Zurick University
of Applied Sciences

School of
Engineering

IEFE Institute of Energy Systems
and Fluid-Engineering

Stability of Photovoltaic Inverters Reactive Power Control by the distribution GRID voltage

Nürnberg, Germany 18th July 2018, www.isenec.org

Franz Baumgartner[1],
Fabian Carigiet[1], Christian Messner[2], Ch. Seitl[2],Thomas Strasser[2], Roland Bründlinger[2]
[1)] Zurich University of Applied Sciences, SoE IEFE, Winterthur, http://www.zhaw.ch/=bauf
[2)] AIT Austrian Institute of Technology, SmartEST Laboratory, Vienna; www.ait.at

AUSTRIAN INSTITUTE OF TECHNOLOGY

Billions Investments in DG needed?

Zurick University
of Applied Sciences

zh aw School of Engineering

IEFE Institute of Energy Systems and Fluid-Engineering

M. Braun, T. Stetz, R. Bründlinger et al.
Prog. Photovolt: Res. Appl. ***(2011)*** *- Research Gate*
PAPER PRESENTED AT 26TH EU PVSEC, HAMBURG, GERMANY 2011

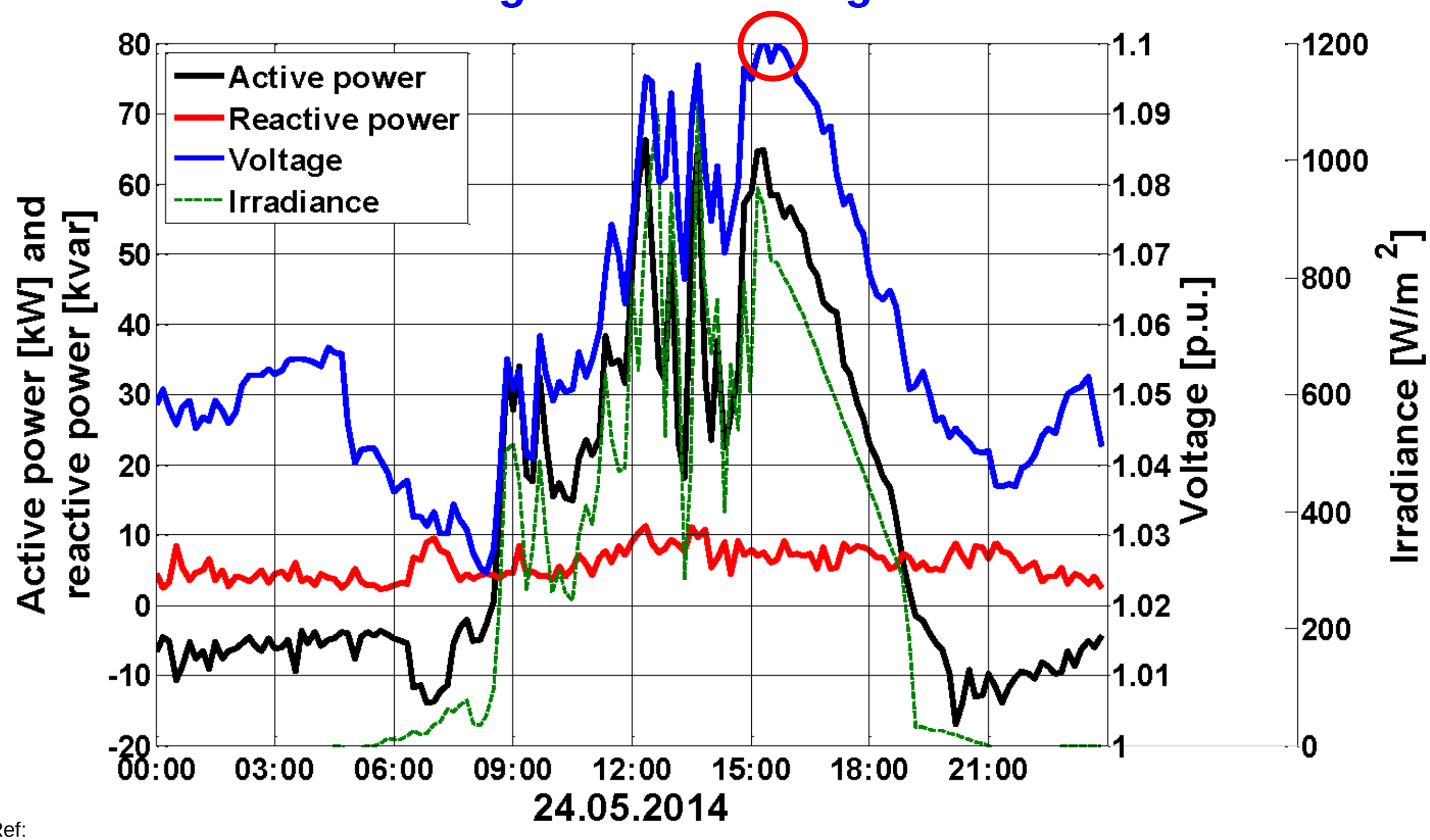
A recent study [32, E-bridge Consult 2011] on the distribution grid extension costs in Germany due to PV and wind integration (scenario 2020: 52-GW PV and 36-GW wind) presents figures in the range of 21–27 billion Euros. This is caused by 240 000-km lines at LV substation and 140 000-km lines at MV substation as well as 33GVA at LV/MV substations and 30GVA at MV/HV substations. These are calculations based on conventional grid planning procedures. As presented in the German case study, smart PV inverter functionalities using active and reactive power control enable reducing grid reinforcement costs significantly. As the present PV market share leader, Germany already has invested billions of Euros in distribution grid extensions and reinforcements due to PV installations. Grid codes are being developed to allow active and reactive power control that can reduce these costs significantly. However, more than 17-GW PV are already installed. More than 90% do not have any of these power control capabilities.

Status 2018 : 45GW PV

Voltage Rise due to Decentralised Generation

Zurick University
of Applied Sciences
zh aw
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Measurement results: voltage for 10min larger than 110% nominal voltage



Ref:
F. Carigiet, M. Niedrist, C. Scheuermann, and F. Baumgartner, 'Case study of a low-voltage distribution grid with high PV penetration in Germany and simulation analyses of cost-effective measures', Prog. Photovolt. Res. Appl., 2015.

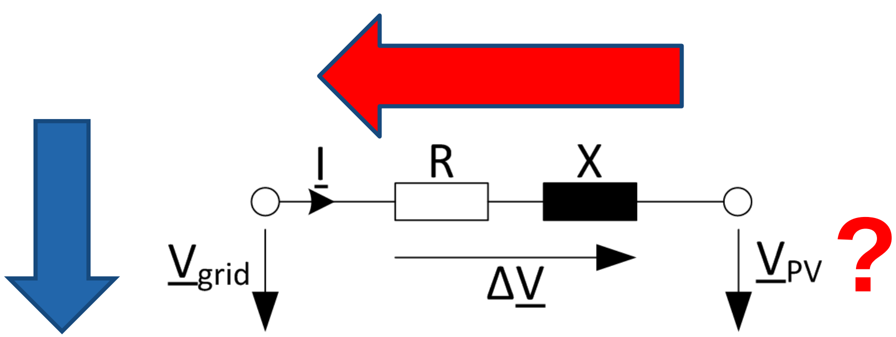
Voltage Dependant Active and Reactive Power Control – PQ(V)

Zurick University of Applied Sciences
zh aw
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Regulations regarding Voltage Rise at PCC:

- EN 50160: $\Delta V \leq 10\%$
- D-A-CH-CZ Technical Rules: $\boldsymbol{\Delta V \leq 3\%}$

Reduction of ΔV by control of P or Q



Project goals

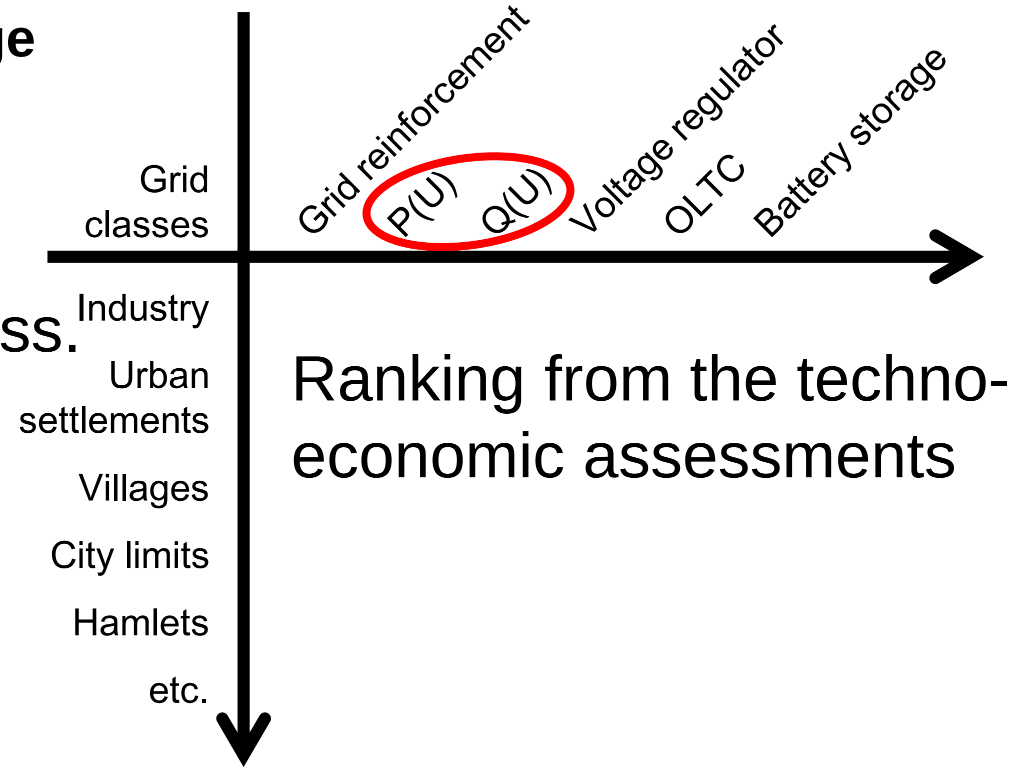
Zurick University
of Applied Sciences

School of Engineering

IEFE Institute of Energy Systems and Fluid-Engineering

Cost effective smart grid solutions for the integration of renewable power sources into the low-voltage networks (CEVSol 2016 to 2019)

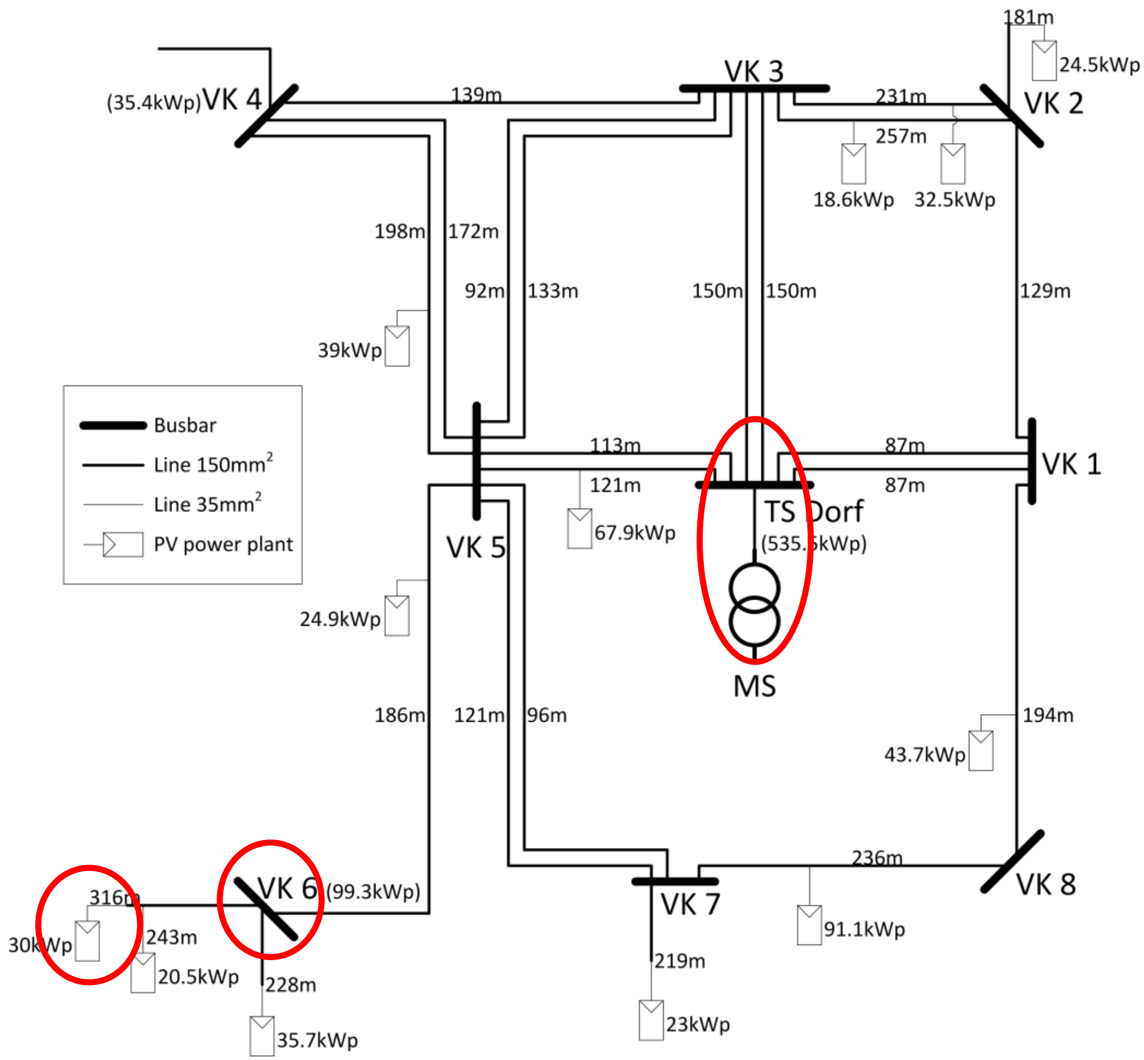
- Most cost-effective solution for individual typical grid class.
- Guideline for distribution system operator (DSO)
- Future cost expectation of the critical grid classes.



Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

Description of LVDG used for verification

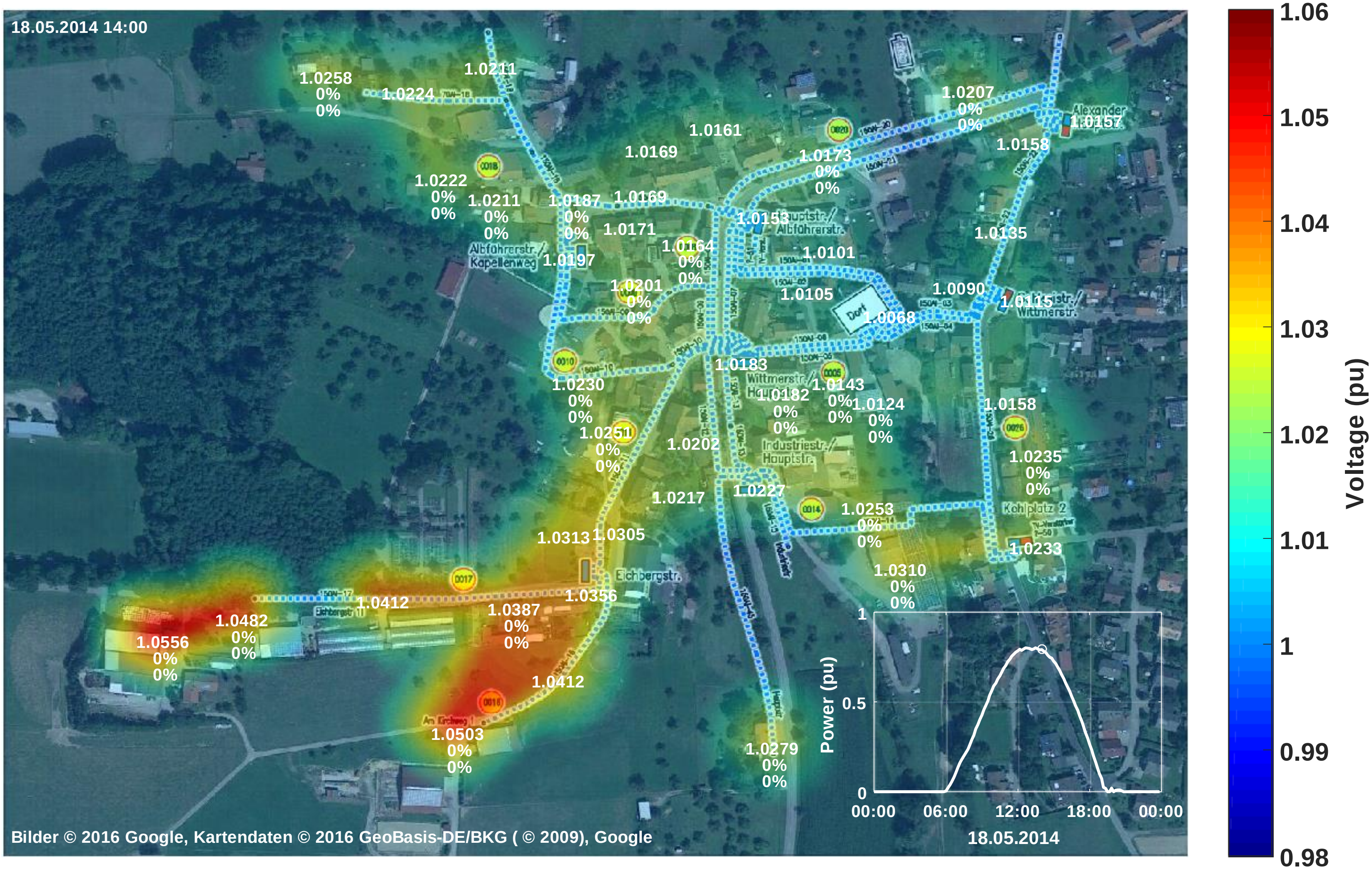
- 400 kVA transfomer
- 33 PV power plants
- 535.5 kWp installed PV power
- 218 nodes
- 228 lines



Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

Zurick University
of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

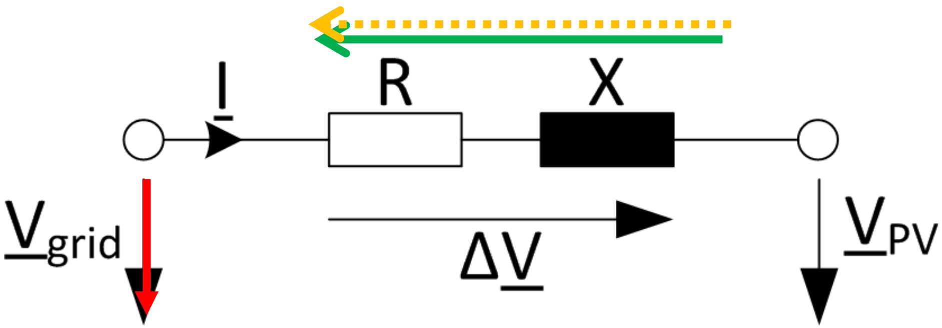
Effect of Decentralised Generation without PQ(V) Control

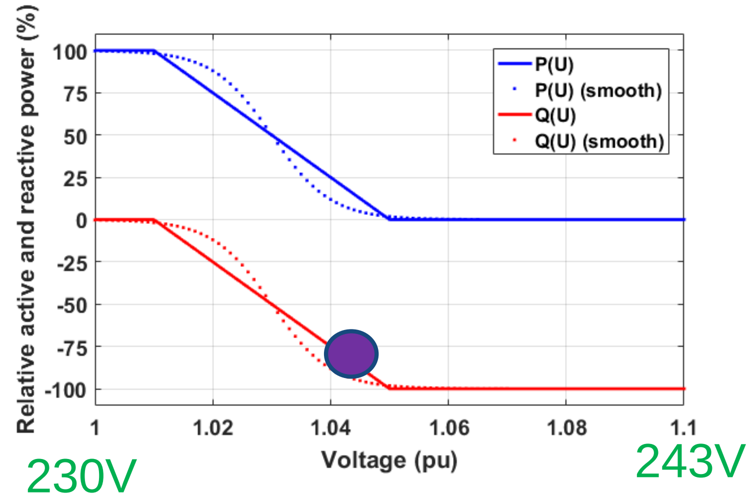


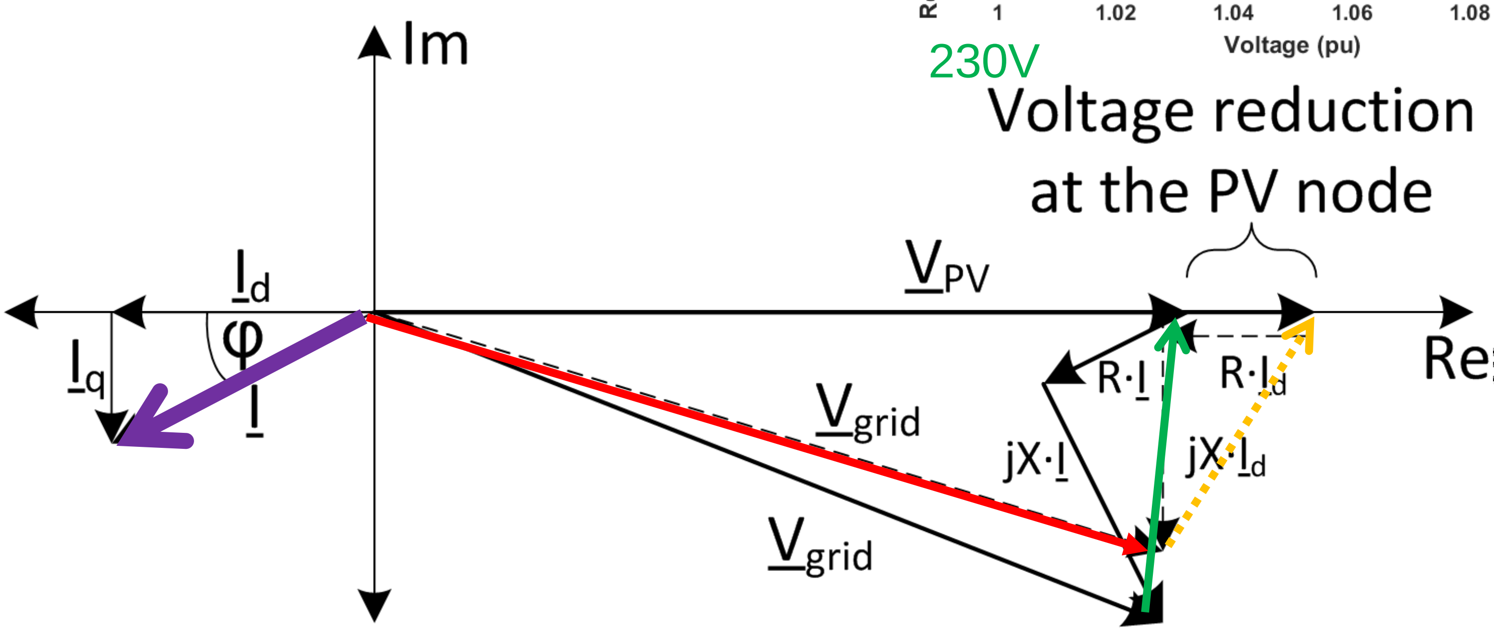
Ref: F. Carigiet et al., «Optimisation of the Load Flow Calculation Method in order to perform Techno-Economic Assessments of Low-Voltage Distribution Grids», EUPVSEC 2017

Zurick University
of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems
and Fluid-Engineering

Reduction of the voltage at PV inverter

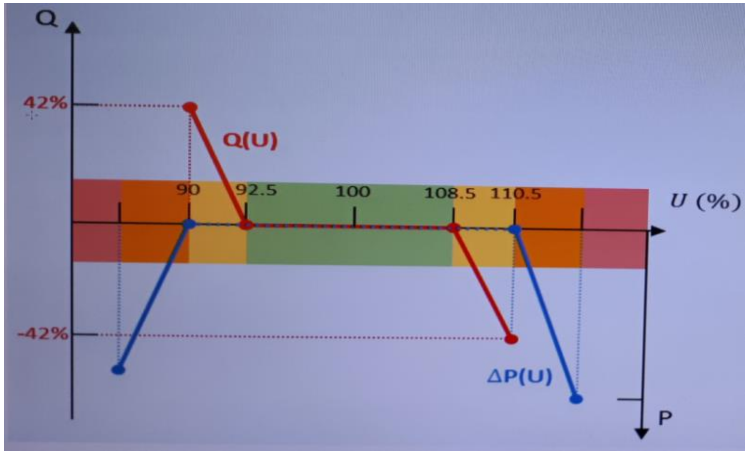


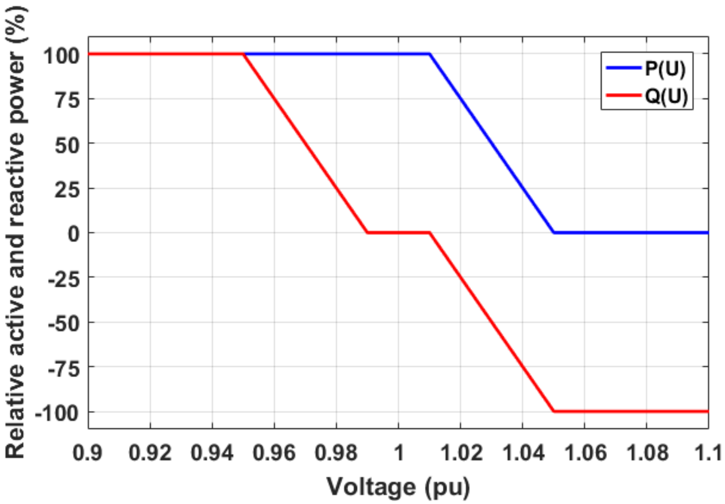




PQ(V) Control Strategies of PV Inverters

- Different ramps possible
- P(V) / Q(V) separate or combined
- Under excited mode to reduce voltage (e.g. high PV feed-in), overexcited mode to increase voltage (e.g. high EV charging)

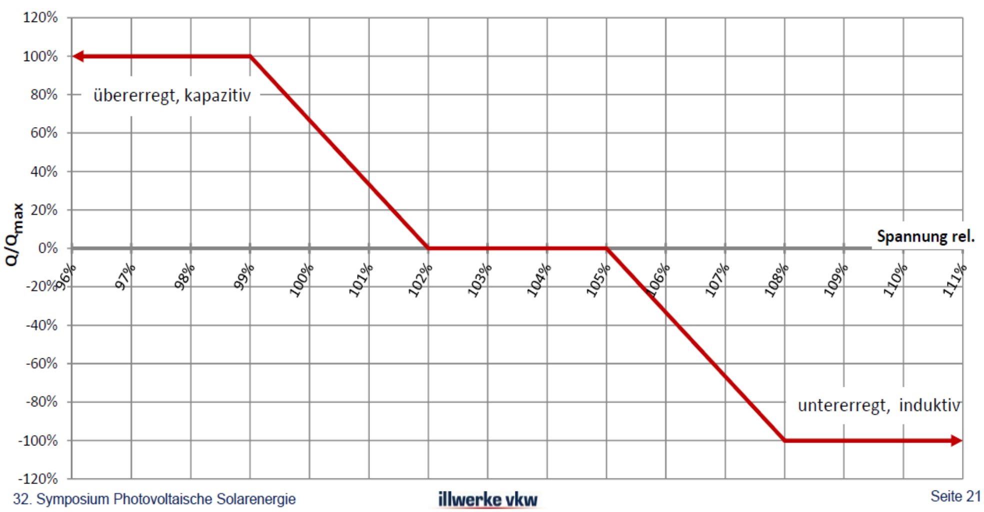




Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

Utilities Q(V) codes of PV inverter

- +30% bis 100% mehr PV vgl. cosφ=1
  (Elbs, **VKW**)
- ¼ weniger Leitungsverluste (Elbs, VKW)
- 80% weniger Blindleistung vgl. mit Q(P)
- keine zusätzlichen IT Kosten !!



Elbs; 32. PV Tagung Deutschland, Staffelstein 2017

BKW

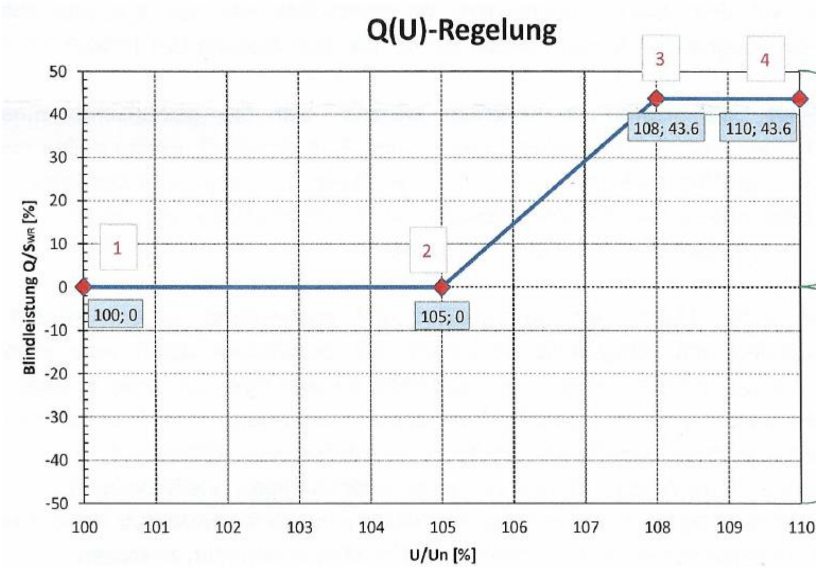
Q(U) Pilot 2015 im Niederspannungsnetz Schulhaus Stadelfeld Wichtrach

http://easyluefter.ch/solar/stadelfeld2/documents/

Mittelspannung Empfehlung Anschlussbedingungen

VSE/AES / NA EEA – CH 2014, Dezember

vgl. z.B. BKW 2017
https://www.bkw.ch/fileadmin/user_upload/11_Netzdienstleistungen/Netzdienstleistungen/Netzanschluss/20140701_TAB_MS_1.4_TAXEF.pdf



SIG Genf - Prof. Allenbach HES, electro suisse buelletin 1

http://bulletin.ch/de/news-detail/un-poste-mt-bt-intelligent.html?file=files/content/news-articles/B_Artikel/1702/B_1702_Allenbach/B_1702_Allenbach.pdf

IEA ISGAN Paper

Table I: Review of Grid Codes for the Volt / VAR function

Country/ Grid Code	Data Requirements	Specified Curve	Default Values
US (California)/ UL 1741 SA: 2015	AC and DC current and voltage. The minimum measurement accuracy shall be 1% or less of rated EUT nominal output voltage and 1% or less of rated EUT output current.	• Q_1 = maximum capacitive reactive power setting • Q_2 = reactive power setting at the left edge of the deadband • Q_3 = reactive power setting at the right edge of the deadband • Q_4 = maximum inductive reactive power setting • V_1 = voltage at Q_1 • V_2 = voltage at Q_2 • V_3 = voltage at Q_3 • V_4 = voltage at Q_4	$V_1 = V_2 - Q_1/KVAR_{max}$, $Q_1 = Q_{max,cap}$ $V_2 = V_n - Deadband_{min}/2$, $Q_2 = 0$ $V_3 = V_n + Deadband_{min}/2$, $Q_3 = 0$ $V_4 = Q_4/KVAR_{max} + V_3$, $Q_4 = Q_{max,ind}$
Germany/ FGW - TR3 Rev23 (optional test)	Displacement factor, P, Q, and V useing a 0.2s (min) sliding average. The settling time shall be determined on the basis of ±5% rated active power.	Aditional tests are carried out for PGUs with reactive power control with Q(U) caricteristic curve. The voltage steps start at the lowest voltage to the highest voltage and vice vcersa.	none
Austria ÖVE/ÖNORM EN50438 (optional - in accordance with DSO, e.g. function used by local DSO - -Vorarlberg Netz)	Displacement factor, P, Q, and V using a 0.2s (min) sliding average. The settling time shall be determined on the basis of ±5% rated active power.	V_{1i}= under voltage at the left edge of the deadband V_{2i}= under voltage at max capacitive reactive power V_{1s}= over voltage at the right edge of the deadband V_{2s}= over voltage at max inductive reactive power Q_{1i}=reactive power at V_{1i} Q_{2i}=reactive power at V_{2i} Q_{1s}=reactive power at V_{1s} Q_{2s}=reactive power at V_{2s} $Q_{max,cap}$ and $Q_{max,ind}$ from capability curve	For grid operator (Vorarlberg Netz) $V_{1i} = 1.02\ V_n$, $Q_{1i} = 0$ $V_{2i} = 0.99\ V_n$, $Q_{2i} = Q_{max,cap}$ $V_{1s} = 1.05\ V_n$, $Q_{1s} = 0$ $V_{2s} = 1.08\ V_n$, $Q_{2s} = Q_{max,ind}$
International / IEC 61850-90-7 VV11	Monitor and record electrical output of EUT. • Voltage • Active power	Pointwise definition with (V_1, Q_1) through (V_x, Q_x) points. • Q_x = Desired reactive power setting at V_x • V_x = Voltage setting at Q_x.	No default. Example settings are: $V_1 = 0.97\ V_n$, $Q_1 = 50\%\ Q_{max,overexcited}$ $V_2 = 0.99\ V_n$, $Q_2 = 0$

EU PVSEC 2015 Conference 14 – 18 Sep 2015 Exhibition 15 – 17 Sep 2015
European PV Solar Energy Conference and Exhibition
CCH Congress Centre Hamburg • Hamburg • Germany

INTERNATIONAL DEVELOPMENT OF ENERGY STORAGE INTEROPERABILITY TEST PROTOCOLS FOR PHOTOVOLTAIC INTEGRATION

David Rosewater, Jay Johnson, Maurizio Verga, Riccardo Lazzari, Christian Messner, Roland Bründlinger, Kathan Johannes, Jun Hashimoto, Kenji Otani

David Rosewater[1], Jay Johnson[1*], Maurizio Verga[2], Riccardo Lazzari[2], Christian Messner[3], Roland Bründlinger[3], Kathan Johannes[3], Jun Hashimoto[4], Kenji Otani[4]

* Corresponding Author
[1]Sandia National Laboratories
P.O. Box 5800 MS1033
Albuquerque, NM 87185-1033 USA
Phone: +1 505-284-9586
Fax: +1 505-844-3952
jjohns2@sandia.gov

[2]Ricerca sul Sistema Energetico-RSE S.P.A.
Via R. Rubattino 54
20134 Milano, Italy
Phone: +39 02-3992-4765
Fax: +39 02-3992-5626
Maurizio.Verga@rse-web.it

[3]Austrian Institute of Technology
Donau-City-Strasse 1
1220 Wien, Austria
Phone: +43 50550 6351
Fax: +43 50550 6390
Roland.Bruendlinger@ait.ac.at

[4]Fukushima Renewable Energy
Institute, AIST (FREA)
Machiikedai, 2-2-9, Koriyama, Fukushima,
963-0298, Japan
Phone: +81-24-963-0827
Fax: +81-24-963-0824
j.hashimoto@aist.go.jp

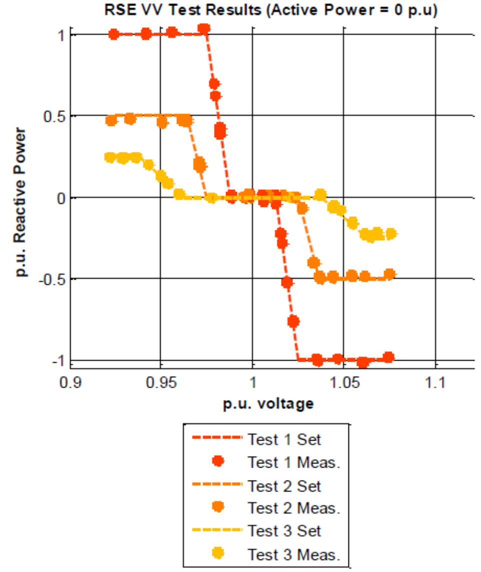


Figure 12: RSE test results for VV function (three test cases with no active power)

Q(V) - PV inverter on the market

List of Q(V)-enabled inverters from Voralberger Energienetze GmbH (VKW)

https://www.vorarlbergnetz.at/inhalt/at/1524.htm (effective from 01.10.2017)

Manufacturer	Allowed	Not allowed	Not yet investigated
ABB (Power One)			Aurora Trio
AEconversion	Plant size <600W		
Bosch		All	
Delta		All	
Dhiel		Platinum	
Fronius	Galvo, Symo, Eco	IG Plus V-3, IG 15/20/30	
Kaco		Powader	
Kostal		Piko	
Refusol		All	
Samil Power		All	
SMA	Tripower	FLX Pro	
SolarEdge	SE4k to SE17k	All larger types	
Solutronic			Solplus 80-120
Steca		All	
Sungrow		All	
Zeversolar			Evershine TLC

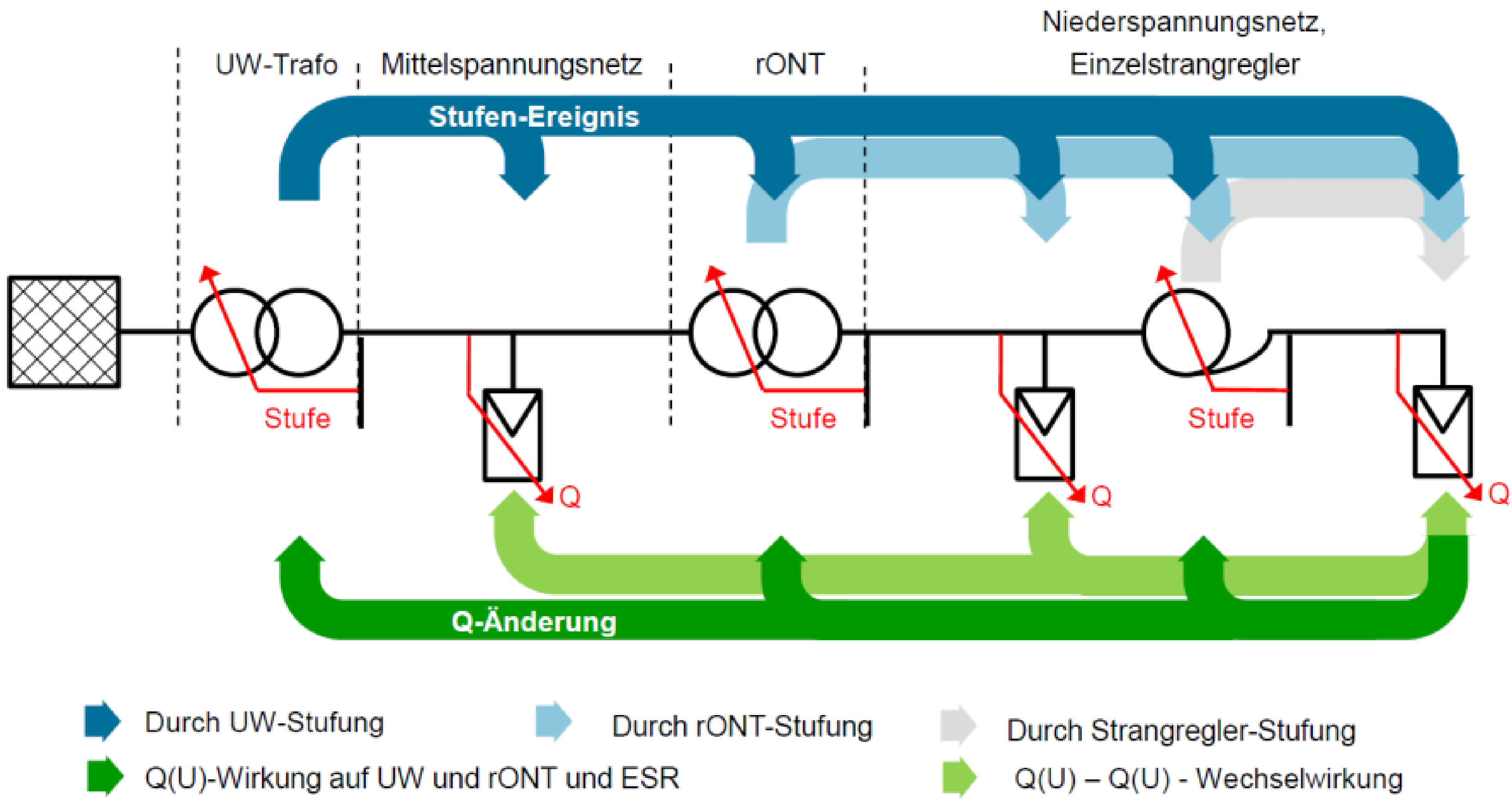
Since 2015, VKW already applied voltage dependent RPC on 2500 PV inverters in Austria

Pros & Cons of PV inv. reactive power

Pros and Cons	const. cosφ	cosφ(P)	cosφ(V)	Q(V)
Degree of voltage reduction	+ +	+ +	+	+
Optional voltage increase	- -	- -	+ +	+ +
Minimal overall reactive power	- -	-	+	+
Active power decoupled from RP	- -	- -	-	+ +
Benefit versus costs DSO	-	-	+	+ +
Costs of parametrization	+ +	+	-	-

Q(V) control loop

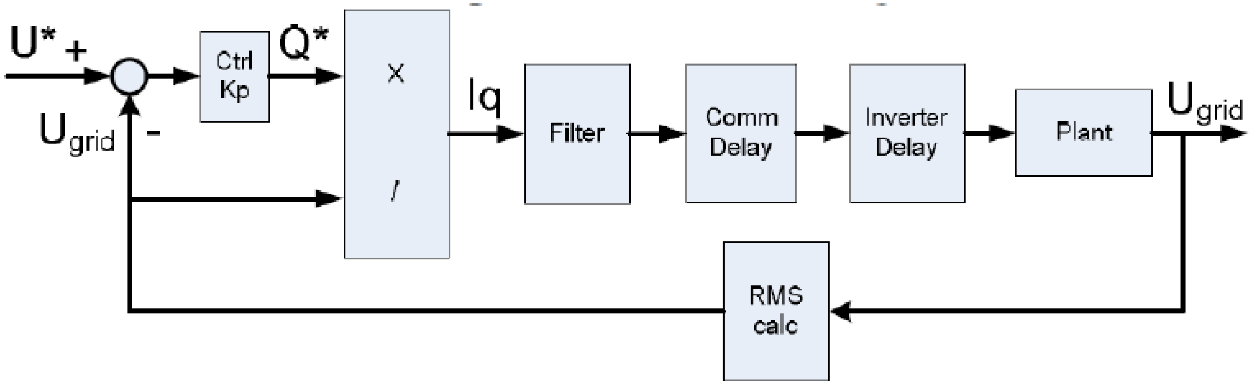
Zurick University
of Applied Sciences
zh aw
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering



Ole Marggraf, 32. PV Tagung Deutschland, Staffelstein 2017

Control Loop

Controller Parameters : k prop. factor, time response τ



$$Kp = \frac{\Delta Q[pu] \cdot S_N}{\Delta U[pu] \cdot U_N} = m \cdot \frac{S_N}{U_N}$$

$$\frac{T}{\tau} \leq \frac{1}{a_\zeta \cdot \frac{\Delta U_{\mathrm{PV}}}{\Delta U_{\mathrm{droop}}} \cdot \frac{\tan \varphi}{R/X} + b_\zeta}$$

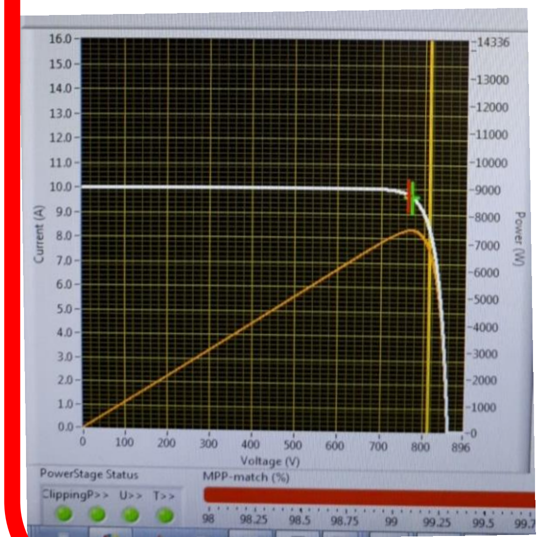
A. Constantin and R. D. Lazar, “Open loop Q(U) stability investigation in case of PV power plants,” in *Proc. 27th Eur. Photovoltaic Solar Energy, Conf. Exhib.*, Frankfurt, Germany, 2012, pp. 3745–3749

PV Inverter Test Lab at AIT

https://www.ait.ac.at/en/about-the-ait/center/center-for-energy/

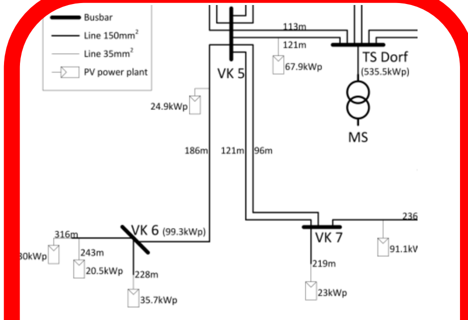
Experimental Setup at AIT

P_{PV}

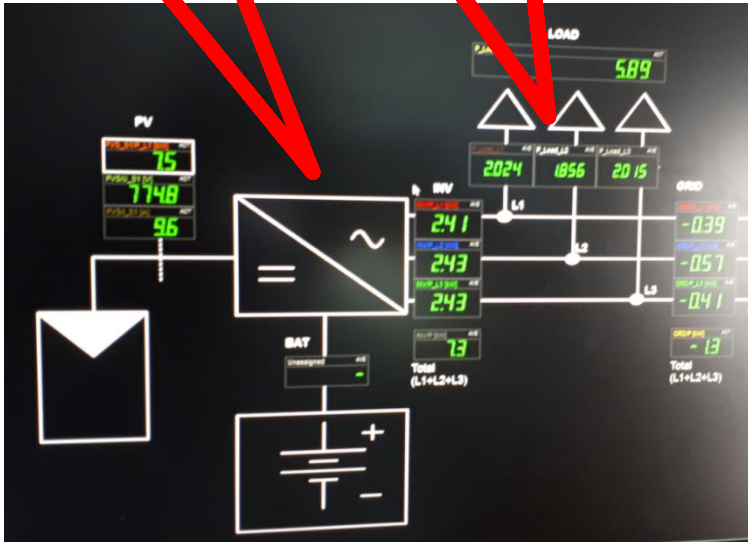


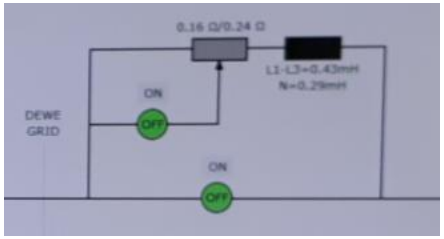
P, Q

P_{Load}



Z_{Grid} (R,L)





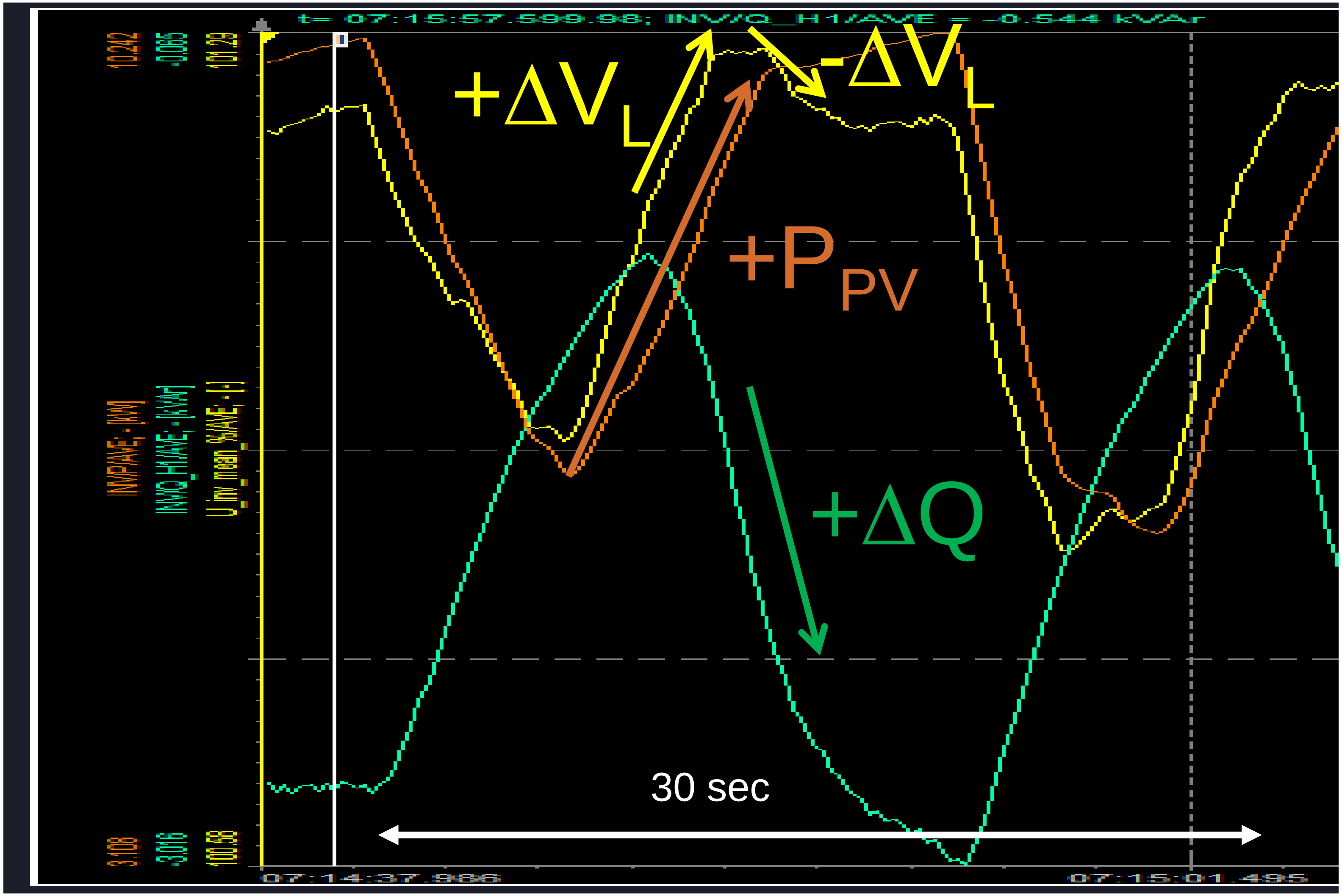
Measurement Results – Q(V) daily char.

Zurick University
of Applied Sciences

zh
aw

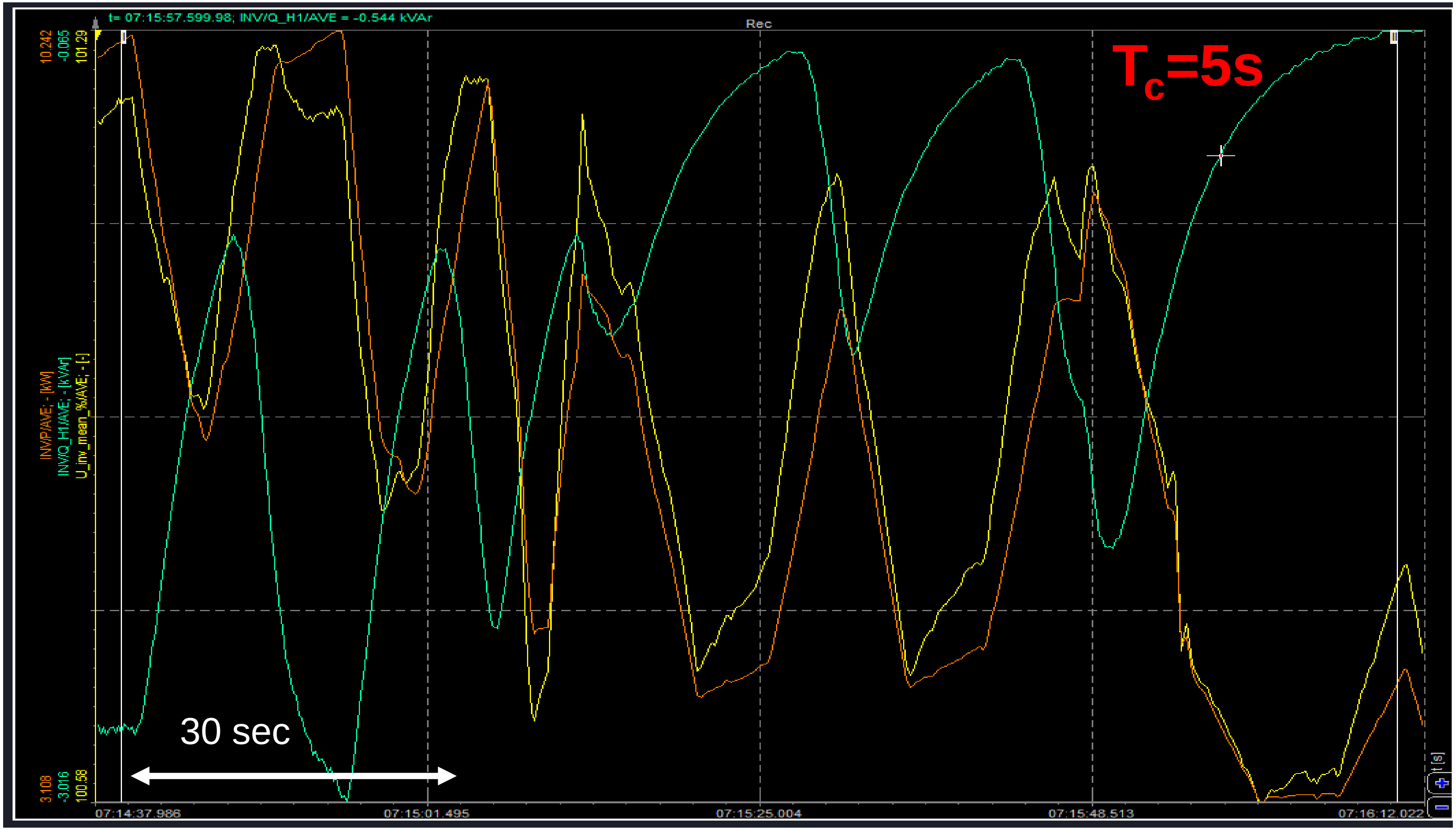
School of Engineering

IEFE Institute of Energy Systems and Fluid-Engineering



T_c=5s

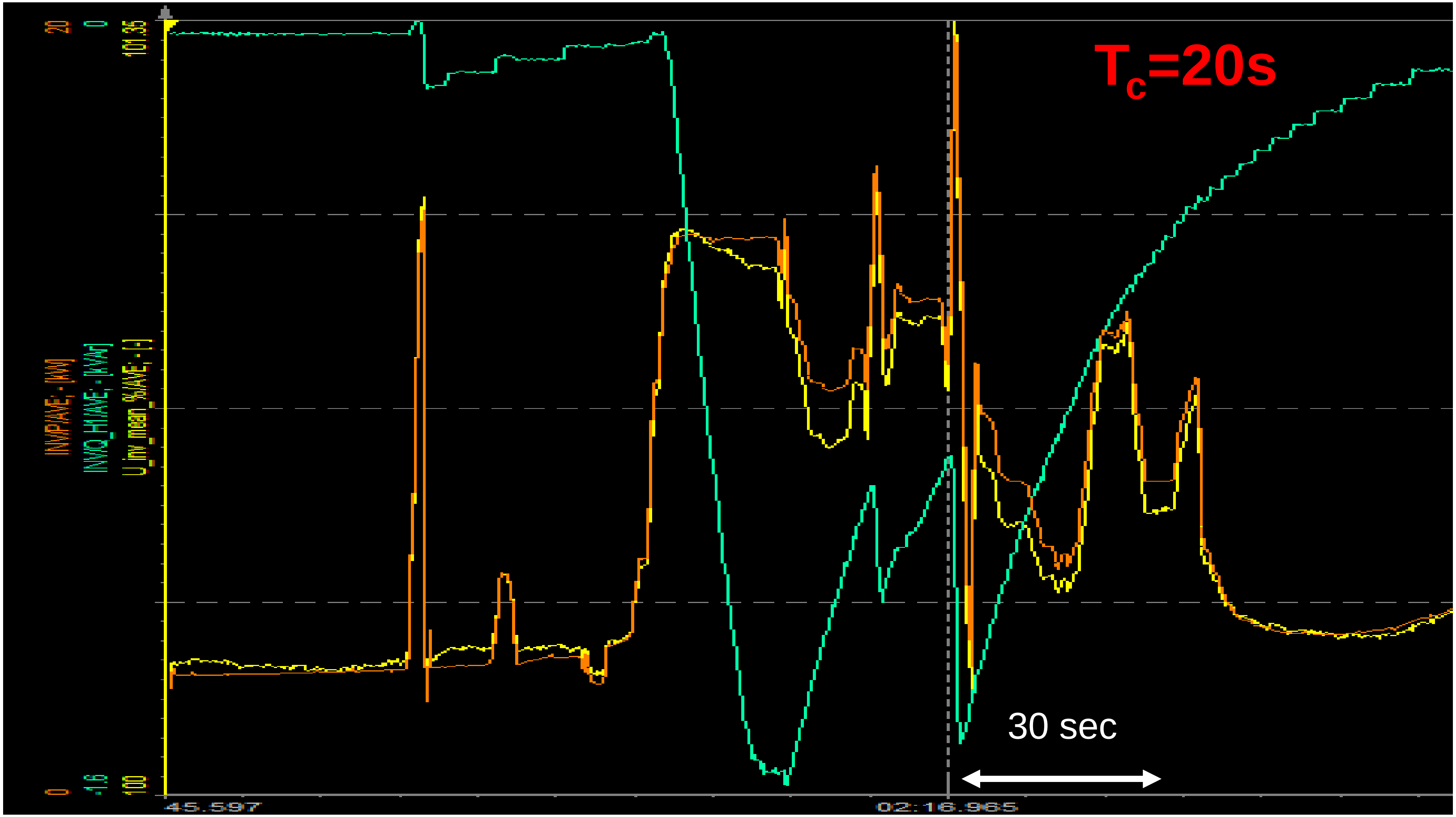
Measurement Results – Q(V) daily char.



Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

Zurick University
of Applied Sciences
zh
aw
School of
Engineering
IEFE Institute of Energy Systems
and Fluid-Engineering

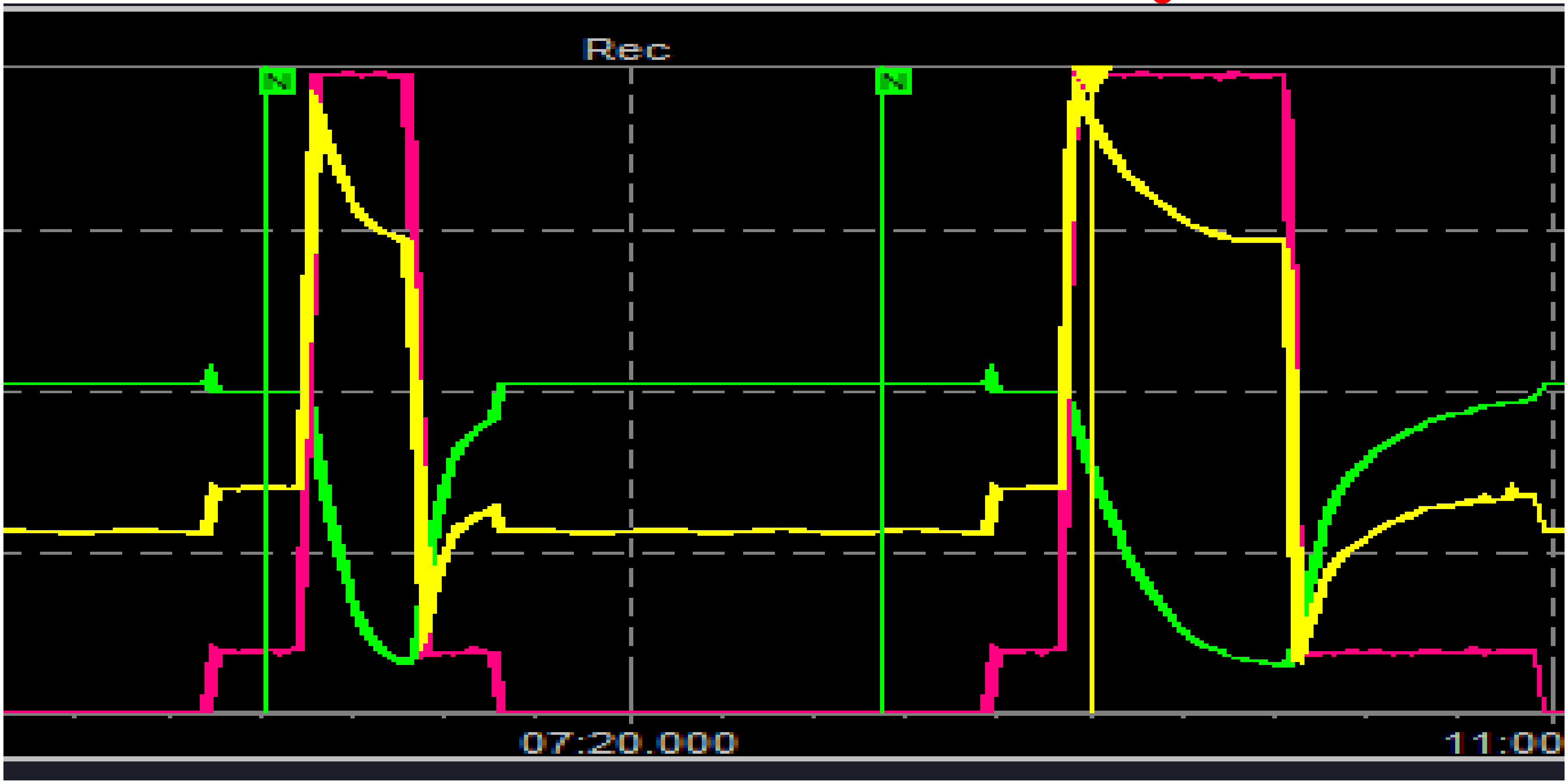
Measurement Results – Q(V) daily char.



P_{PV} – step function Q(V) response

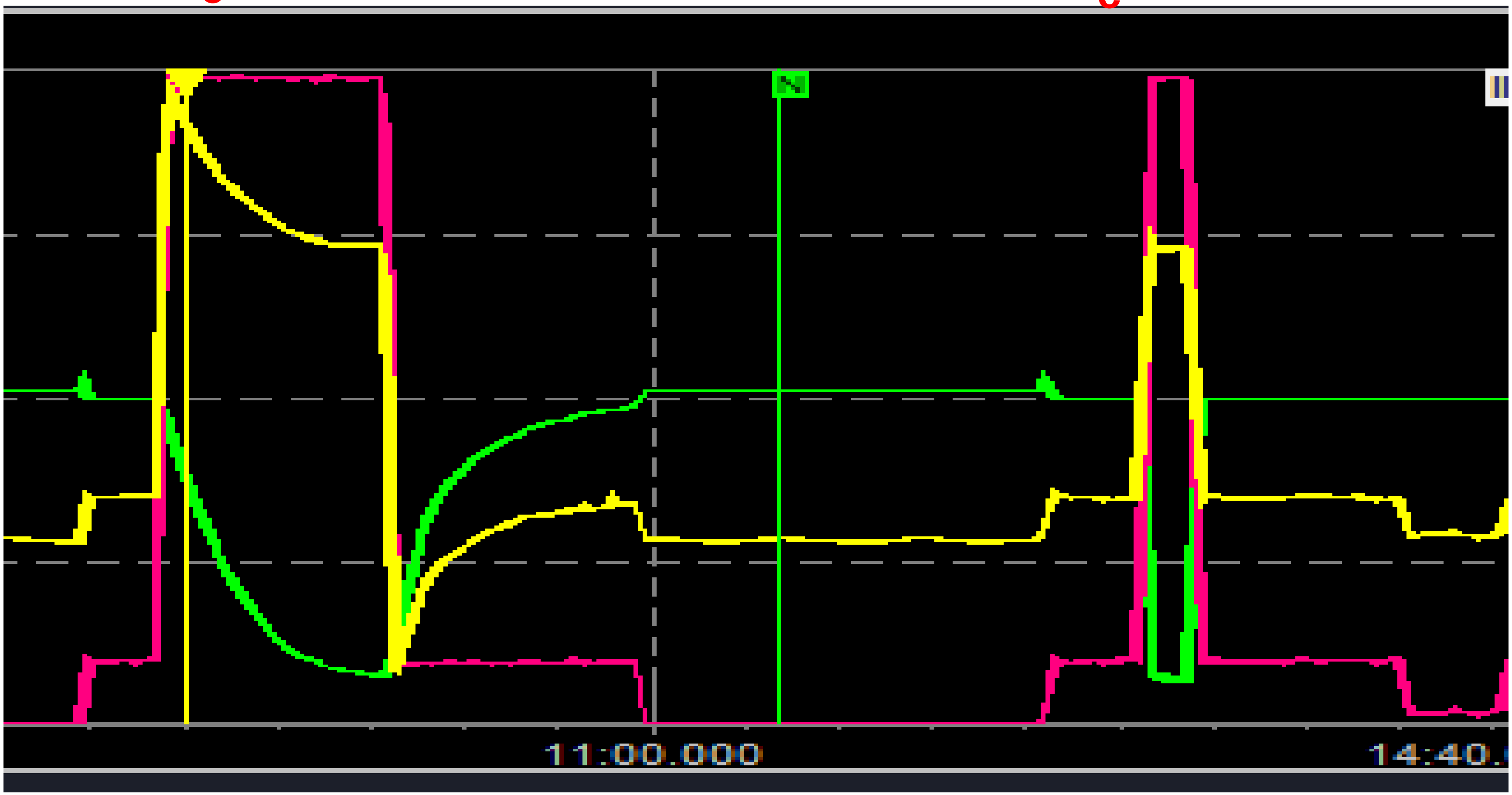
Zurick University
of Applied Sciences
zh aw
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

T_c=5s T_c=10s



P_{PV} – step function Q(V) response

T_c=10s T_c=0.5s

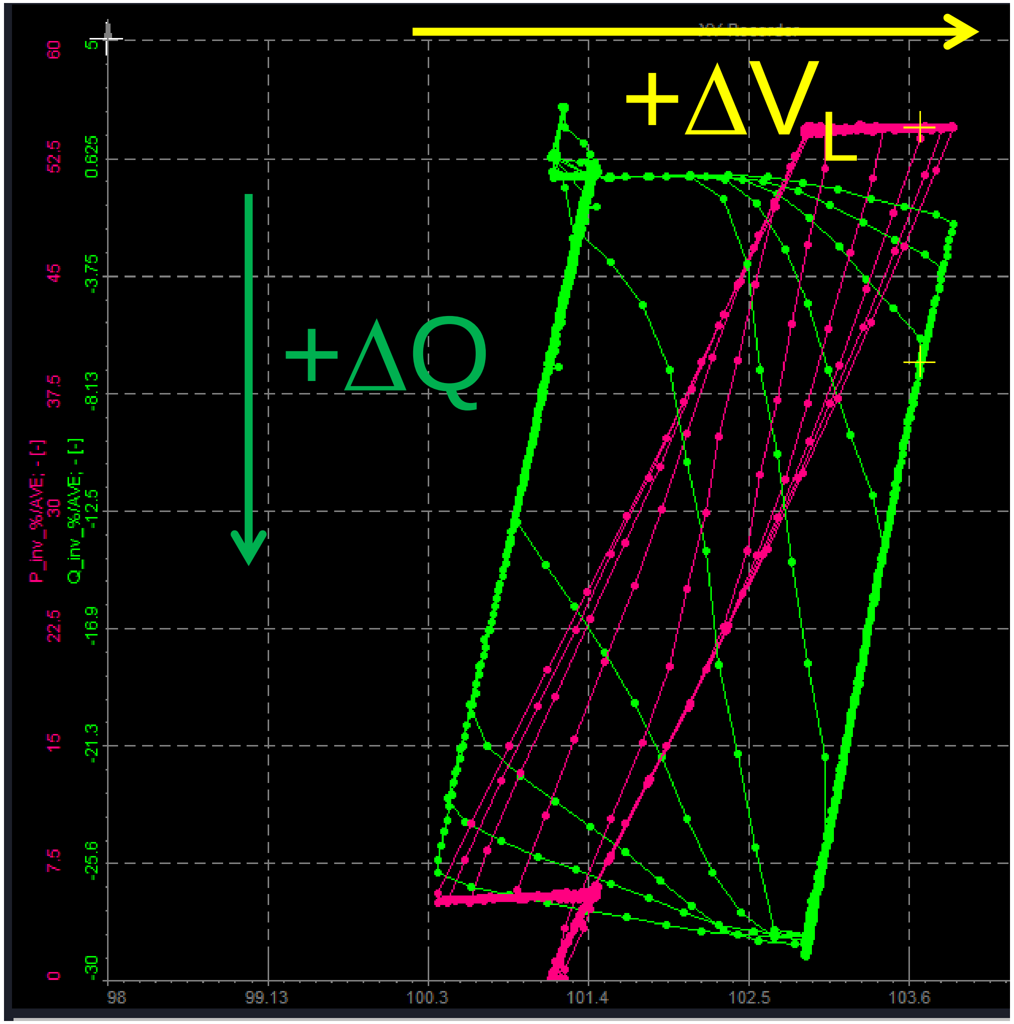


Controller time constant

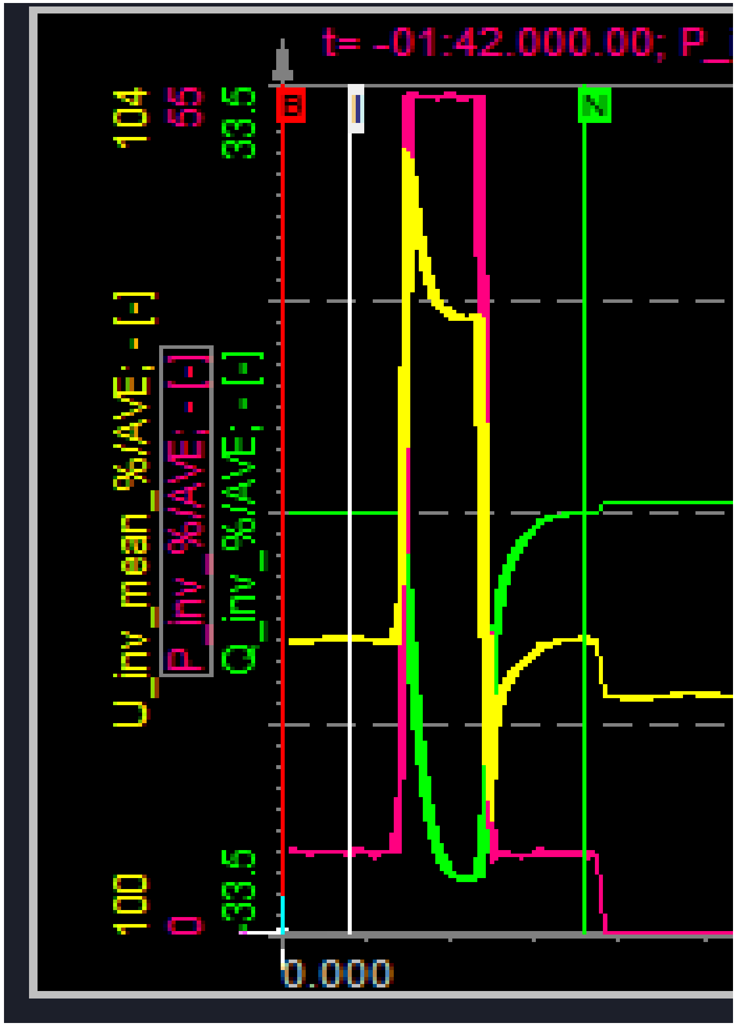
Zurick University
of Applied Sciences

School of Engineering

IEFE Institute of Energy Systems and Fluid-Engineering



T_c=
20s
10s
5s
2s
0.5s



Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

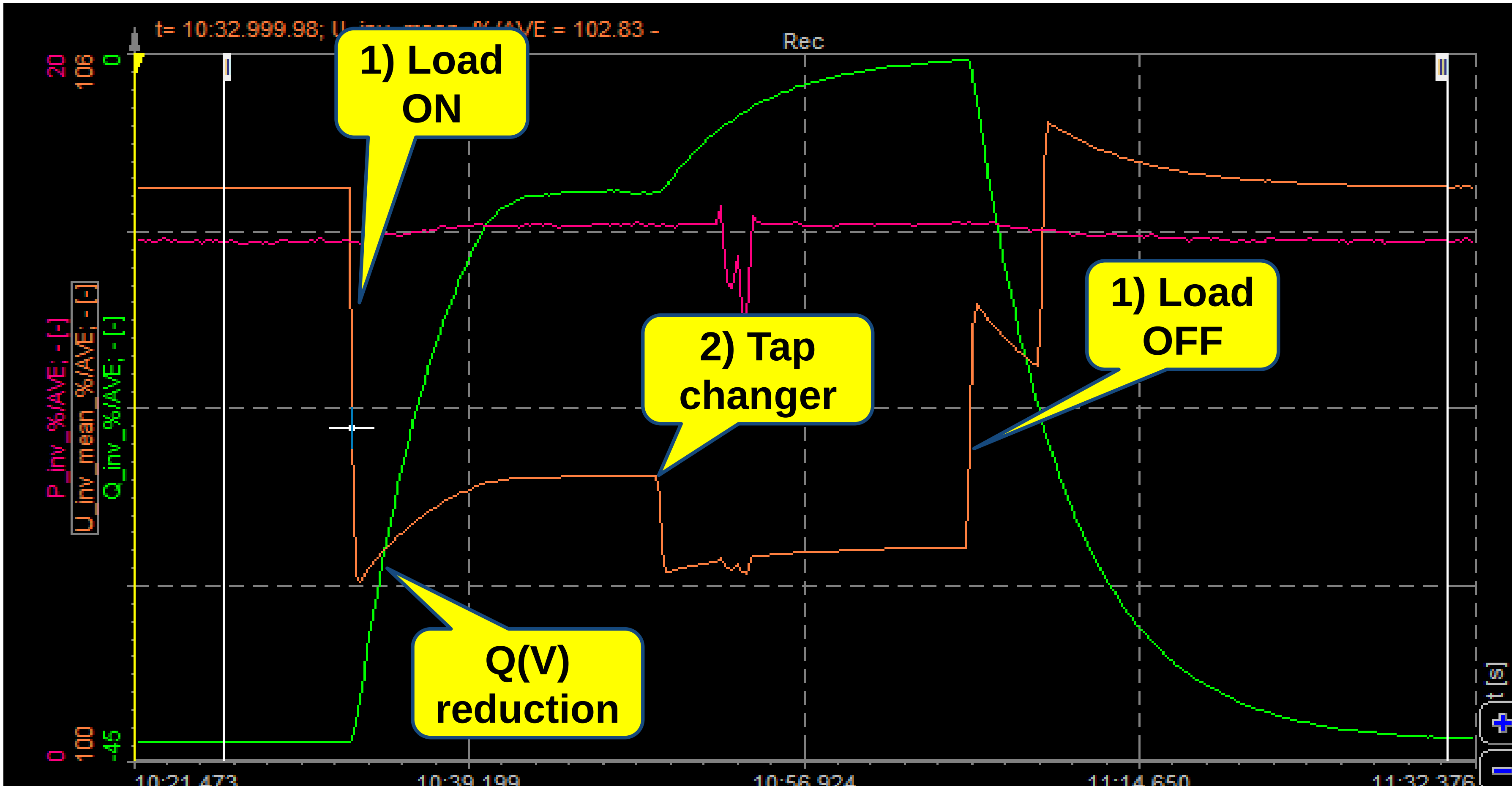
Zurick University
of Applied Sciences

School of
Engineering

IEFE Institute of Energy Systems
and Fluid-Engineering

Two line voltage steps – fast T=1sec

Events producing ΔVL step: 1) step change in load 2) substation tap changer

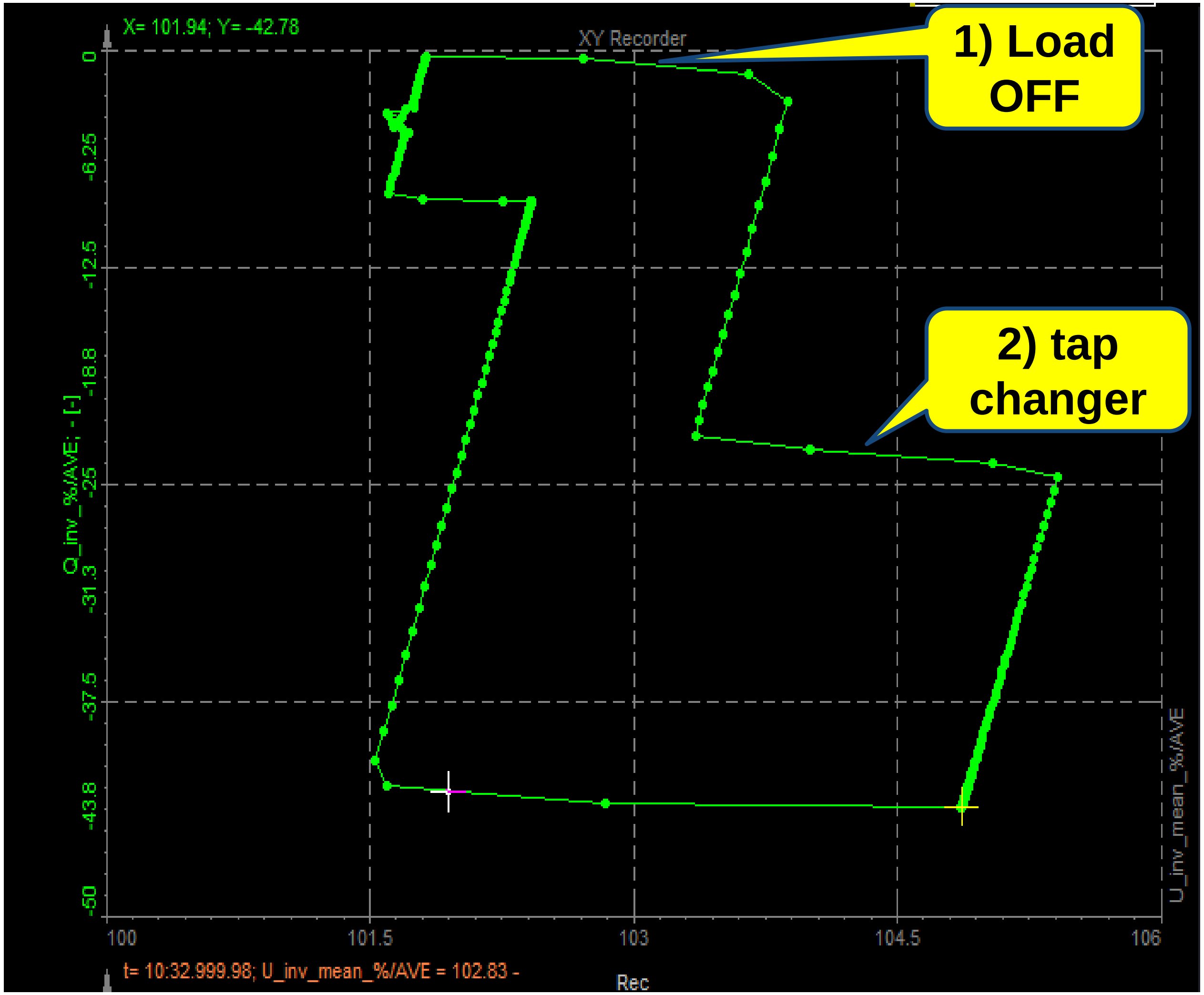


AUSTRIAN INSTITUTE OF TECHNOLOGY

Zurich University of Applied Sciences;, Franz Baumgarrtner et. al. http://www.zhaw.ch/=bauf

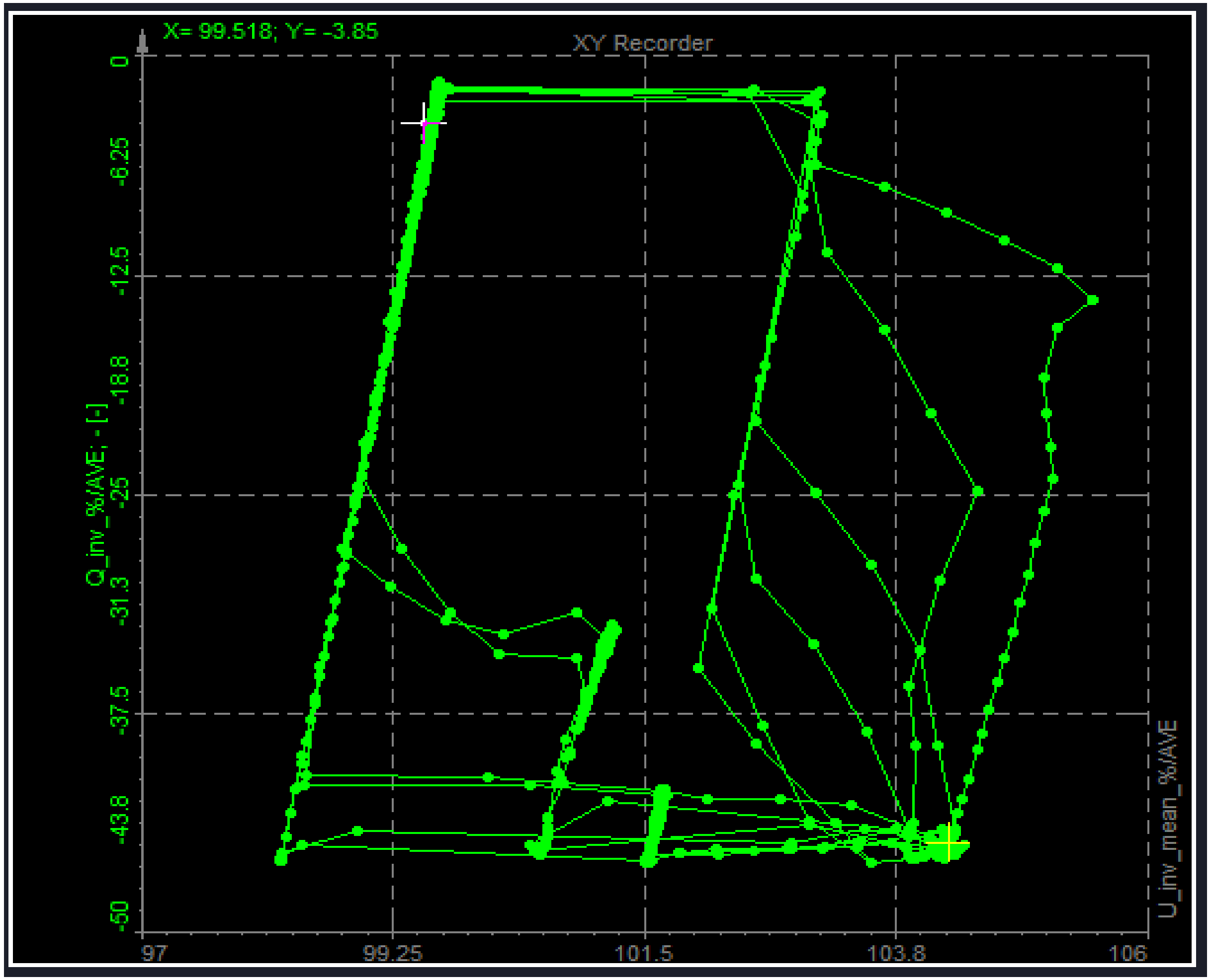
Two line voltage steps – fast T=0.5sec

Zurick University
of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems
and Fluid-Engineering



Two line voltage steps – fast to slow

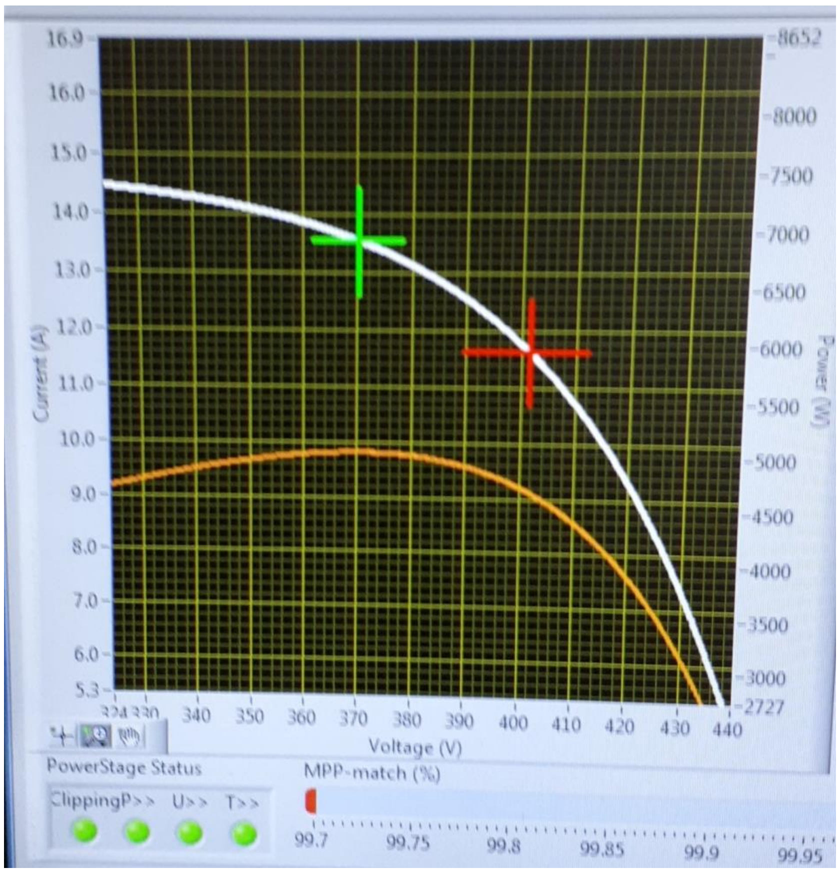
Zurick University
of Applied Sciences
zh
aw
School of
Engineering
IEFE Institute of Energy Systems
and Fluid-Engineering

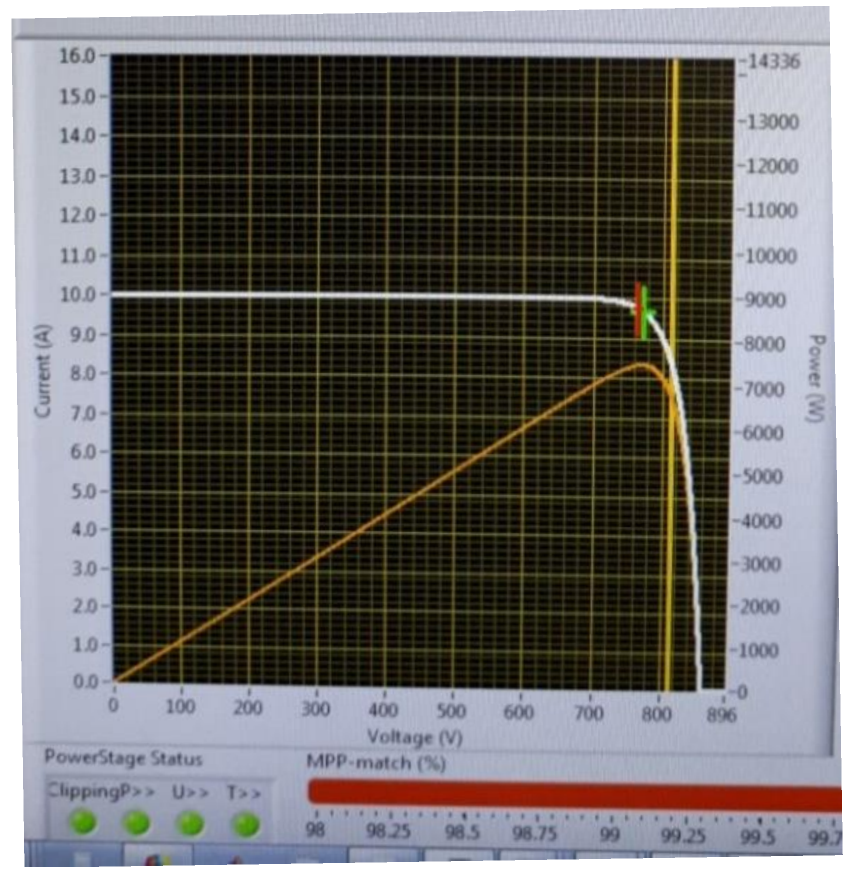


T_c=
20s
10s
5s
2s
0.5s

S apparent power limit and MPP mismatch

Interference of Q(V) controller at the current limit of apparent power may cause small Q oscillations in sec range coupled with the PV maximum power tracker Voc.





Zurick University
of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

PV Inverters are Part of the Solution

...Faster than a tap changer

...More powerful than a rotating machine

...Able to leap deep voltage sags in a single bound

Courtessy of B. Lydic, Fronius

Jay Johnson, Sandia Labs, USA
India Smart Grid Week, March 7-10, 2017
ManekshawCenter, New Delhi, India.

Conclusion

Zurick University
of Applied Sciences
zh
aw
School of Engineering
IEFE Institute of Energy Systems
and Fluid-Engineering

Voltage dependent APC and RPC…

- PQ(V) control is a promising low-cost, low-tech method to reduce voltage rise
- PV inverters can be used to reduce impact of EV charging
- is a **very cost-effective solution** and it doesn't need further investments into IT infrastructures or hardware.
- Recommended Q(V) controller time constant τ should be **lower than 5 sec closer to 1 sec** without the risk of instability and thus reducing overshoot of reactive power in the distribution grid

Zurick University
of Applied Sciences
School of Engineering
IEFE Institute of Energy Systems and Fluid-Engineering

Thank you for your attention

Connecting European Smart Grid Infrastructures

Project is funded by European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out; Ref. No 03.007-2017; TIPI-GRID

Thanks to our industrial partners:

EKZ

EKS

Part of the project is funded by the Swiss Federal Office of Energy (SFOE) under the contract number SI/501370-01