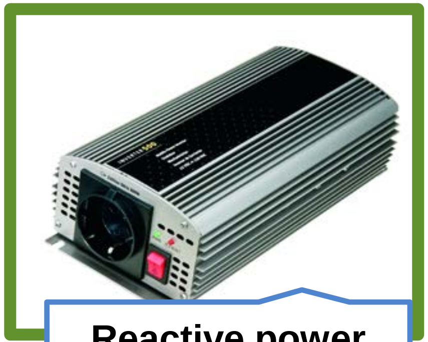
Active power curtailment



Demand side management



Storage system & Electrical vehicles

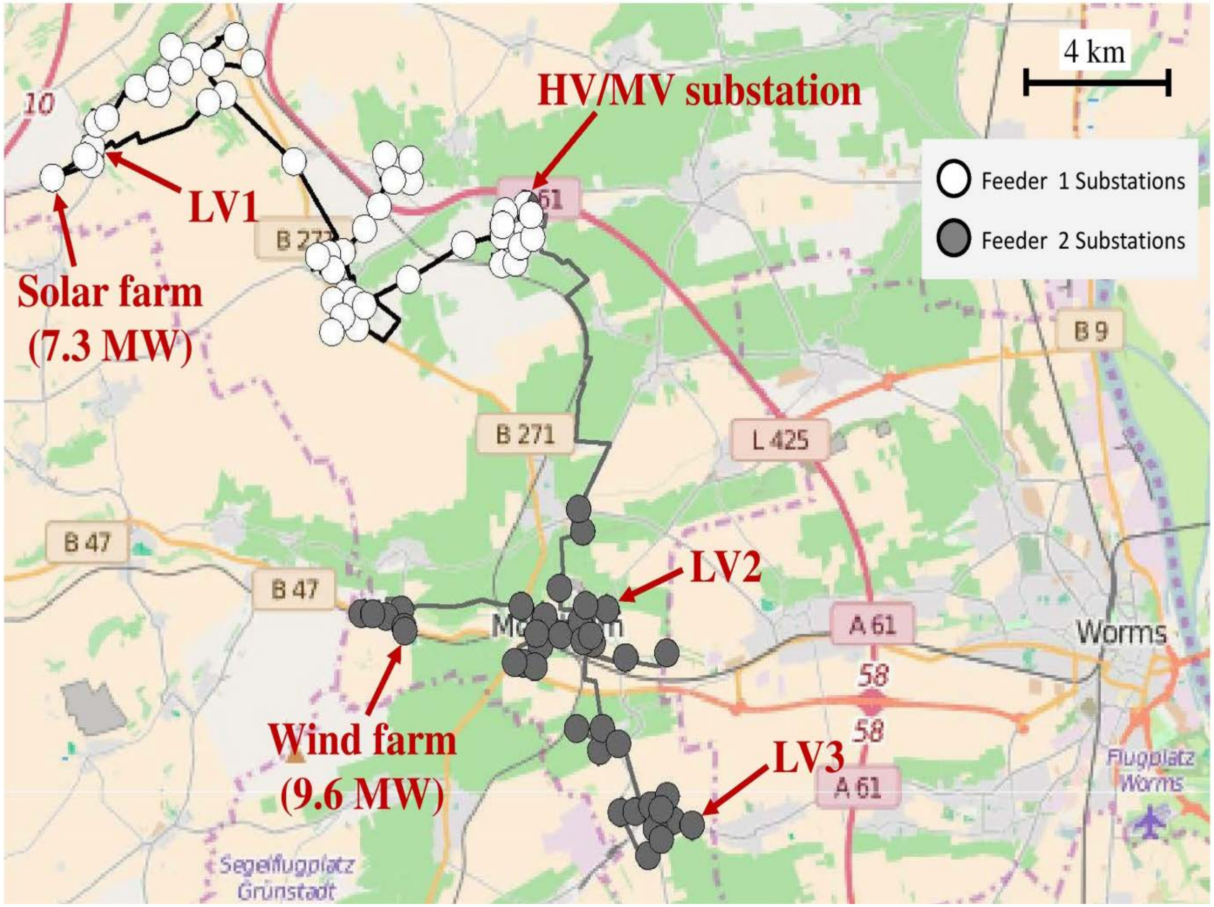


Reactive power control

Grid Specification

Network introduction

Investigated network



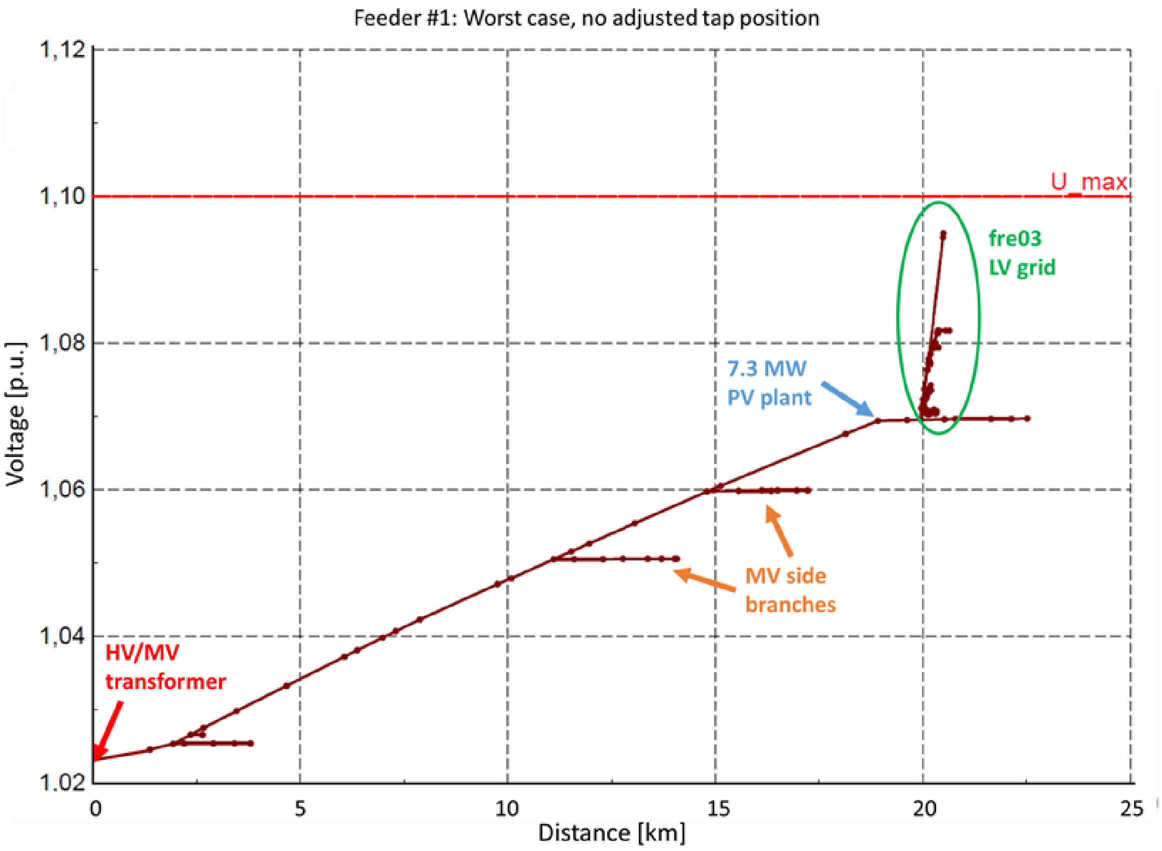
Network details

Investigated network

		Feeder 1	**Feeder 2**
Total feeder length (km)		22.3	19.5
R/X ratio in MV grid		0.9 - 1.7	0.9 - 1.7
Customer #	**Small-scale**	3700	2900
	Large-scale	12	20
	Max. load in 2015 (MW)	3.7	5.7
Total consumption	**Small-scale (GWh)**	15.6	12.2
	Large-scale (GWh)	1.2	19.2
RES penetration level	**Total (%)**	76	88
	LV connected (%)	32	13
	MV connected (%)	44	75
LV connected PV	**Number**	278	189
	Installed capacity (MW)	4.4	3.2
MV connected RES	**Type / Capacity (MW)**	Solar / 7.3	Wind / 9.6
	Distance to HV sub (km)	18.7	18.2
Max. revers power	**(MW)**	7.2	7.9
Total production	**LV connected (GWh)**	5.4	3.97
	MV connected (GWh)	7.4	23.55

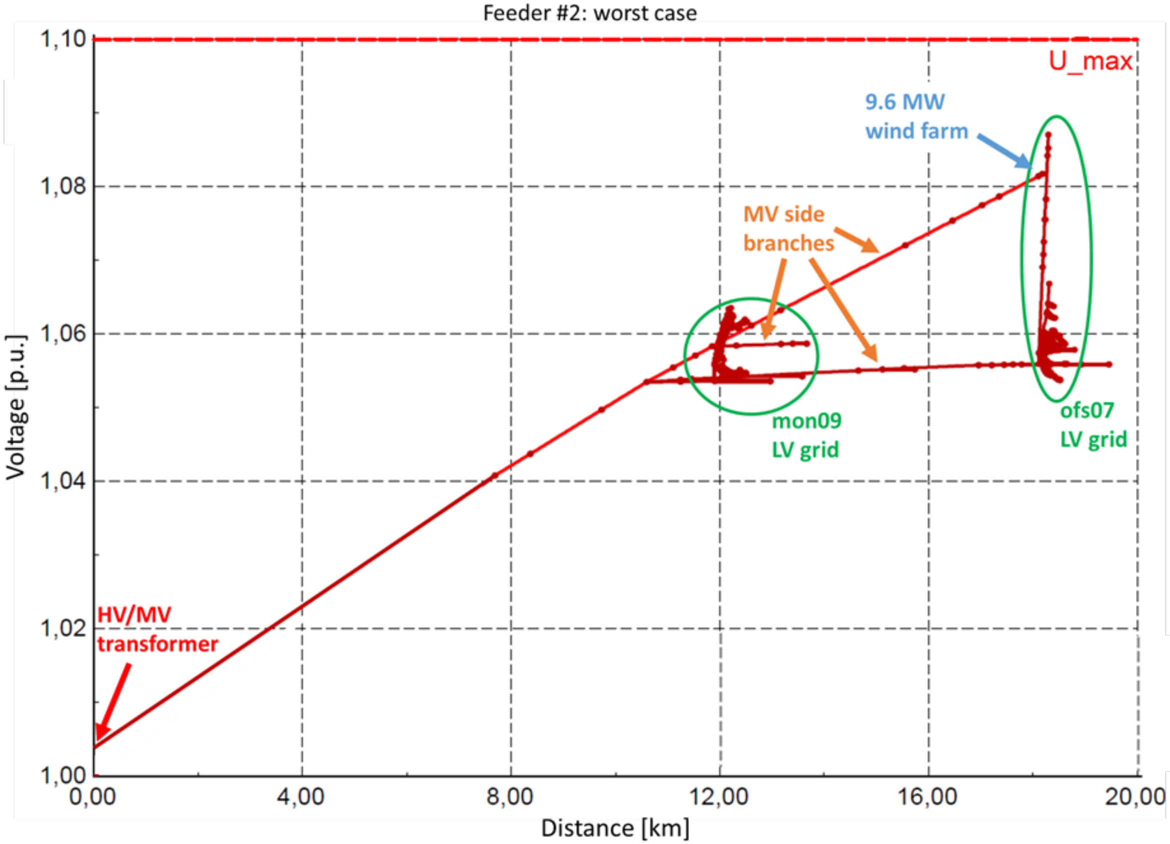
Maximum Voltage profile - Feeder #1

Investigated network



Maximum Voltage profile - Feeder #2

Investigated network



Load & Generation Profile Estimation

Estimation method

Estimation method

1- Measurement of large units

2- Estimation of consumption profiles by Standard Load Profiles (SLP)

3- Estimation of Small-Scale production using the nearest large production profile

4- Detailed LV Model or aggregated load model in substations

5- Determine the PF by minimizing the reactive power error

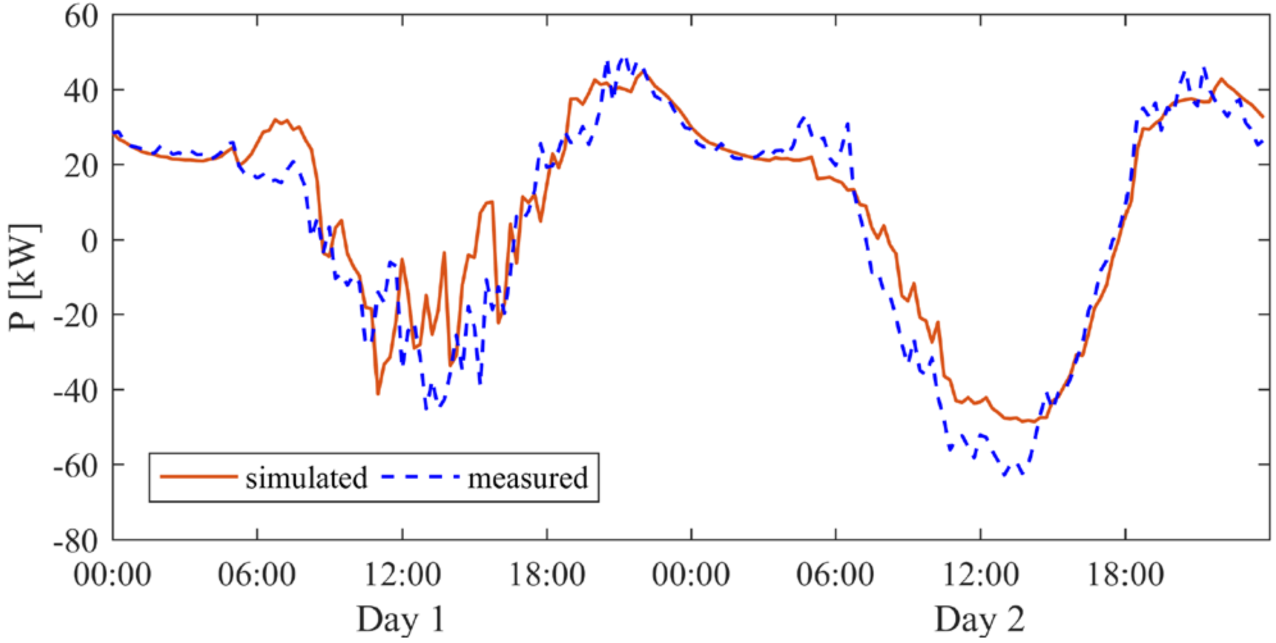
6- Primarily Substation Model (controller of OLTC)

Model Validation

Model Validation

Active power validation

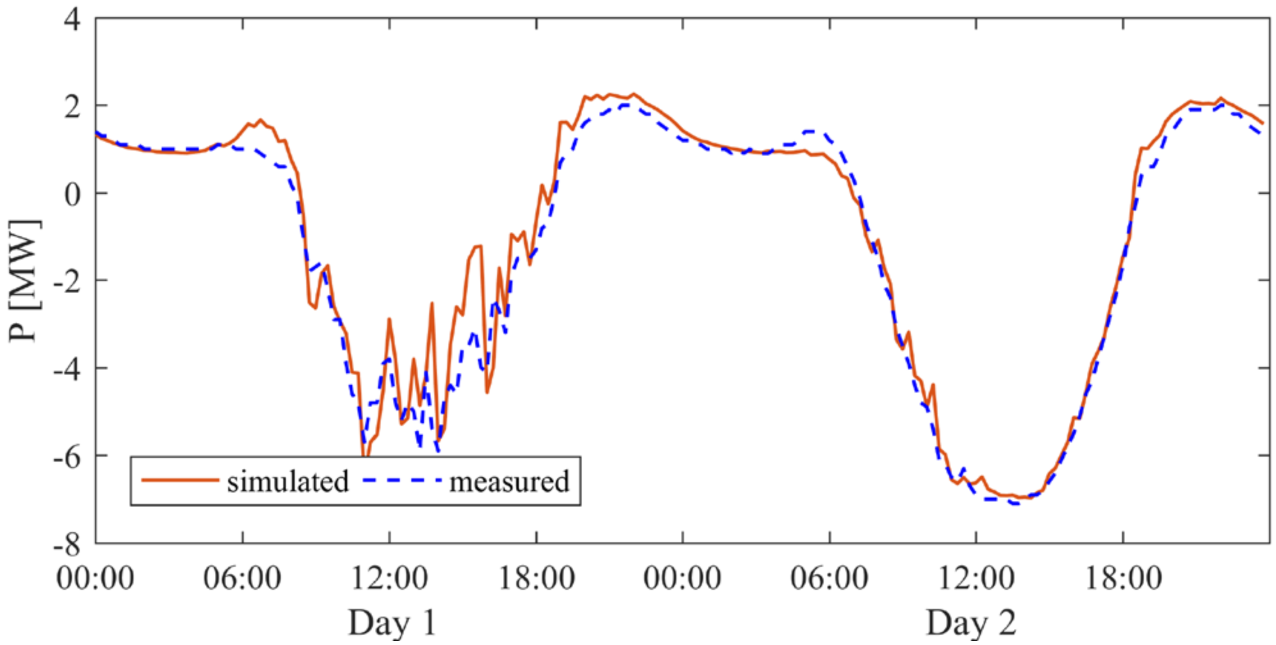
Active power flow in a secondary substation located in feeder 1, one km away from the solar park.



Active power validation

Model Validation

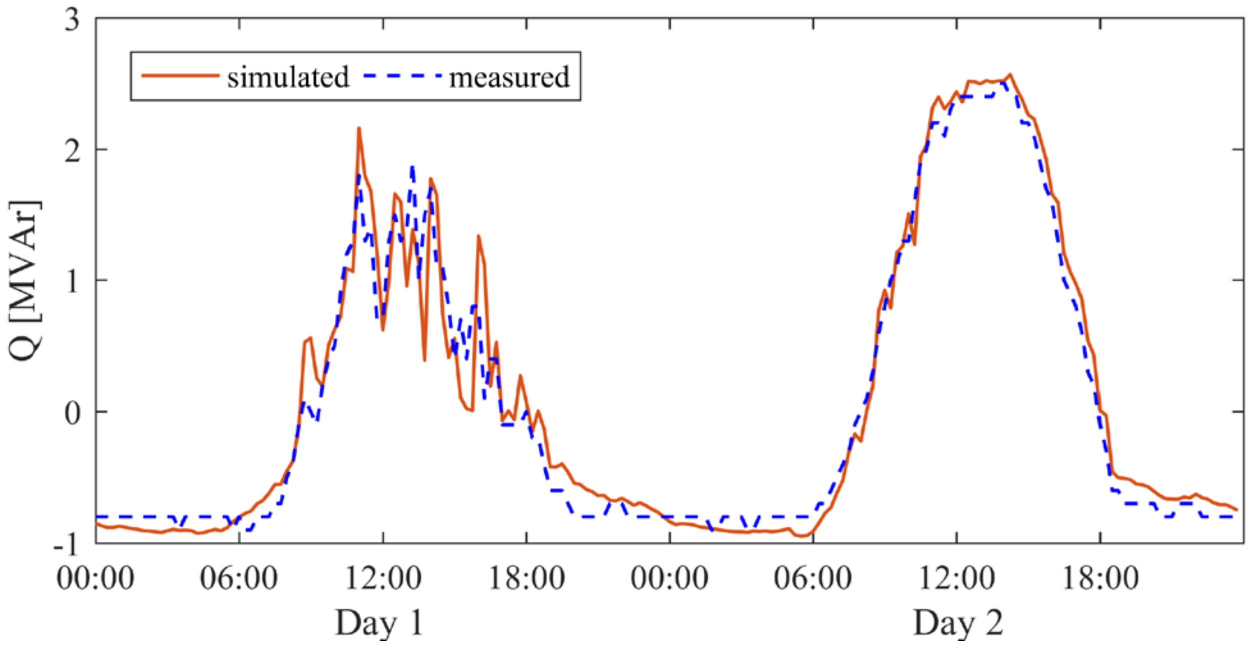
Active power flow in feeding point of feeder 1.



Reactive power validation

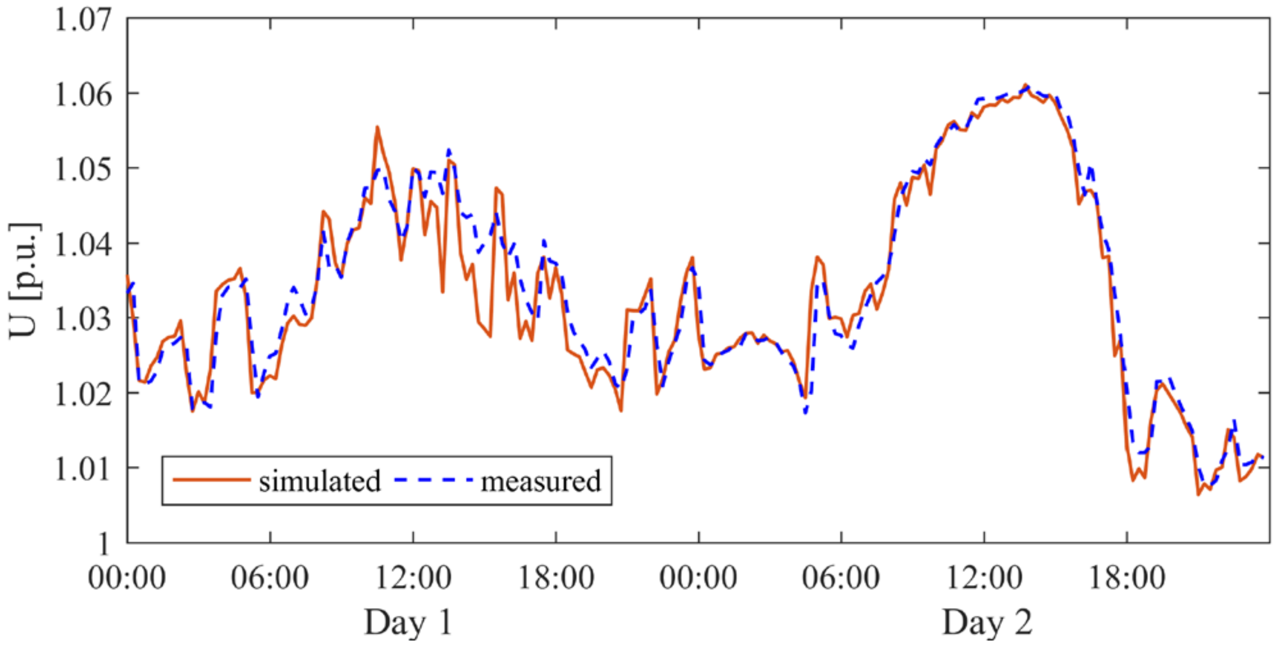
Model Validation

Reactive power flow in feeding point of feeder 1.



Voltage validation

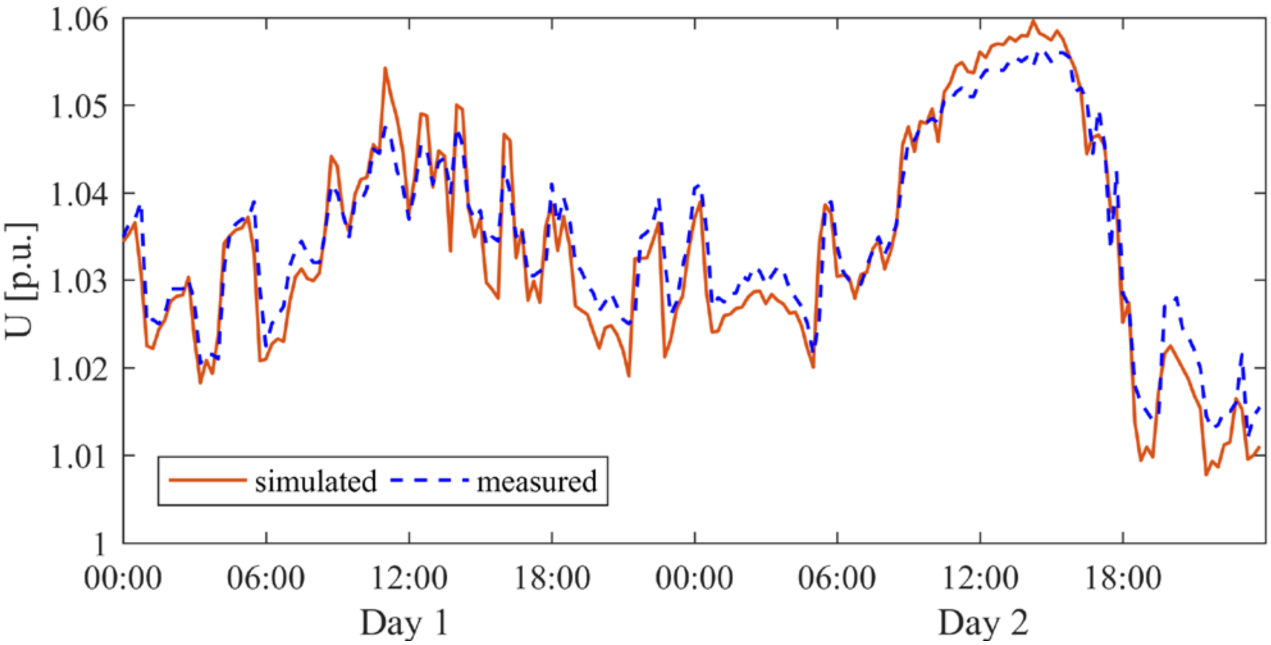
Voltage profile of a secondary substation located in feeder 1, one km away from the solar park.



Model Validation

Voltage validation

Voltage profile of the solar park in feeder 1.



Central Battery Storage System

Battery storage system

ESS

Battery bank

- Price: 250-1350 (Euro/KWh) depend on technology

Convertor

- Price: 200-600 (Euro/kVA)

Active Power Control

Reactive Power Control

Major Challenge

ESS

High cost

- Sizing the BSS (Battery Bank & Convertor Unit)
- Placement
- Control of system based on generation and demand profiles

Previous works:

- Use sensitivity analysis for placement (Do not Work)
- Neglect the reactive power injection
- Not select convertor size separately from storage size

Major Challenge

ESS

High cost of ESS

- Sizing the BSS (Battery Bank & Convertor Unit)
- Placement
- Control of system based on generation and demand profiles

Using Optimization to maximize the Hosting capacity

Optimization Formulation

$$\max_{P_{BSS,j}(t),\, Q_{BSS,j}(t)} \quad HC\left(P_{BSS,j}(t),\, Q_{BSS,j}(t),\, j,\, SOC_M, \mathrm{SOC}(0), \mathrm{S}_M\right)$$

Maximizing the HC

s.t.

$$F_i(P_{L,i}(t) - k_i\, P_{PV,i}(t) - \mathrm{P}_{\mathrm{BSS,i}}(t),\, Q_{L,i}(t) - k_i\, Q_{PV,i}(t) - Q_{\mathrm{BSS},i}(t)) = 0,$$

$$I_k(t) < \mathrm{I}_{k,\max},$$

$$V_{\min} < V_i(t) < V_{\max},$$

Grid Constraints

ESS

$$SOC(t+1) = \begin{cases} SOC(t) + \eta P_{BSS}(t) & \text{Charging} \\ SOC(t) - \dfrac{P_{BSS}(t)}{\eta} & \text{Discharging} \end{cases},$$

$$SOC_m \le SOC(t) \le SOC_M,$$

$$SOC(T) = SOC(0),$$

Battery Constraints

$$P_m \le P_{BSS}(t) \le P_M,$$

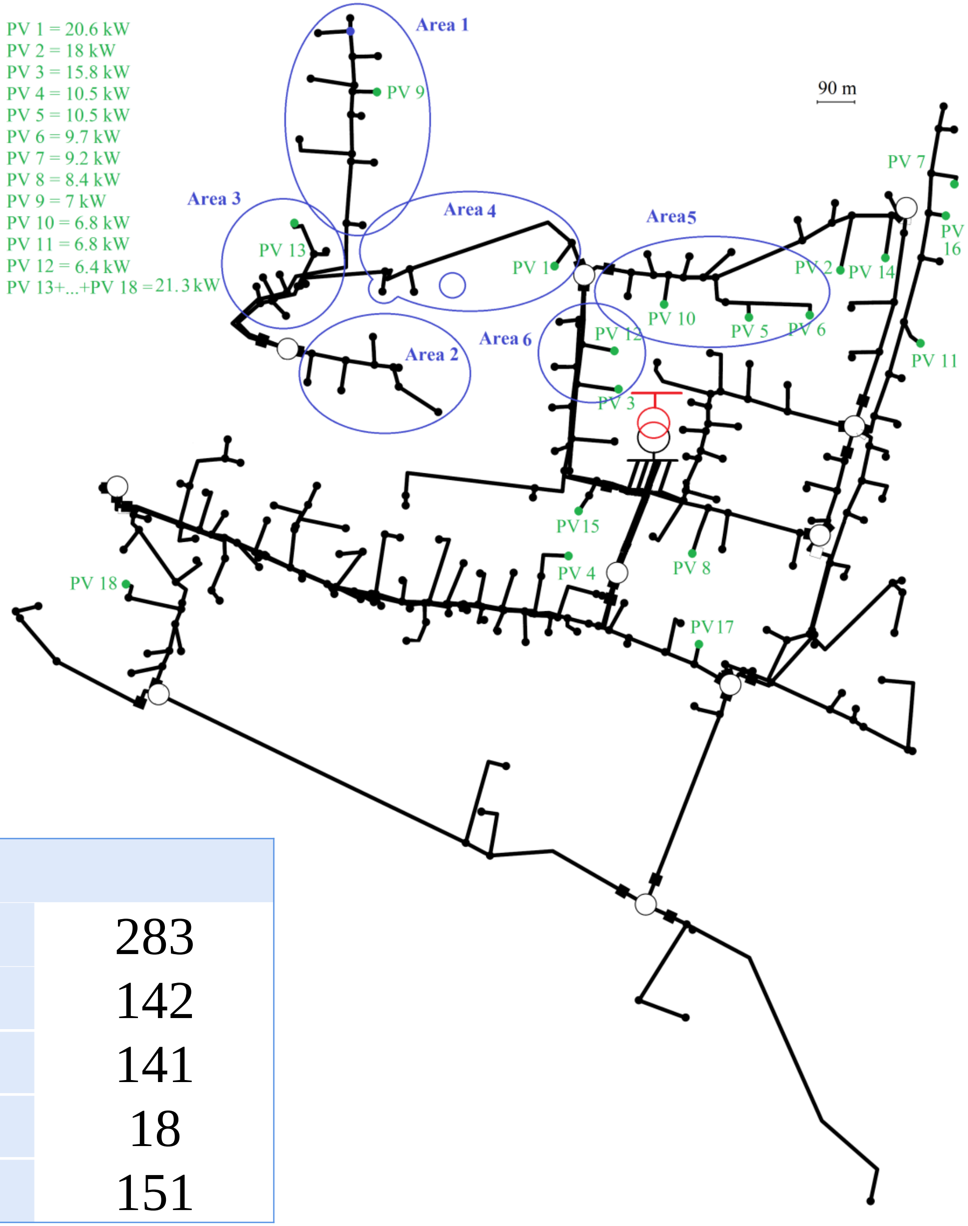
$$Q_m \le Q_{BSS}(t) \le Q_M,$$

$$\sqrt{P_{BSS}(t)^2 + Q_{BSS}(t)^2} < S_M.$$

Convertor Constraints

LV grid

ESS

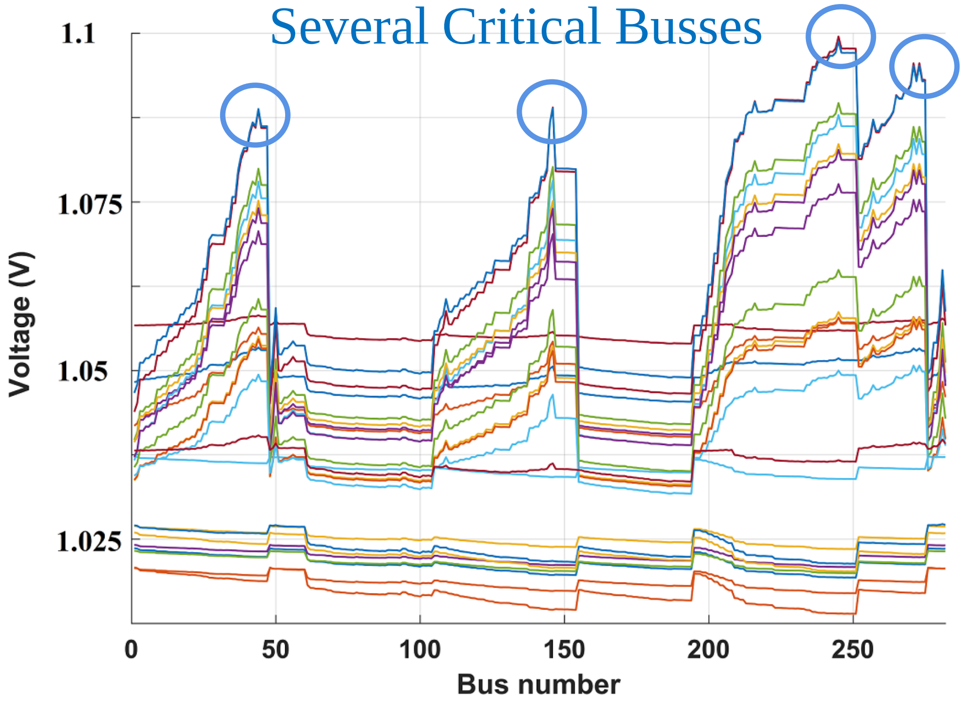


LV 2 Specification	
Number of LV bus node	283
Number of customer node	142
Number of Junction node	141
Number of PV plants	18
Capacity of PV plants (kW)	151

The maximum HC

LV grid voltage in the critical day at the maximum HC without BSS (24 profiles for t=1 to 24)

ESS



Battery and Converter Size (1)

The HC improvement (%) in different battery size (SOC_M) and the convertor size (S_M)

ESS

		SOC_M (kWh)					
	S_M (kVA)	0	20	40	60	80	
	20	10,1	11,9	12,1	12,3	12,3	Case 1
	40	16,4	17,9	18,5	18,8	19,0	
	60	22,2	24,0	24,7	24,7	24,7	
Case 2	80	28,2	29,2	29,5	29,5	29,5	Case 3
	100	34,4	34,5	34,5	34,5	34,5	
	120	38,7	38,8	38,8	38,8	38,8	
	140	43,1	43,2	43,1	43,1	43,1	
Case 4	160	47,6	47,6	47,6	47,6	47,6	

Battery and Converter Size (2)

Battery Li-Ion: 1000 €/kWh

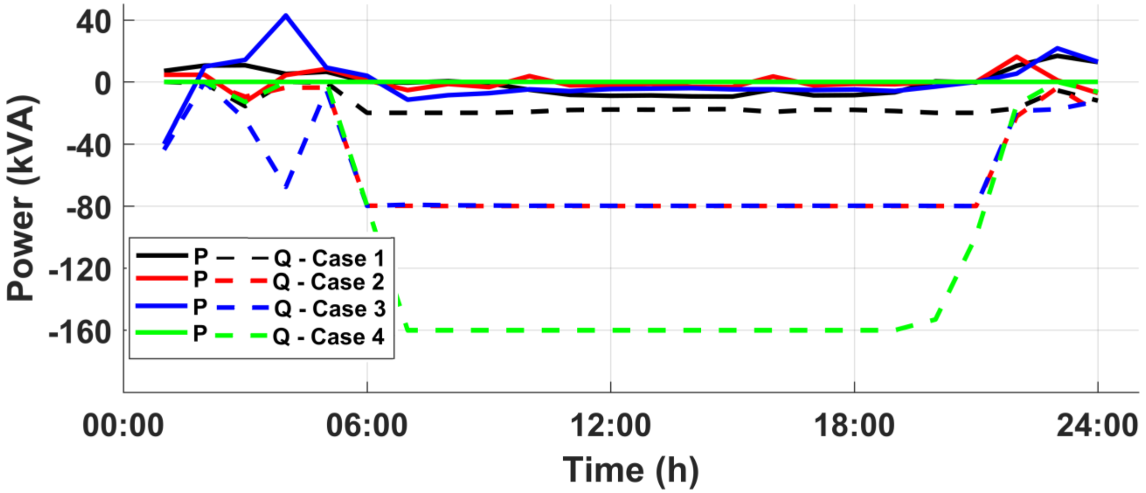
Convertor: 350 €/kW

- **Case 1:** 80 kWh battery bank, 20 kVA converter (87 k €)
- **Case 2:** 20 kWh battery bank, 80 kVA converter (48 k €)
- **Case 3:** 80 kWh battery bank, 80 kVA converter (108 k €)
- **Case 4:** 160 kVA converter without battery bank (56 k €)

Battery and Converter Size (3)

ESS

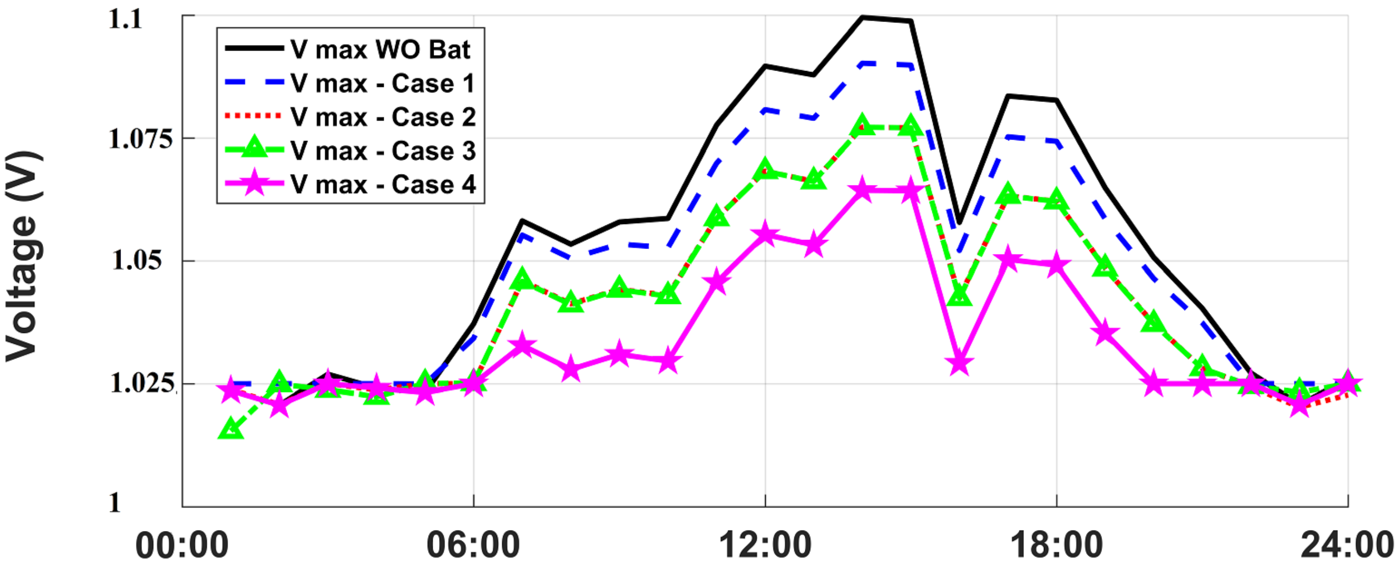
The Optimum active and reactive output power in different cases



Battery and Converter Size (4)

The maximum voltage of the LV grid (critical bus voltage) during time

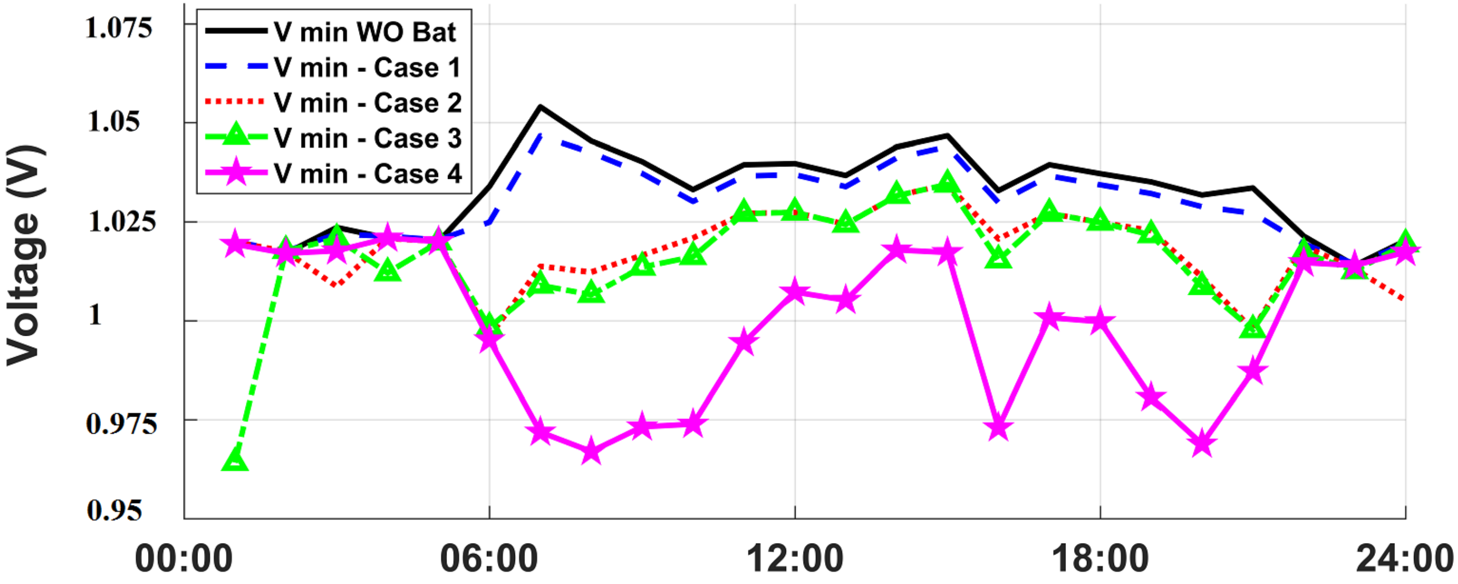
ESS



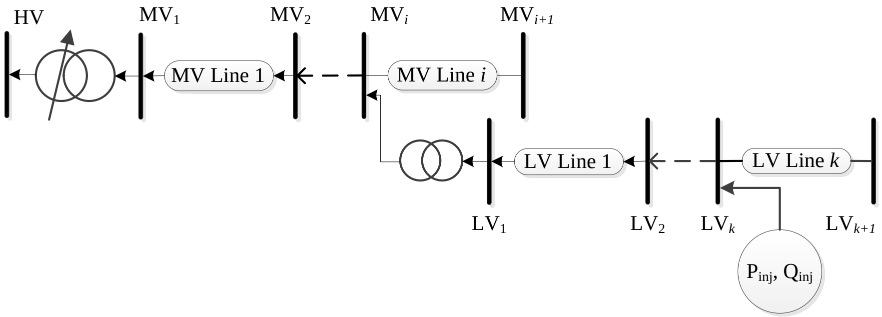
Battery and Converter Size (5)

The minimum voltage of the LV grid during time

ESS



The cumulative R/X ratio



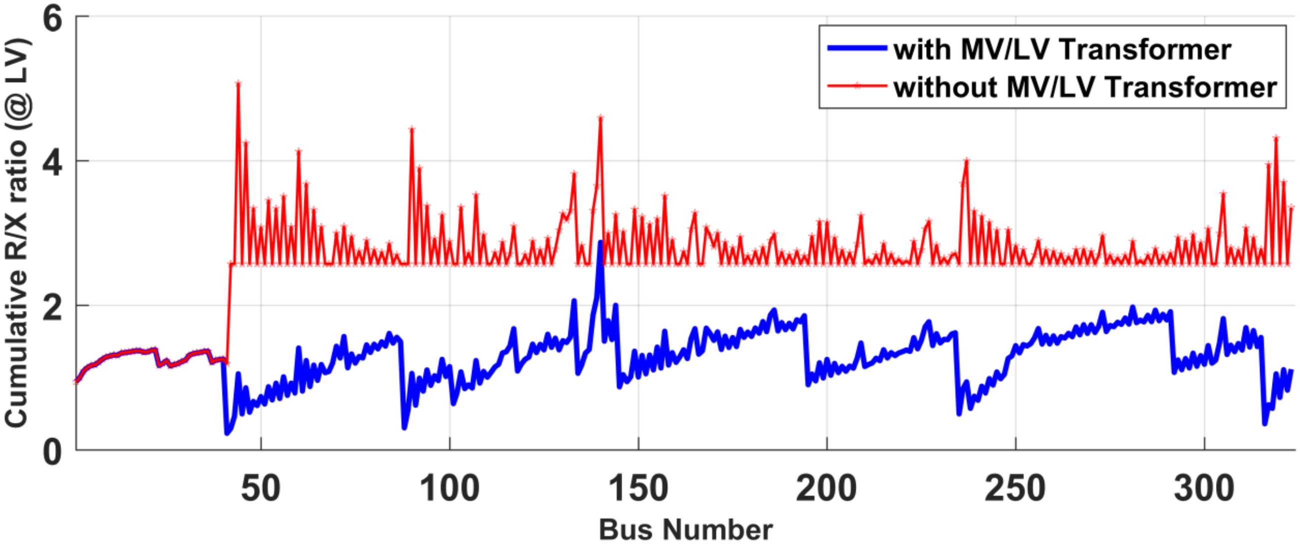
$$\Delta V = V_{LV,\mathrm{k}} - V_{HV} \simeq R_{c,k} P_{inj,k} + X_{c,k} Q_{inj,k}.$$

$$R_{c,k} = R_{MV,1} + \ldots + R_{MV,\mathrm{i}} + R_{MV/LV} + R_{LV,1} + \ldots + R_{LV,\mathrm{k}-1},$$

$$X_{c,k} = X_{MV,1} + \ldots + X_{MV,\mathrm{i}} + X_{MV/LV} + X_{LV,1} + \ldots + X_{LV,\mathrm{k}-1}.$$

The cumulative R/X ratio

ESS



Battery and Converter Size (6)

The maximum current change in MV/LV Transformer

ESS

	SOC$_M$ (kWh)				
S$_M$ (kVA)	0	20	40	60	80
20	0,48	-0,49	-0,86	-1,15	-1,34
40	1,04	-0,29	-0,97	-1,50	-1,79
60	1,68	0,14	-0,61	-0,61	-0,61
80	2,39	1,64	1,35	1,34	1,34
100	3,20	2,38	2,04	1,86	1,86
120	4,08	3,15	2,69	2,48	2,46
140	5,04	3,93	3,47	3,12	3,12
160	6,09	4,70	4,25	3,92	3,83

Battery and Converter Size (7)

ESS

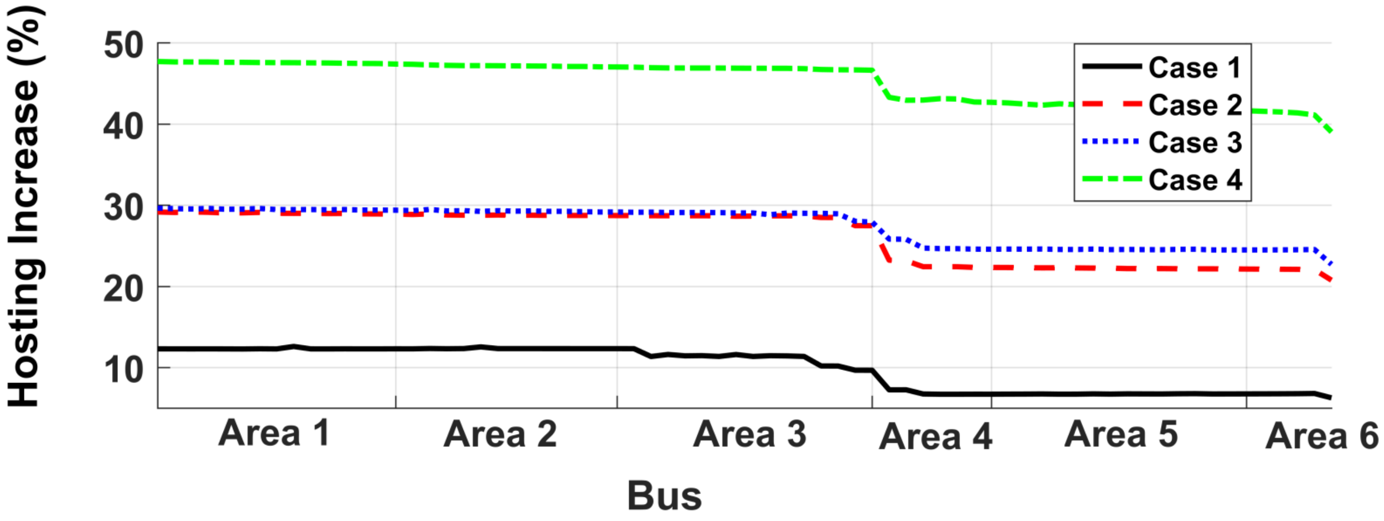
Energy loss of the LV grid (%), in regard to the total energy produced by PVs. (η=90%)

	SOC_M (kWh)				
S_M (kVA)	0	20	40	60	80
20	0,135	0,139	0,143	0,148	0,153
40	0,141	0,145	0,148	0,154	0,158
60	0,151	0,154	0,157	0,162	0,167
80	0,165	0,158	0,160	0,166	0,167
100	0,182	0,180	0,179	0,181	0,180
120	0,203	0,206	0,198	0,195	0,187
140	0,229	0,231	0,232	0,206	0,210
160	0,258	0,262	0,264	0,242	0,229

Central BSS Place

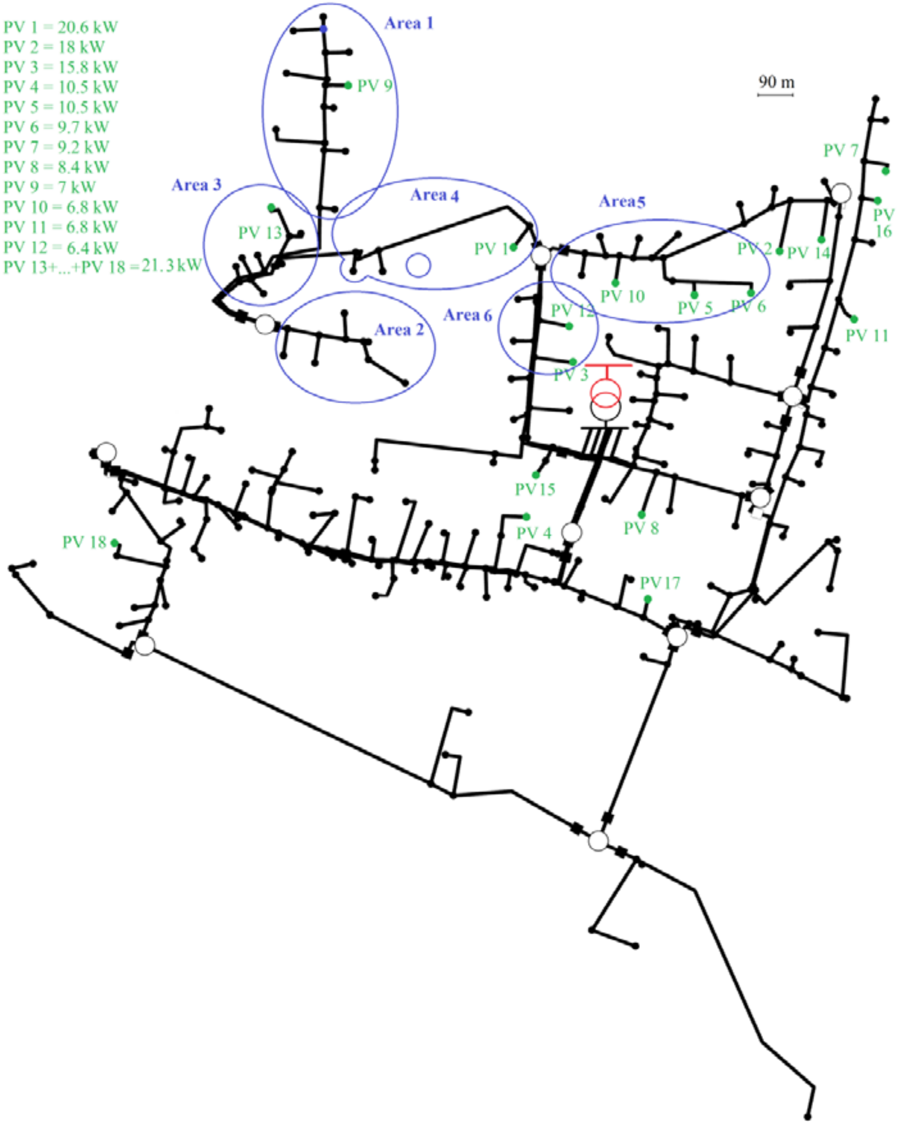
- Long distance to substation (large cumulative impedance)
- Closeness to large PVs

ESS



Central BSS Place

ESS



Conclusions

ESS

- Almost same effect of active and reactive power in voltage regulation
- Battery bank has a higher price and less effect in compare to converter unit,
- Larger battery bank (active power control) can slightly reduce the maximum current and loss
- Larger power converter (reactive power control) increases slightly the maximum current and loss
- Reactive power control can improve the HC with much lower cost (D-STATCOM, TCR, …)

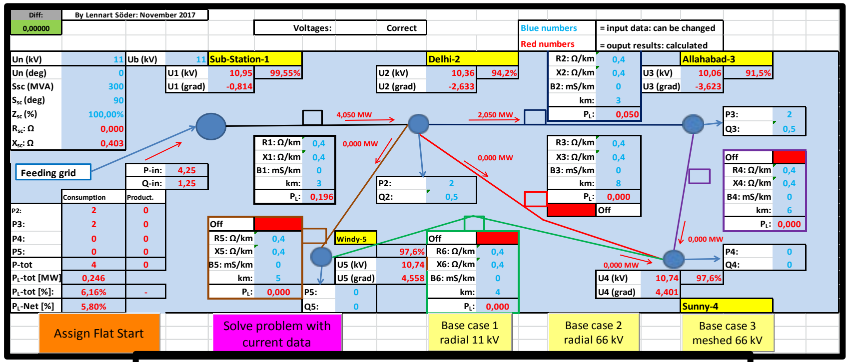
Thank you

Tutorial T2 on voltage control at solar and wind power in radial and meshed grids

- **Impact from solar and wind power:**
  - o Selection of power factor
  - o Impact on local voltage
  - o Hosting capacity
  - o Impact on losses (where to produce reactive power?)
  - o Possibility to supply feeding grid with reactive power (from where?)
  - o Use of OLTC (On Load Tap Changers) in transformer
  - o Impact from grid strength.
  - o Impact from R/X quota of grid. Can be different in different lines.

Tutorial T2 on voltage control and wind power

- **Tool: Excel Load Flow program**



Diff:	By Lennart Söder: November 2017
0,00000	

Voltages: Correct

Blue numbers = input data: can be changed
Red numbers = ouput results: calculated

Un (kV)	11
Un (deg)	0
Ssc (MVA)	300
S_{sc} (deg)	90
Z_{sc} (%)	100,00%
R_{sc}: Ω	0,000
X_{sc}: Ω	0,403

Ub (kV) 11

Feeding grid
P-in: 4,25
Q-in: 1,25

	Consumption	Product.
P2:	2	0
P3:	2	0
P4:	0	0
P5:	0	0
P-tot	4	0
P_L-tot [MW]	0,246	
P_L-tot [%]:	6,16%	-
P_L-Net [%]	5,80%	

Sub-Station-1
U1 (kV) 10,95 99,55%
U1 (grad) -0,814

4,050 MW
0,000 MW

R1: Ω/km 0,4
X1: Ω/km 0,4
B1: mS/km 0
km: 3
P_L: 0,196

Delhi-2
U2 (kV) 10,36 94,2%
U2 (grad) -2,633

P2: 2
Q2: 0,5

2,050 MW

R2: Ω/km 0,4
X2: Ω/km 0,4
B2: mS/km 0
km: 3
P_L: 0,050

Allahabad-3
U3 (kV) 10,06 91,5%
U3 (grad) -3,623

P3: 2
Q3: 0,5

0,000 MW

R3: Ω/km 0,4
X3: Ω/km 0,4
B3: mS/km 0
km: 8
P_L: 0,000
Off

Off
R4: Ω/km 0,4
X4: Ω/km 0,4
B4: mS/km 0
km: 6
P_L: 0,000

0,000 MW

Off
R5: Ω/km 0,4
X5: Ω/km 0,4
B5: mS/km 0
km: 5
P_L: 0,000

Windy-5
97,6%
U5 (kV) 10,74
U5 (grad) 4,558
P5: 0
Q5: 0

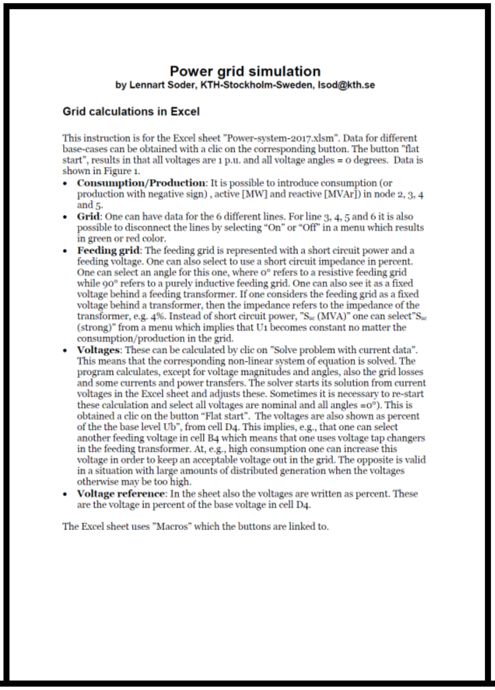
Off
R6: Ω/km 0,4
X6: Ω/km 0,4
B6: mS/km 0
km: 4
P_L: 0,000

0,000 MW

P4: 0
Q4: 0
U4 (kV) 10,74 97,6%
U4 (grad) 4,401
Sunny-4

Assign Flat Start | Solve problem with current data | Base case 1 radial 11 kV | Base case 2 radial 66 kV | Base case 3 meshed 66 kV

Power-system-2017.xlsm



Power grid simulation
by Lennart Soder, KTH-Stockholm-Sweden, lsod@kth.se

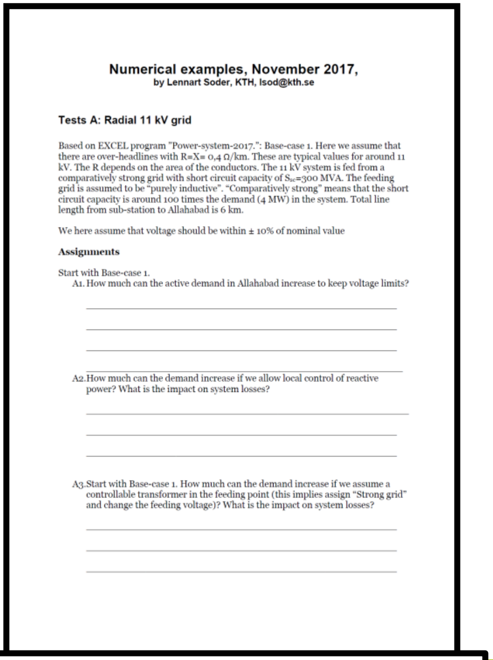
Grid calculations in Excel

This instruction is for the Excel sheet "Power-system-2017.xlsm". Data for different base-cases can be obtained with a clic on the corresponding button. The button "flat start", results in that all voltages are 1 p.u. and all voltage angles = 0 degrees. Data is shown in Figure 1.

- **Consumption/Production**: It is possible to introduce consumption (or production with negative sign) , active [MW] and reactive [MVAr]) in node 2, 3, 4 and 5.
- **Grid**: One can have data for the 6 different lines. For line 3, 4, 5 and 6 it is also possible to disconnect the lines by selecting "On" or "Off" in a menu which results in green or red color.
- **Feeding grid**: The feeding grid is represented with a short circuit power and a feeding voltage. One can also select to use a short circuit impedance in percent. One can select an angle for this one, where 0° refers to a resistive feeding grid while 90° refers to a purely inductive feeding grid. One can also see it as a fixed voltage behind a feeding transformer. If one considers the feeding grid as a fixed voltage behind a transformer, then the impedance refers to the impedance of the transformer, e.g. 4%. Instead of short circuit power, "S_{sc} (MVA)" one can select"S_{sc} (strong)" from a menu which implies that U1 becomes constant no matter the consumption/production in the grid.
- **Voltages**: These can be calculated by clic on "Solve problem with current data". This means that the corresponding non-linear system of equation is solved. The program calculates, except for voltage magnitudes and angles, also the grid losses and some currents and power transfers. The solver starts its solution from current voltages in the Excel sheet and adjusts these. Sometimes it is necessary to re-start these calculation and select all voltages are nominal and all angles =0°). This is obtained a clic on the button "Flat start". The voltages are also shown as percent of the the base level Ub", from cell D4. This implies, e.g., that one can select another feeding voltage in cell B4 which means that one uses voltage tap changers in the feeding transformer. At, e.g., high consumption one can increase this voltage in order to keep an acceptable voltage out in the grid. The opposite is valid in a situation with large amounts of distributed generation when the voltages otherwise may be too high.
- **Voltage reference**: In the sheet also the voltages are written as percent. These are the voltage in percent of the base voltage in cell D4.

The Excel sheet uses "Macros" which the buttons are linked to.

Excel-instructions-171031.pdf



Numerical examples, November 2017,
by Lennart Soder, KTH, lsod@kth.se

Tests A: Radial 11 kV grid

Based on EXCEL program "Power-system-2017.": Base-case 1. Here we assume that there are over-headlines with R=X= 0,4 Ω/km. These are typical values for around 11 kV. The R depends on the area of the conductors. The 11 kV system is fed from a comparatively strong grid with short circuit capacity of S_{sc}=300 MVA. The feeding grid is assumed to be "purely inductive". "Comparatively strong" means that the short circuit capacity is around 100 times the demand (4 MW) in the system. Total line length from sub-station to Allahabad is 6 km.

We here assume that voltage should be within ± 10% of nominal value

Assignments

Start with Base-case 1.

A1. How much can the active demand in Allahabad increase to keep voltage limits?

____

____

____

____

A2. How much can the demand increase if we allow local control of reactive power? What is the impact on system losses?

____

____

____

A3. Start with Base-case 1. How much can the demand increase if we assume a controllable transformer in the feeding point (this implies assign "Strong grid" and change the feeding voltage)? What is the impact on system losses?

____

____

____

Examples-171110.pdf