Energy Internet
The Challenge of Smart Micro-Grids

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Outline

- **Diffusion of Renewable Energy Sources (RES)**
- **Evolution of distribution grid architecture**
- **Role and impact of micro- and nano-grids**
- **Architecture and components of low-voltage micro-grids**
- **Control hierarchy in low-voltage micro-grids**
- **Power-based control of low-voltage micro-grids**
- **Off-line and real-time simulation**
- **Experimental results**
- **What comes next**
- **Conclusions**

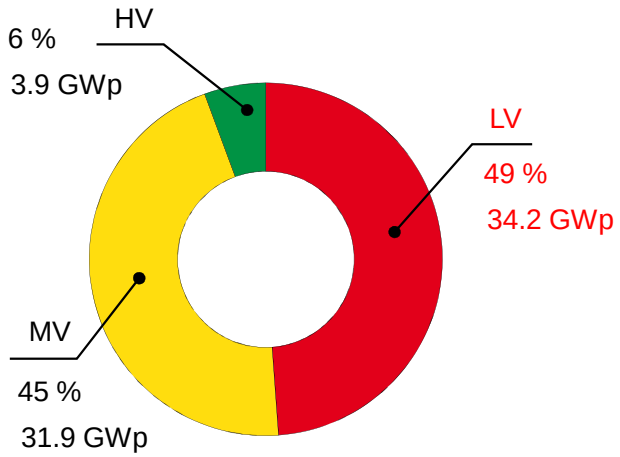
Renewable Energy / PV – Future trend

- **Photovoltaics (PV) is one of the main pillars of future energy supply. According to IEA (International Energy Agency), in 2050 PV energy will contribute to more than 15% of the world electricity demand. (1)**
- **EU has set the target of 27% renewable energy in 2030. Assuming that nearly 40% will come from PV, at least 220 GWp of new PV capacity shall be installed in Europe by 2030. (2)**

(1) **International Energy Agency, PV Roadmap until 2050, September 2014.**

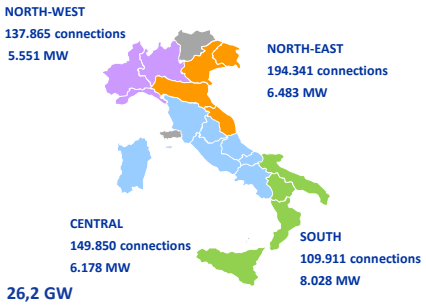
(2) **European Photovoltaic Technology Platform, Position Paper on the Future of the Photovoltaic Manufacturing Industry in Europe, March 2015.**

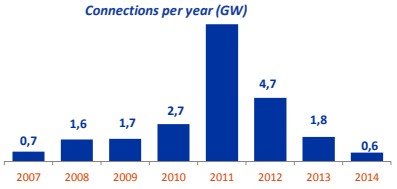
PV Impact on Distribution Grid (EU 2014)

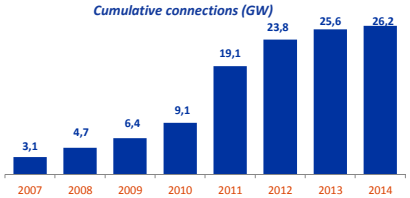


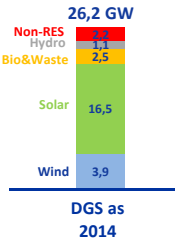
Source: www.pvgrid.eu

Distributed Generation in Italy (2014)







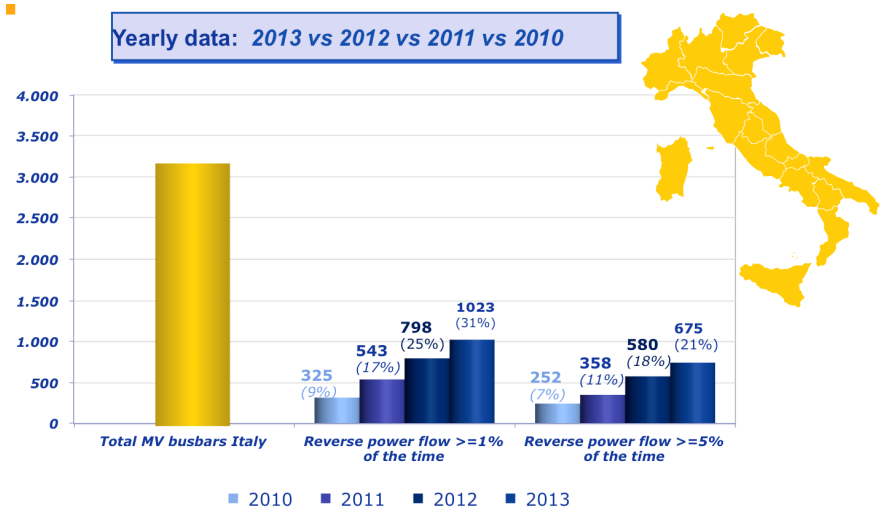


TOTAL
591.967 connections
26.240 MW

>500.000 LV prosumers invested some 25 B€

Source: www.pvgrid.eu

MV busbars with reverse power flow in Italy (2014)



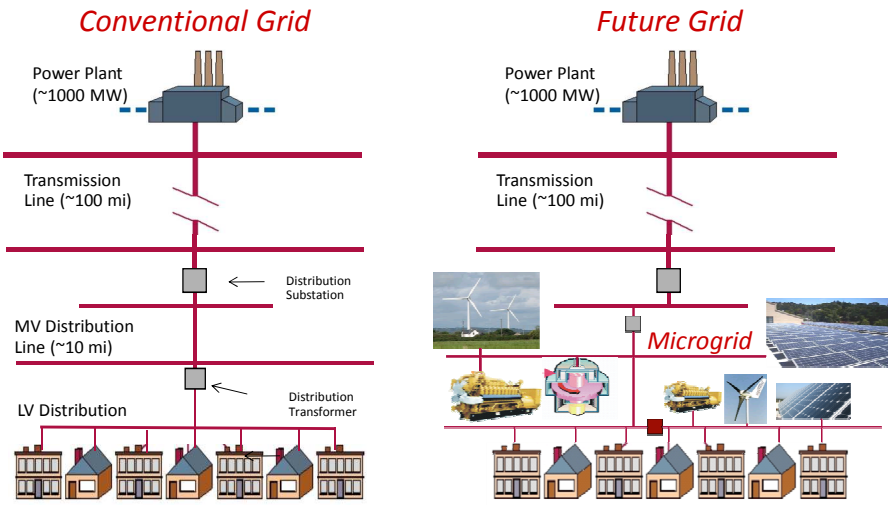
Source: www.pvgrid.eu

Effects of renewable energy penetration in LV grids

- **Intermittent** power generation
- Alteration of **voltage profiles** due to local power injection
- Reduction of **power quality** due to circulation of reactive currents, injection of unbalanced power by single-phase equipment, increase of THD due to resonances
- Possibility of **unintentional islanding**
- **Reversal of power flow** in distribution busbars
- …

Solution: Aggregate distributed energy sources into LV "smart" micro-grids capable of efficient power sharing, flexible interaction with the utility, and off-grid operation.
For/Against: This approach would revolutionize the electrical market structure and economy (↑), but is currently prevented by DSOs (Distribution System Operators) at regulatory level (↓).

Evolution of Electric Grid



Micro & Nano-grids: Impact

ENERGY – ENVIRONMENT – QUALITY OF SERVICE

- Pervasive use of green energy
- Reduction of carbon footprint
- Synergistic exploitation of energy sources
- Improved power quality even in remote locations
- Increased hosting capacity of existing infrastructure

SOCIAL – ECONOMICS - MARKET

- Strong involvement of citizens (environmental awareness, economics)
- Reinforced prosumers' role by aggregation of communities
- New functions and players in the energy market: ESCOs, technology providers, web service providers, aggregators, etc.
- Enhanced role of national and local authorities to warrant and regulate the electrical market
- Huge potential for green collars, investors and entrepreneurs

TOWARD AN ELECTRICAL MARKET REVOLUTION

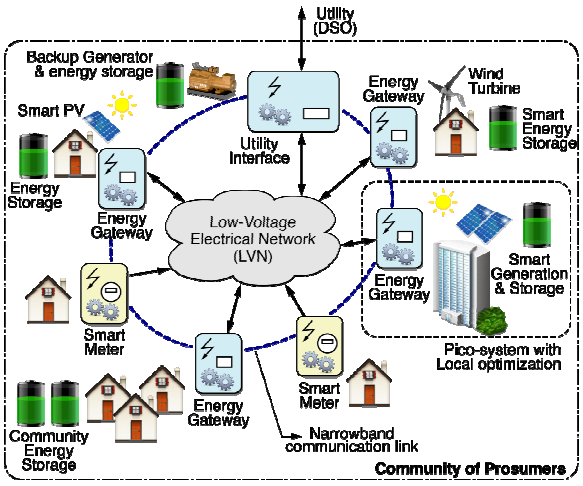
THE INTERNET OF ENERGY

Micro & Nano-grids: Technological Challenges

- Implement cheap ICT platforms for distributed control and communication
- Restructure network protections
- Pursue flexibility and scalability (from buildings to townships)
- Develop layered architectures (micro-grids as tiles of larger patchworks)
- Pursue energy efficiency at any levels
- Integrate micro-grid control and domotics
- Assure data security and privacy
- Revise accounting principles and methodologies
- Retrofit existing plants
- …..

TECHNOLOGY IS NOT THE BOTTLENECK !

LV Micro-Grid Architecture

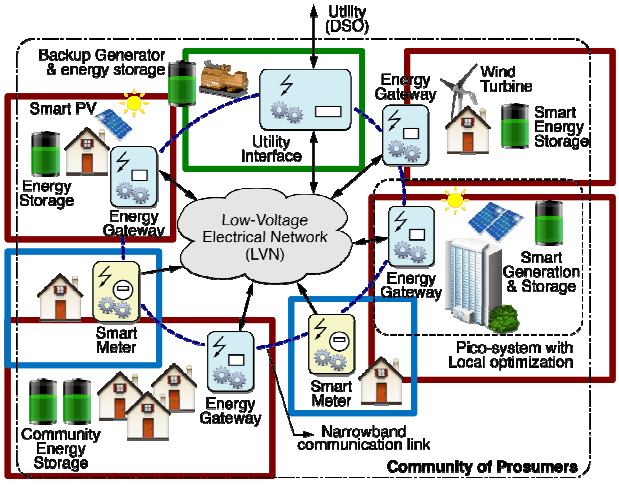


Elements:

- LV distribution grid
- **ICT infrastructure**
- Passive loads
- Renewable energy sources
- Energy storage devices
- **Smart meters**
- **Energy gateways (EG)**
- **Utility Interface (UI) / Master Controller (MC)**

The Utility Interface is a key element to ensure safe dynamic operation of the micro-grid and effective interaction with the mains

Role of "Smart" Elements



Utility Interface allows optimum micro-grid operation in steady state (minimum losses, maximum power quality) and enables black start and soft transition to/from islanding condition.

Smart meters

- Local metering
- One-way communication to UI/MC

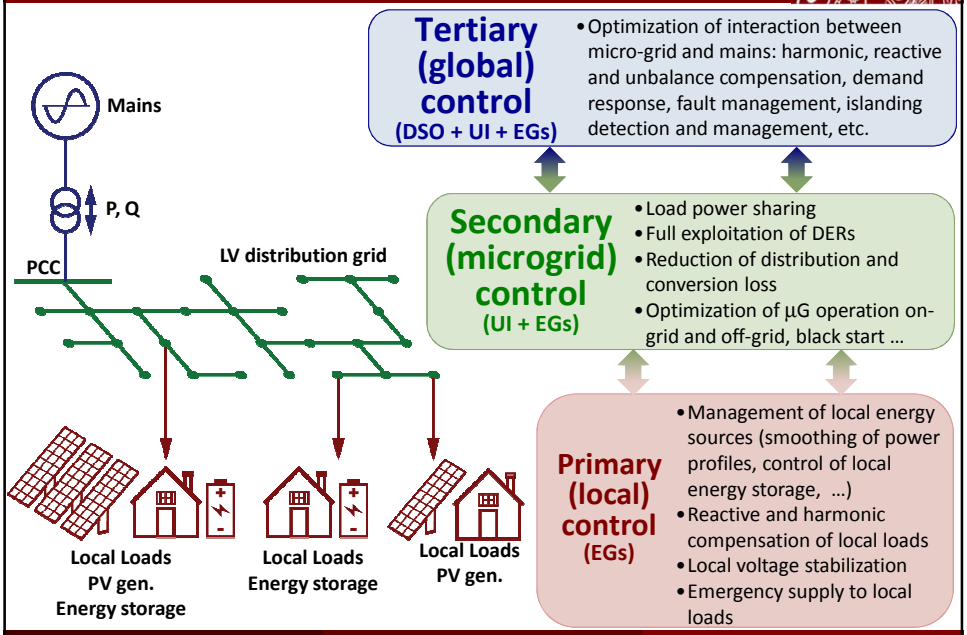
Energy Gateways

- Current sources
- Interface local sources and LV grid
- Control slaves (two-way communication to UI/MC)

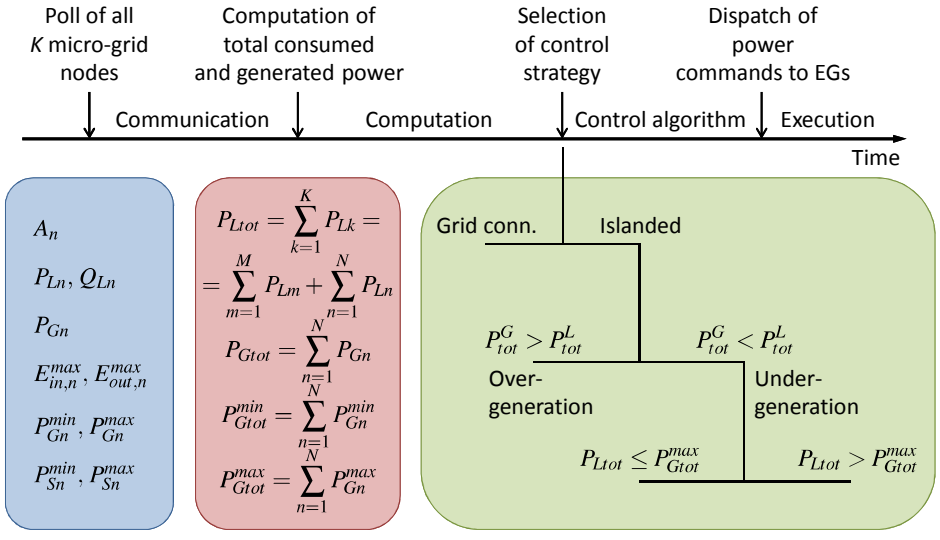
Utility Interface

- Voltage Source
- Interfaces micro-grid and utility
- Control master (two-way communication to EGs and DSO)

Control Hierarchy



Power-Based Control – Data processing



Power commands do not need synchronization !

Power-Based Control - Features

Control features	Hierarchic control level	Agents	Objectives
• **Local voltage support**	Primary	EGs	• **Cooperative operation of DERs**
• **Full exploitation of distributed energy sources including storage**	Primary/Secondary	UI & EGs	• **Minimum power loss**
• **Full exploitation of power converter control capability (active, reactive, unbalance and distortion power control)**	Primary / Secondary	UI & EGs	• **Fast dynamic response** • **Control of voltage profiles**
• **Optimum power sharing**	Secondary	UI & EGs	• **Micro-grid to operate as a single aggregate prosumer**
• **Transition on-grid ↔ off-grid**	Tertiary	UI	
• **Demand response**	Tertiary	UI & EGs	• **Islanded operation**

System features

- **Plug & play integration** of energy sources and storage units
- **Scalability of architecture**
- **Asynchronous control** of distributed power sources
- **Broadcasted power commands** (one-way communication)
- **EGs operated as current sources** (grid impedances not affected)
- **Controllable power factor** at utility terminals
- **Demand response** (micro-grid responds to utility power requests)

What comes next – Energy SuperNet

Active integration of micro-grids in MV distribution grids

Aim: to take full advantage of distributed control capability

- Control of amplitude and direction of active and reactive power flow
- Integration and management of community energy storage
- Dynamic control of voltage profiles
- Planning and management of demand response
- Active protection in case of fault
- Improved distribution efficiency
- Synergistic control and exploitation of distributed power sources
- Extended flexibility of operation
- Implementation of layered architectures
- **Increased hosting capacity of existing infrastructure**

GREAT DEVELOPMENT EFFORT, BUT NO BOTTLENECKS IN TECHNOLOGY !

Smart micro-grids: a win-win solution

END-USERS (prosumers) take advantage of:
- Energy savings, reduced electricity bill, increased power quality
- Upgrade of role in electrical market, increased negotiation capability

DSOs and ESCOs take advantage of :
- Aggregation of end-users into efficient and programmable macro-users
- Participation of end-users to investments for distributed energy generation, storage and management
- Improved flexibility and efficiency of distribution network operation

ENVIRONMENT, SOCIETY & ECONOMY take advantage of:
- Low-carbon energy
- Active citizen participation to energy market
- New services for prosumers' community (warrants, regulators, aggregators, traders, app developers …. **Internet-like**)

Traditional oligarchic electric market evolves toward democracy !

Conclusions

- Distributed generation, from small environmental sources to residential renewable energy, is experiencing a huge diffusion worldwide.
- This will dramatically change some traditional and consolidated markets, like electric distribution, and open entirely new and pervasive application domains, like nano- and micro-grids.
- The expected investments on distributed generation technologies in the next decade are very high (tens of B$ in North-America, Europe, China, Japan, Korea ..) , under the pressure to reduce carbon footprint, preserve environment and improve health and quality of life.
- Key elements of such innovations are ICT and power electronic devices and systems, that can provide distributed and effective power management at low cost, high efficiency and compactness.
- **After one century of substantial stability the electrical market is now approaching a bottom-up revolution, under the pressure of stringent environmental politics, aggressive and distributed investment strategies, ICT market push, and technology advancement.**

List of References - 1

[1] G. Meneghesso, " Solar Energy Conversion: Photovoltaic" Levi Cases "Retreat Day" Jan 18, 2016.

[2] A. Cerretti, "Analysis of the coordination of interface protection system with Distributed Energy Resources compliant with most recent evolution of the standards: the unintentional islanding case", Symposium on Smart Inverter Testing and Interoperability, Bilbao, October 2015

[3] D. Boroyevich, "REN Miniconsortium", CPES Conference (www.cpes.vt.edu)

[4] P. Mattavelli, D. Boroyevich, "Small-Signal Stabiliy and Sybsystem Interactions in Three-Phase Nano-grids", Tutorial at 2012 CPES Conference, Blackburg, VA

[5] D. Boroyevich, Class notes from ECE5274

[6] Peng Xiao, G. Venayagamoorthy, and K. Corzine, "A Novel Impedance Measurement Technique for Power Electronic Systems," in *Power Electronics Specialists Conference, 2007. PESC 2007. IEEE*, 2007, pp. 955–960.

[7] L.R. Lewis, B.H. Cho, F.C. Lee, B.A. Carpenter, "Modeling, analysis and design of distributed power systems," in *Power Electronics Specialists Conference, 1989. PESC 1989. IEEE,* 1989 , pp.152-159 .

[8] S.Y. Erich, W.M. Polivka, "Input filter design for current-programmed regulators," in *Applied Power Electronics Conference and Exposition (APEC), 1990 Fifth Annual IEEE*, 1990, pp. 781–791.

[9] Y. Jang, R.W. Erickson, "Physical origins of input filter oscillations in current programmed converters," *Power Electronics, IEEE Transactions on*, vol.7, no.4, pp.725-733, 1992.

[10] Byungcho Choi; B.H. Cho, , "Intermediate line filter design to meet both impedance compatibility and EMI specifications," *Power Electronics, IEEE Transactions on*, vol.10, no.5, pp.583-588, 1995.

[11] C.M. Wildrick, F.C. Lee, B.H. Cho, B. Choi, "A method of defining the load impedance specification for a stable distributed power system," *Power Electronics, IEEE Transactions on*, vol.10, no.3, pp.280-285, 1995 .

[12] Feng Xiaogang; Ye Zhihong; Xing Kun; F.C. Lee, D. Borojevic, "Impedance specification and impedance improvement for DC distributed power system," in *Power Electronics Specialists Conference, 1999. PESC 1999. IEEE,* 1999, pp.889-894 .

List of References - 2

[13] A. MacFarlane and I. Postlethwaite, "The generalized Nyquist stability criterion and multivariable root loci," in *Int. Jour. of Control,* vol. 25, pp. 81-127, 1977.

[14] M. Belkhayat, R. Cooley, A. Witulski, "Large signal stability criteria for distributed systems with constant power loads," in *Power Electronics Specialists Conference, 1995. PESC 1995, IEEE* , 1995, pp.1333-1338

[15] Y. A. Familiant, Jing Huang, K. A. Corzine, and M. Belkhayat, "New Techniques for Measuring Impedance Characteristics of Three-Phase AC Power Systems," *Power Electronics, IEEE Transactions on*, vol. 24, no. 7, pp. 1802–1810, 2009.

[16] Sun Jian; "Impedance-Based Stability Criterion for Grid-Connected Inverters," *Power Electronics, IEEE Transactions on*, vol.26, no.11, pp.3075-3078, 2011

[17] Xiaogang Feng, Jinjun Liu, and F. C. Lee, "Impedance specifications for stable DC distributed power systems," *Power Electronics, IEEE Transactions on DOI - 10.1109/63.988825*, vol. 17, no. 2, pp. 157–162, 2002.

[18] Barkley and E. Santi, "Improved Online Identification of a DC–DC Converter and Its Control Loop Gain Using Cross-Correlation Methods," *Power Electronics, IEEE Transactions on DOI - 10.1109/TPEL.2009.2020588*, vol. 24, no. 8, pp. 2021–2031, 2009.

[19] M. Belkhayat, "STABILITY CRITERIA FOR AC POWER SYSTEMS WITH REGULATED LOADS," Purdue Univerisity, West Lafayette, IN, 1997.

List of References - 3

[20] M. Sumner, B. Palethorpe, D. W. P. Thomas, P. Zanchetta, and M. C. Di Piazza, "A technique for power supply harmonic impedance estimation using a controlled voltage disturbance," *Power Electronics, IEEE Transactions on*, vol. 17, no. 2, pp. 207–215, 2002.

[21] Y. L. Familiant, K. A. Corzine, J. Huang, and M. Belkhayat, "AC Impedance Measurement Techniques," in *Electric Machines and Drives, 2005 IEEE International Conference on*, 2005, pp. 1850–1857.

[22] Y. L. Familiant, "AC impedance measurement techniques in power systems," University of Wisconsin, Milwaukee, 2006.

[23] Jian Sun, "AC power electronic systems: Stability and power quality," in *Control and Modeling for Power Electronics, 2008. COMPEL 2008. 11th Workshop on*, 2008, pp. 1–10.

[24] M. L. Gasperi, "AC power line impedance monitoring method and system," U.S. Patent 716427516-Jan-2007.

[25] R. Burgos, D. Boroyevich, F. Wang, K. Karimi, and G. Francis, "Ac stability of high power factor multi-pulse rectifiers," in *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE*, 2011, pp. 3758–3765.

[26] Z. Staroszczyk, "Accuracy problems in on-line one-phase distribution/load system identification task," in *Industrial Electronics, 1996. ISIE '96., Proceedings of the IEEE International Symposium on*, 1996, vol. 1, pp. 354–357 vol.1.

[27] S. D. Sudhoff, S. F. Glover, P. T. Lamm, D. H. Schmucker, and D. E. Delisle, "Admittance space stability analysis of power electronic systems," *Aerospace and Electronic Systems, IEEE Transactions on DOI - 10.1109/7.869516*, vol. 36, no. 3, pp. 965–973, 2000.

List of References - 4

[28] G. Francis, R. Burgos, D. Boroyevich, F. Wang, and K. Karimi, "An algorithm and implementation system for measuring impedance in the D-Q domain," in *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE*, 2011, pp. 3221–3228.

[29] V. Valdivia, A. Lazaro, A. Barrado, P. Zumel, C. Fernandez, and M. Sanz, "Black-Box Modeling of Three-Phase Voltage Source Inverters for System-Level Analysis," *Industrial Electronics, IEEE Transactions on DOI - 10.1109/TIE.2011.2167730*, vol. PP, no. 99, p. 1, 2011.

[30] Knop and F. W. Fuchs, "High frequency grid impedance analysis with three-phase converter and FPGA based tolerance band controller," in *Compatibility and Power Electronics, 2009. CPE '09.*, 2009, pp. 286–291.

[31] L. Harnefors, M. Bongiorno, and S. Lundberg, "Input-Admittance Calculation and Shaping for Controlled Voltage-Source Converters," *Industrial Electronics, IEEE Transactions on DOI - 10.1109/TIE.2007.904022*, vol. 54, no. 6, pp. 3323–3334, 2007. Sgarbossa, R.; Lissandron, S.; Mattavelli, P.; Turri, R.; Cerretti, A., "Analysis of load-induced unintentional islanding in Low Voltage grids with PV generators," in Control and Modeling for Power Electronics (COMPEL), 2014 IEEE 15th Workshop on , vol., no., pp.1-8, 22-25 June 2014

[32] Sgarbossa, R.; Lissandron, S.; Mattavelli, P.; Turri, R.; Cerretti, A., "Analysis of ΔP-ΔQ area of uncontrolled islanding in low voltage grids with PV generators," in Energy Conversion Congress and Exposition (ECCE), 2014 IEEE , vol., no., pp.5667-5674, 14-18 Sept. 2014.

[33] Lissandron, Stefano; Sgarbossa, Riccardo; Dalla Santa, Luca; Mattavelli, Paolo; Turri, Roberto; Cerretti, Alberto, "Impact of non-simultaneous P/f and Q/V grid code requirements on PV inverters on unintentional islanding operation in distribution network," in Power Electronics for Distributed Generation Systems (PEDG), 2015 IEEE 6th International Symposium on , vol., no., pp.1-7, 22-25 June 2015